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Improve performance of scanning probe microscopy by balancing tuning fork prongs ☆

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ABSTRACT

This paper presents an approach for improving the *Q*-factor of tuning fork probe used in scanning probe microscopes. The improvement is achieved by balancing the fork prongs with extra mass attachment. An analytical model is proposed to characterize the *Q*-factor of a tuning fork probe with respect to the attachment of extra mass on the tuning fork prongs, and based on the model, the *Q*-factors of the unbalanced and balanced tuning fork probes are derived and compared. Experimental results showed that the model fits well the experimental data and the approach can improve the *Q*-factor by more than a factor of three. The effectiveness of the approach is further demonstrated by applying the balanced probe on an atomic force microscope to obtain improved topographic images.

1. Introduction

Tuning fork probe is widely used in scanning probe microscopes (SPMs), particularly in scanning near-field optical microscopes where it is essential to avoid unnecessary optical interference [1]. A tuning fork probe is formed by a tuning fork with a fiber probe glued on one prong. In operation, the tuning fork probe is excited to its resonant status which is sensitive to the tiny force received by the probe when it is brought to the nanoscale proximity of the sample. In order to have a higher sensitivity, a high quality factor (*Q*-factor) of the tuning fork probe is desired. However, practices have shown that the *Q*-factor of a tuning fork is significantly reduced after it is attached with a probe. In the past years, much effort has been contributed on improving the *Q*-factor of tuning fork probe. The improvement is investigated from various aspects including probe attachment [2–7], tuning fork design [8], operation of tuning fork [9–11], and excitation of tuning fork [12–14]. The resultant tuning fork probes have attained improved *Q*-factors subject to some practical constraints in fabrication and alignment. This paper presents a new approach to further improve the *Q*-factor of existing tuning fork probes by balancing the tuning fork prongs with extra mass.

The idea of balancing the effective masses was mentioned in [13] but it was not demonstrated. In [13], a tuning fork probe is characterized by two coupled oscillators which are only unbalanced in their effective masses. Although the model can explain the decrease in *Q*-factor, experiments for practical tuning fork probes show significant discrepancies of this model in calculating the *Q*-factor. In this paper, the tuning fork probe is considered as two coupled oscillators which are unbalanced not only in the effective masses but also in the damping ratios. The *Q*-factor of the tuning fork probe is characterized by an rational fraction model of the changes in effective mass and damping ratio. Experiment results in the paper show that attaching the probe or adding extra mass on the prongs of the tuning fork changes the unbalance status in the effective mass and the damping ratio, but the coefficients of the rational fraction model can be treated as constants. Thus, the model not only characterizes quantitatively the decrease of *Q*-factor due to the attachment of a fiber probe on a bare tuning fork, but more meaningfully, it also suggests that the *Q*-factor of a tuning fork probe can be improved by balancing the prongs with extra mass and the improvement can be accurately characterized by the proposed model.

In this paper, an analytical expression is first derived by using the proposed model to relate the *Q*-factors before and after the balancing, which justifies the improvement. Then the analytical relation is verified by experiments on tuning fork probes. It is shown that the theoretical analysis tallies well with the experimental results and the proposed approach can improve the *Q*-factor of the tuning fork probe at least by a factor of three. The improved tuning fork probe is further tested on an atomic force microscope. The obtained topographic results have shown clearer nano-structures than those obtained without using the improved

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approach. Since the proposed approach only exploits the balancing of the two prongs of the tuning fork, it can also be incorporated into all existing SPM systems that use only a single prong of a tuning fork, to further improve the Q-factors of these systems.

2. Theoretical model of the Q-factor improvement

In this paper a tuning fork probe is described by two coupled oscillators as

$$m_1\ddot{x_1} + kx_1 + \alpha(x_1 + x_2) + \tfrac{1}{2}\beta(m_1\dot{x_1} + m_2\dot{x_2}) + m_1\gamma_1\dot{x_1} = F_1(t), \quad (1)$$

$$m_2\ddot{x_2} + kx_2 + \alpha(x_1 + x_2) + \tfrac{1}{2}\beta(m_1\dot{x_1} + m_2\dot{x_2}) + m_2\gamma_2\dot{x_2} = F_2(t), \quad (2)$$

where m_1 and m_2 are the effective masses, γ_1 and γ_2 are the damping ratios, k is the stiffness constant, F_1 and F_2 are the excitation sources of the prongs, and α and β are the coupling coefficients of the tuning fork, respectively.

