Dynamic behavior of tuning fork shear-force feedback

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The dynamics of a tuning fork shear-force feedback system, used in a near-field scanning optical microscope, have been investigated. Experiments, measuring amplitude and phase of the tuning fork oscillation as a function of driving frequency and tip-sample distance, reveal that the resonance frequency of the tuning fork changes upon approaching the sample. Either amplitude or phase of the tuning fork can be used as distance control parameter in the feedback system. Using amplitude a second-order behavior is observed while with phase only a first-order behavior is observed, and confirmed by numerical calculations. This first-order behavior results in an improved stability of our feedback system. A sample consisting of DNA strands on mica was imaged which showed a height of the DNA of 1.4 nm. © *1997 American Institute of Physics.* [S0003-6951(97)02027-5]

In near-field scanning optical microscopy (NSOM) a high resolution optical image is obtained by scanning a sub-wavelength light source over the sample surface.[1,2] The most widely used sub-wavelength light source consists of a tapered optical fiber which is subsequently coated with Aluminum creating a 50 nm aperture at the end point of the fiber. In order to obtain a high resolution optical image the aperture has to be scanned close to the sample surface well within the range of the aperture size. In practice the probe to sample distance is kept below 10 nm, using the shear-force distance control mechanism.[3,4] In this technique the fiber is vibrated at resonance parallel to the sample surface. Upon approaching the sample, a decrease in the amplitude of oscillation is observed, generally attributed to a damping of the oscillation by the surface.

In one of the first experiments Betzig[3] used a laser spot, diffracted from the fiber, to measure the vibration amplitude. Also interferometric techniques have been used to measure the amplitude.[4] These techniques have the disadvantages that additional stray light is brought into the vicinity of the aperture and that accurate alignment of these systems with respect to the probe is necessary. An alternative method is to use piezo-electric materials which generate a piezoelectric voltage proportional to the amplitude of the oscillation.[5–8] Based on this idea, the use of tuning forks for detecting the probes amplitude was demonstrated recently.[5] The fiber is attached to one arm of the tuning fork and the tuning fork is oscillated at resonance. When approaching the sample surface, a decrease of the oscillation amplitude of the tuning fork is observed. The origin of this decrease is still not clearly understood. In this letter we present the effect of this interaction on the amplitude and phase of the oscillation of the tuning fork and demonstrate the consequences for the dynamics of a feedback mechanism acting on either one of these signals.

In order to get a better understanding of the interaction mechanism a series of experiments has been performed. A tapered fiber probe was glued to one arm of a tuning fork (32768 Hz), with its base attached to a driving piezo element, and oriented perpendicular to the sample surface. The total system was mounted on an xyz scanner. Frequencies between 32630 and 32740 Hz were used to drive the tuning fork. The amplitude of the tuning fork has been measured using an rms detection scheme (5 kHz bandwidth) and will from here on be referred to as the rms signal. The phase between the tuning fork excitation and the tuning fork oscillation has been measured with a sensitivity of 1 V/10° and a bandwidth of 2 kHz. Measurements were performed detecting the rms and phase signal as a function of the driving frequency and probe-sample distance, displayed in Fig. 1. The excitation of the tuning fork was 14 pm, and the quality factor of the fork out of contact was 1600. The sample consisted of freshly cleaved mica. The zero point on the z-displacement scale is chosen at an arbitrary position as the actual point of contact cannot be determined.

It was observed that the resonance frequency shifted about 20 Hz to a higher frequency when approaching the sample. Correspondingly, the 90° phase point shifted 20 Hz higher. The shift in resonance frequency of the tuning fork can be explained by its geometry. In contact the end point of the fiber (50 nm) touches the sample thereby effectively enlarging the tuning forks spring constant. The Q-factor only

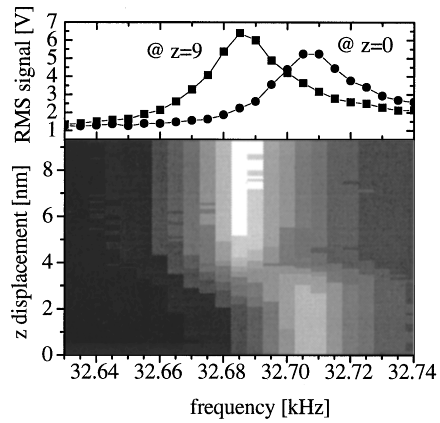

FIG. 1. (Top) Frequency response curves of the rms signal in and out of contact. (Bottom) rms signal (in grayscale) measured as a function of tip-sample distance and driving frequency.