A similar two oscillators model was used in [13] and other references as well, but here, the attachment of the probe or extra mass on prongs of the tuning fork is considered to cause unbalance in both effective masses and damping ratios, rather than only the unbalanced effective masses. We will show subsequently that this modification together with (9) provides an improved model capable of characterizing accurately the Q-factor of a tuning fork probe with respect to the attachment of extra mass on the tuning fork prongs.

Here we consider an electrically excited tuning fork probe, then $F_2(t) = -F_1(t) = F(t)$. Hence, the displacement of each individual prong can be expressed in frequency domain as

$$x_1(w) = F\frac{(-m_2w^2 + \mathrm{j}w(\gamma_2 + \beta)m_2 + k + 2\alpha)}{H(w)}, \quad (3)$$

$$x_2(w) = F\frac{(-m_1w^2 + \mathrm{j}w(\gamma_1 + \beta)m_1 + k + 2\alpha)}{H(w)}, \quad (4)$$

where

$$\begin{aligned} H(w) = {} & (-m_1w^2 + \mathrm{j}w(\gamma_1 + \tfrac{1}{2}\beta)m_1 + k + \alpha) \\ & \times(-m_2w^2 + \mathrm{j}w(\gamma_2 + \tfrac{1}{2}\beta)m_2 + k + \alpha) \\ & - (\alpha + \mathrm{j}w\tfrac{1}{2}\beta m_1)(\alpha + \mathrm{j}w\tfrac{1}{2}\beta m_2) \end{aligned} \quad (5)$$

with w being the frequency of excitation. The output signal detected can be expressed as $y = cx_2$ where c is a constant gain. These coefficients of the oscillators can be obtained by fitting the system frequency responses.

Now we derive the expression of the Q-factor of the tuning fork probe. As in [13], we take the advantage of the asymmetrical and the symmetric modes which are defined as $z_1 = x_1 - x_2$ and $z_2 = x_1 + x_2$, respectively. The above equations can be solved by substituting $z_1(t) = z_{11}\exp(-\mathrm{j}wt)$ and $z_2(t) = z_{21}\exp(-\mathrm{j}wt)$ where z_{11} and z_{21} denote the complex amplitudes. The complex amplitudes of the two modes and their ratio is obtained by

$$\left|\frac{z_{11}}{z_{21}}\right| \approx \frac{2q\left(1 + 2q - \dfrac{k}{2\alpha}q^2\right)}{\left(\dfrac{k}{\alpha}q^2 + 8\dfrac{\alpha}{k}q + 4\dfrac{\alpha}{k}\right)(1+q)}, \quad (6)$$

at the resonance frequency given by

$$\begin{aligned} w_{11}^2 &= \frac{(k+\alpha)(1+q)}{m_1(2q+1)} - \frac{\alpha(q+1)}{m_1(2q+1)}\sqrt{1 + \frac{(2k\alpha + k^2)q^2}{\alpha^2(q+1)^2}} \\ &\approx \frac{k(\alpha + 2\alpha q - kq^2/2)}{m_1\alpha(1+2q)(1+q)}, \end{aligned} \quad (7)$$

where

$$p = \frac{\gamma_2 - \gamma_1}{2\gamma_1} \quad \text{and} \quad q = \frac{m_2 - m_1}{2m_1}. \quad (8)$$

To proceed, we introduce an approximation of the ratio of these modes with respect to the Q-factor as follows:

$$\begin{aligned} \frac{1}{Q}\left|\frac{z_{11}}{z_{21}}\right| &= \frac{(c_3q^3 + c_2q^2 + c_1q + c_0)(c_4p + 1)}{1 + c_5pq} \\ &\approx \frac{q(c_3q^2 + c_2q + c_1)(c_4p + 1)}{1 + c_5pq}, \end{aligned} \quad (9)$$

where c_0, c_1, c_2, c_3, c_4, and c_5 are constants. These parameters can be obtained by using (9) to fit the measured Q-factor of the tuning fork probe once the probe is formed. We can also neglect c_0 because it is insignificantly small as compared to the other coefficients.

Using the model given in (1), (2), and (9), the Q-factor for unbalanced tuning fork probe, denoted as $Q_{unbalanced}$, can be obtained by

$$Q_{unbalance} = \frac{4c_1\left(1 + 2q - \dfrac{k}{2\alpha}q^2\right)(1 + c_5pq)}{\left(\left(\dfrac{k}{\alpha}\right)q^2 + 8q + 4\right)(c_3q^2 + c_2q + c_1)(c_4p + 1)(1+q)}Q_0, \quad (10)$$

where Q_0 denotes the Q-factor of a bare tuning fork without probe attached. It is given by $Q_0 = (1/\gamma)\sqrt{k/3m}$ [1] where m and γ denote, respectively, the effective mass and the damping ratio of a prong of a bare tuning fork.

Next, we derive the Q-factor of the balanced tuning fork probe obtained by adding appropriate extra mass on the free prong of the probe. We denote the initial unbalancing status by $m_1 = m$, $m_2 = (1+2q)m$, $\gamma_1 = \gamma$, and $\gamma_2 = (1+2p)\gamma$. After adding on the extra mass on the free prong to balance the tuning fork probe, the effective masses are given by $m_1 = m_2 = m(1+2q)$ and the damping ratios satisfy $\gamma_1 = \gamma_2$. For the balanced oscillators, the asymmetry mode z_{11} disappears, and only the symmetry mode is left. The symmetry mode is governed by the equation

$$\ddot{z}_2 + \gamma\dot{z}_2 + w_{22}^2z_2 = F_m\mathrm{e}^{-\mathrm{j}wt}, \quad (11)$$

where $w_{22}^2 = (k+2\alpha)/m(1+2q)$, and $F_m = F/m(1+2q)$.

Solving the equation by substituting $z_2 = z_{21}\exp(-\mathrm{j}wt)$, we obtain

$$z_{21} = \frac{F_m}{w_{22}^2 - w^2 - \mathrm{j}\gamma w}, \quad (12)$$

$$|z_{21}|^2 = \frac{F_m^2}{(w_{22}^2 - w^2)^2 + (\gamma w)^2}. \quad (13)$$

Thus, the resonance frequency is given by w_{22}. After several algebraic manipulations, the FWHM of z_{21}, denoted as Δw_{22}, can be obtained by $\Delta w_{22} = \gamma\sqrt{3}$.

Thus, by definition, the Q-factor after balancing is obtained by

$$Q_{balanced} \triangleq \frac{w_{22}}{\Delta w_{22}} = \frac{1}{\gamma\sqrt{3(1+2q)}}\sqrt{\frac{k}{m}} = \frac{1}{\sqrt{(1+2q)}}Q_0. \quad (14)$$

Compared to (10), the Q-factor is improved by

$$\frac{Q_{balanced}}{Q_{unbalanced}} = \frac{\left(\left(\dfrac{k}{\alpha}\right)^2q^2 + 8q + 4\right)(c_3q^2 + c_2q + c_1)(c_4p + 1)(q+1)}{4c_1\left(1 + 2q - \dfrac{k}{2\alpha}q^2\right)(1 + c_5pq)\sqrt{(1+2q)}}. \quad (15)$$

It can be seen that the Q-factor of the balanced probe is improved. Take a typical tuning fork probe as an example. Before attaching the probe, the tuning fork has a Q-factor of 11 000, and after attaching a probe, the Q-factor of the tuning fork probe drops to 5170. By fitting the frequency curves, it is found that the attachment of the probe creates 4% difference in effective masses and 50% in damping ratios, i.e., $q = 0.04$ and $p = 0.5$. The coefficients in (9) take values as $c_1 = 0.9009 \times 10^{-4}$, $c_2 = 2.01 \times 10^{-5}$, $c_3 = 0.0606$, $c_4 = 0.93$, and $c_5 = 7.98$, respectively. Thus, the Q-factor of the tuning fork can be improved by a factor of two after balancing, according to (15). The measured Q-factor for the balanced tuning fork probe is 10 781.

3. Experiments

Experiments are conducted to verify the analytical model and the improvement in the Q-factor. The set-up for measuring the

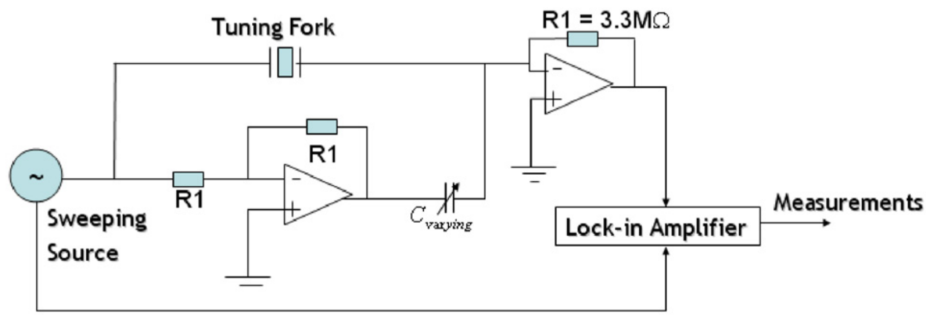

Fig. 1. Experimental setup for measuring Q-factor.