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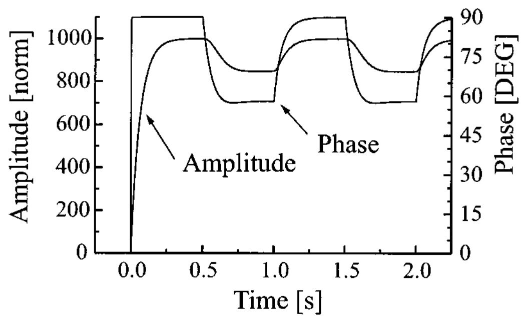

FIG. 2. Simulation of a second-order system, amplitude and phase as a function of time.

slightly reduces compared to the out of contact value. Mainly a shift in resonance frequency is observed, which cannot be caused by a viscous damping of the oscillation by the sample.

When using a constant driving frequency for excitation of the tuning fork one can do feedback on either the rms signal or the phase signal. In practice we experience that feedback on phase is faster than when using the rms signal. This can be explained by looking at the tuning fork as a second-order mechanical system.[9] The equation of motion is:

$$\ddot{x}+2\beta\omega_s\dot{x}+\omega_s^2x=\frac{F_o}{m}\cos\,\omega_d t, \tag{1}$$

where x is the tuning fork deflection, m is the effective mass of the tuning fork, β is the damping constant, ω_s $(=\sqrt{k/m})$ is the resonance frequency of the oscillating system, ω_d is the driving frequency and F_o is the driving force. In contact the spring constant k increases, so ω_s increases and the system effectively gets driven off resonance. Using $x(t)=\mathrm{Re}\,[\hat{A}(t)\exp(i\omega_d t)]$ it follows:

$$\ddot{\hat{A}}+(2i\omega_d+2\beta\omega_s)\dot{\hat{A}}+(\omega_s^2-\omega_d^2+2i\beta\omega_s\omega_d)\hat{A}=F_o/m \tag{2}$$

with general solution

$$\hat{A}(t)=\hat{C}\,\exp(\beta\omega_s t)\exp[i(\omega_s\sqrt{1-\beta^2}-\omega_d)t]+\frac{F_o/m}{\omega_s^2-\omega_d^2+2i\beta\omega_s\omega_d}, \tag{3}$$

where $\hat{C}$ is a complex constant adjusted to fit the boundary conditions. Analyzing $\hat{A}(t)$ after a frequency change reveals that the phase, $\arg[\hat{A}(t)]$, has a maximum slope directly after the frequency change whereas the amplitude $|\hat{A}(t)|$ does not instantaneously reach a maximum slope, but shows a more continuous behavior.

To further illustrate this, a second-order tuning fork system has been simulated numerically with the following parameters: the driving frequency $\omega_d/2\pi=32000$ Hz, the tuning fork frequency out of contact $\omega_{s,out}/2\pi=32000$ Hz and in contact $\omega_{\mathrm{s,in}}/2\pi=32010$ Hz, the damping term and drive term are kept constant, $\beta\omega_s/2\pi=16$ Hz ($\mathrm{Q}\approx1000$) and $F_o/m=\omega_d^2$ ms^{-2} for normalization.

Figure 2 is obtained by calculating the amplitude and phase of the oscillation while modulating the resonance frequency between 32000 and 32010 Hz with a modulation

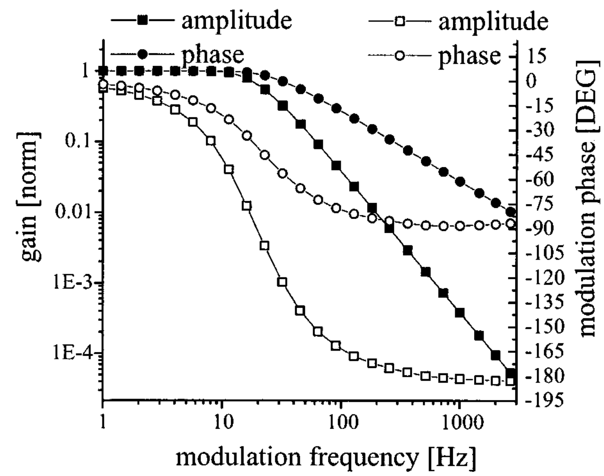

FIG. 3. Frequency response of both rms and phase signals as result of a series of simulations.

frequency of 1 Hz. It was observed that during the first half second the amplitude builds up towards the Q-value. Upon changing the systems resonance frequency, the slope of the phase signal changes instantaneously whereas no discontinuity is visible in the slope of the rms signal. From Fig. 2 the modulation depth of the rms and the phase signal and modulation phase of both signals can be determined. Increasing the modulation frequency the total frequency response of the rms and phase signals can be determined. The results are plotted in a gain-phase diagram, Fig. 3. These results reveal that the rms signal response curve corresponds to that of a second-order system, whereas the phase-signal response curve corresponds to that of only a first-order system. Both curves show the same cutoff frequency, which can be derived from the exponential decay term of Eq. (3) to be, $\omega_{cutoff}/2\pi=\beta\omega_s/2\pi=\omega_s/(4\pi Q)\approx16$ Hz, which agrees reasonably well with Fig. 3. This has of course immediate consequences for the dynamics of a feedback system acting on either rms or phase signal. Especially the modulation phase behavior of Fig. 3 limits the maximum bandwidth of the feedback system. Due to the limited bandwidth of our electronics and scanning system, an additional phase change will be added to the one displayed in Fig. 3 causing a feedback system acting on the rms signal to oscillate at a lower feedback bandwidth than when using the phase signal.