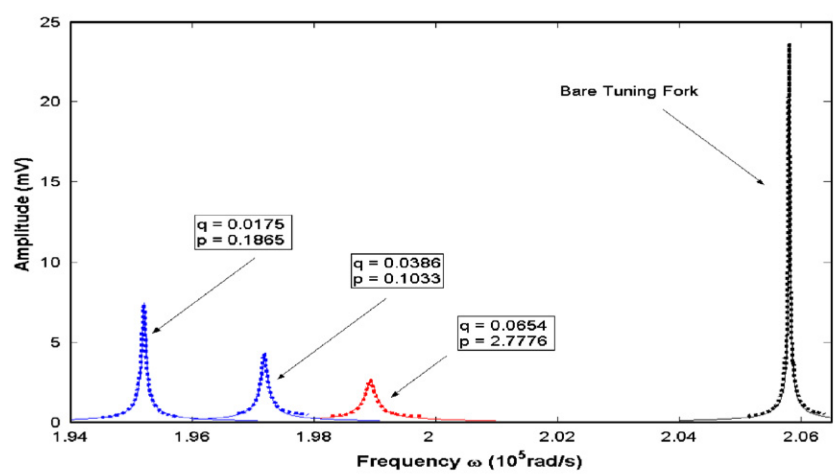

Fig. 2. Frequency responses of the tuning fork probe under different unbalancing scenarios. (Dotted lines: experimental; solid lines: calculated from model.)

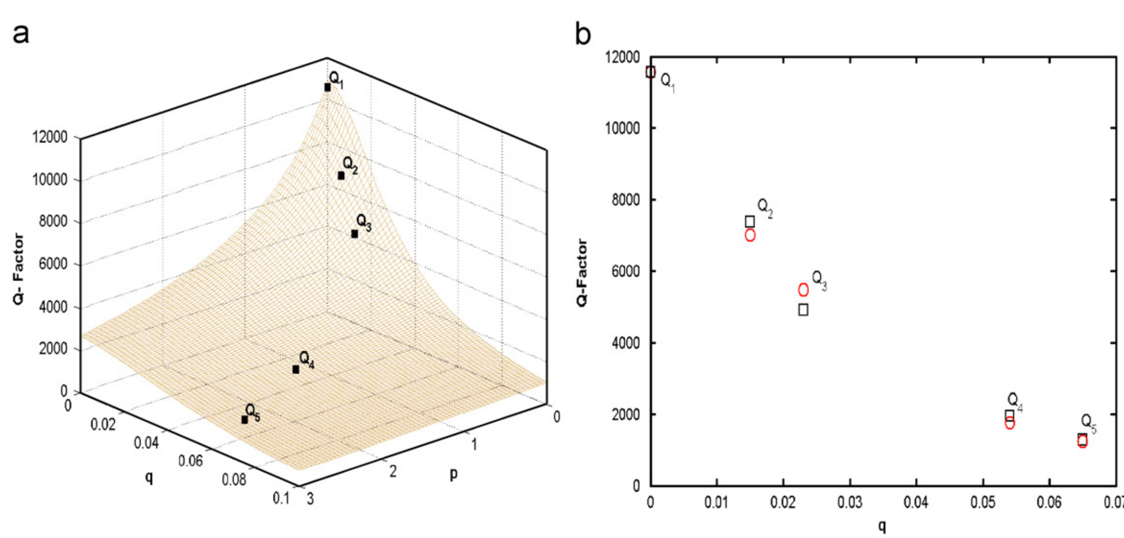

Fig. 3. Experiment data and calculation results of the Q-factors under different unbalancing scenarios. (Square: experimental data; mesh plot: calculation results; circle: calculation results. The corresponding data points (p, q) are $Q_1 = (0, 0)$, $Q_2 = (0.23, 0.015)$, $Q_3 = (0.26, 0.023)$, $Q_4 = (1.82, 0.054)$, $Q_5 = (2.74, 0.065)$.) (a) 3-D plot of Q-factor with respect to p and q; (b) projection of the Q-factor against q.

responses and the Q-factor of a tuning fork probe is shown in Fig. 1 where the tuning fork is excited electrically and the packaging capacitance of the tuning fork is compensated by the invert tunable capacitor as suggested in [11]. In the experiments, the input excitation source for the tuning fork is 1 mV, the gain at the pre-amplifier is 3.3 MΩ, and the frequency sweeping step size is taken as 0.1 Hz.

3.1. Validation of the model characterizing Q-factor

We first take a bare tuning fork and measure its frequency response that is shown in Fig. 2. We calculate the system parameters in (1) and (2) by using a least-squares approach to fit the frequency response. Then, we attach the probe on the tuning fork. We measure the frequency responses and calculate the system parameters again. We also measure the Q-factor and calculate the asymmetric and symmetric modes. Using (9), we determine the constants c_i (for $i = 1, 2, 3, 4, 5$) as $c_1 = 1.1092 \times 10^{-4}$, $c_2 = 1.458 \times 10^{-4}$, $c_3 = 0.1317$, $c_4 = 0.931$ and $c_5 = 5.981$. Using this probe, we repeat for several times adding an extra mass on the same prong with the probe. At each time, we measure the frequency responses and the Q-factors, meanwhile we calculate the frequency responses by using (1) and (2). The measured and calculated frequency responses are shown in Fig. 2. The curves show that the proposed models (1) and (2) fit the measurement data.

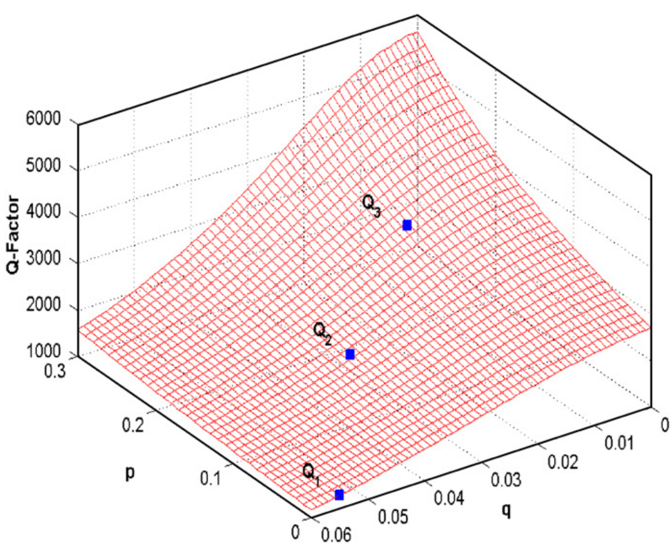

Fig. 4. Improved Q-factors by balancing the free prong of the tuning fork probe. (Square: experimental data; mesh plot: calculation results.)

Fig. 3 depicts in a 3-D plot the Q-factors measured each time when an extra mass is added. These Q-factors are highlighted in a projection of the 3D distribution on a $p = 0$ plane. As comparison, the figure also includes a 3-D plot of Q-factors with respect to p and q which characterize different unbalancing scenarios. The 3-D plot is calculated from model (10) with the coefficients taking values obtained above. It is shown that the calculated Q-factors fit the measured ones very well. This validates that the model in (1), (2), and (9) can well characterize the Q-factor of tuning fork probe.

Another point worthy of mentioning is that the measured Q-factors do not fall on any cross-sectional plane of the 3-D plot in Fig. 3. This means that adding extra mass on the prong of the tuning fork influences not only the effective masses but also the damping ratios of the coupled oscillators. This explains the discrepancy of the model in [13] where only the influence on q is considered and the Q-factors are expected to fall on a cross-section of 3-D plot.

3.2. Q-factor improvement by balancing the tuning fork probe

To see the Q-factor improvement by balancing the prongs of the tuning fork probe, we continue the above experiment, but we add gradually extra masses to the free prong of the tuning fork probe. Similarly, we measure the Q-factors and calculate the values of the corresponding p and q by fitting the frequency responses at each time of adding an extra mass. The obtained values are depicted in Fig. 4. The Q-factors calculated from the model is also plotted in the figure as a reference. They are calculated by using (10) with all the same constants c_i (for $i = 1, 2, 3, 4, 5$) as above. But Q_0 is replaced by $Q_{balanced}$ with q taking the value of the added mass in the last experiment in Section 3.1.

These values demonstrate that the improvement in Q values after the balancing was done by adding an extra mass on the prong. The Q-factor of the tuning fork before balancing is 1336, while the Q-factor of the tuning fork after balancing is 4189, an improvement by a factor of three. Continuing the balancing process, the improvement can go up by more than three times.

3.3. AFM topography imaging with the balanced tuning fork probe

The effectiveness of the improved tuning fork probe is further demonstrated in AFM imaging. A traditional tuning fork probe and its balanced version are, respectively, used in a home made AFM system to image a calibration sample TDG01/Au from NT-MDT. The sample is a smooth periodic grating as shown by its SEM image in Fig. 5. Fig. 5 also gives the AFM images obtained, respectively, by the traditional probe and its balanced version, and the line scan signals corresponding to the lines indicated in Fig. 5

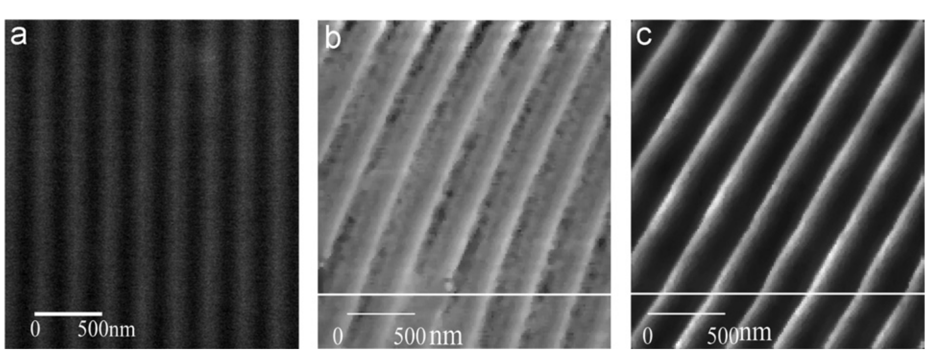

Fig. 5. Comparing the AFM images using unbalanced and balanced tuning fork probes. (a) SEM image (10.0 kV); (b) AFM image using a traditional tuning fork probe (unbalanced); (c) AFM image using the balanced tuning fork probe.

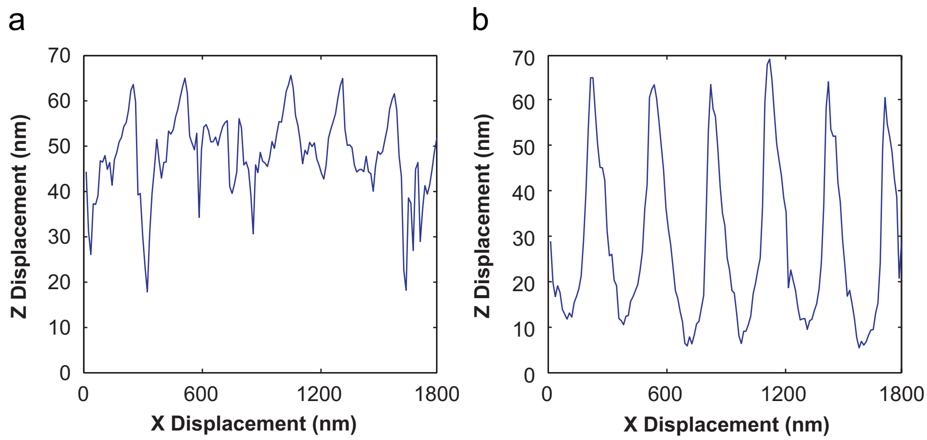

Fig. 6. Line scan of the AFM image. (a) traditional tuning fork probe (unbalanced); (b) balanced tuning fork probe.

are shown in Fig. 6. Comparing the line scan curves, the balanced tuning fork probe has demonstrated a much smoother and more consistent topography.

4. Conclusion

In this paper, an approach is proposed to improve the Q-factor of a tuning fork probe by balancing the two fork prongs with extra mass. A theoretical model is also proposed to characterize the Q-factor improvement due to balancing the tuning fork prongs. Experimental results have validated the proposed model and demonstrated the effectiveness of the proposed approach. The balancing can be easily done for all existing tuning fork probes, so the approach can provide an effective and efficient way to attain higher sensitivity of existing SPMs.

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