To verify this simulation experimentally the dynamic behavior of the shear force system has been investigated with a spectrum/network analyzer (HP 3589A). The output of the network analyzer generated a modulation of the z-displacement of our xyz scanner (12 nm peak-peak) while rms and phase signals were monitored at the input. Doing so the modulation gain and modulation phase of both signals could be determined. The initial tip-sample distance was less than 12 nm in order to have the tip moving in and out of contact during one period of the modulation frequency. The measurements are displayed in Fig. 4, and show good agreement with the simulations. The gain of the rms signal drops with 12 dB/oct and the gain of the phase signal drops with exactly 6 dB/oct, corresponding to a second- and first-order system, respectively. The modulation phase in Fig. 4 shows that the modulation phase of the rms signal changes twice as

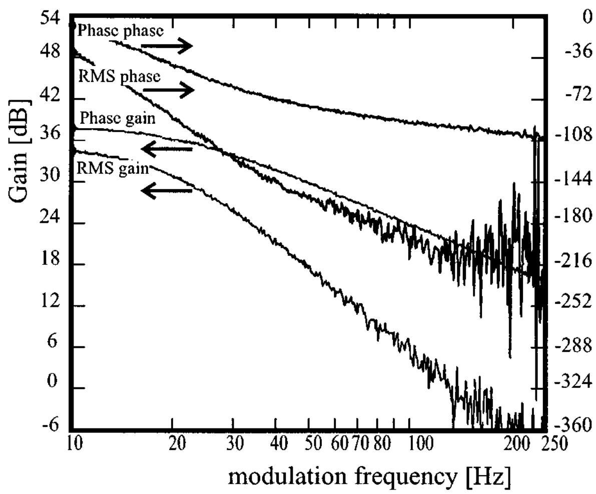

FIG. 4. Measurement of the (gain and phase) frequency response of both RMS and phase signals.

fast as the modulation phase of the tuning forks phase signal. The changes, however, are not exactly 90° and 180° but are larger because of the additional phase change generated in the rest of our system, as mentioned above. In Fig. 4 it can be seen that using the rms signal, already at 80 Hz a change in modulation phase of 180° is reached, resulting in an unstable feedback system, whereas for the phase signal the change in modulation phase stays well within the 180° for the frequency range displayed. So although the cutoff frequency in the feedback circuit is located below 20 Hz the bandwidth of the feedback circuit can exceed this limit. It is primarily limited by the modulation phase behavior displayed in Fig. 4, which stresses the benefit of a first-order response curve resulting in an increased feedback bandwidth.

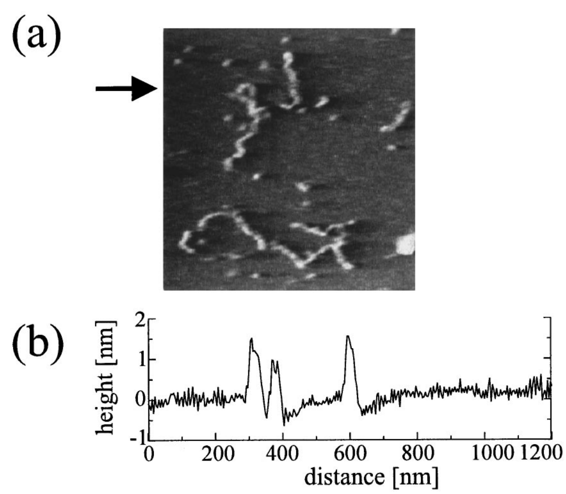

FIG. 5. (a) Measurement of double stranded DNA on mica, image size $1.2\times1.2\ \mu$m. (b) Line profile at the marked position.

In order to show that this system, based on phase signal feedback, can be used for imaging and that the forces between tip and sample necessary to induce this phase change are small we imaged double stranded DNA. The DNA, solved in a $MgCl_2$ buffer, was precipitated on a mica surface.[10] The height is about 2 nm based on the known structure of the double stranded DNA and measured with noncontact atomic force microscopy (AFM).[11] The height of DNA measured by tapping-mode atomic force microscopy is usually a factor of 2 smaller than would be expected based on the known structure of double stranded DNA. This effect is commonly attributed to indentation of the DNA.[12–14] The image shown in Fig. 5 was measured in our shear-force microscope using phase feedback with a phase set-point close to the out-of-contact value and a scanning speed of $\sim$2.5 μm/s. The associated line trace shows a height of the DNA of 1.4 ± 0.2 nm. Taking a few consecutive images we noticed no visible degradation of the DNA. However, by enlarging the set-point in our feedback system towards the in-contact value the DNA could be cut, as can be seen by the vertical cut at a distance of 500 nm. Imaging the DNA with feedback on the rms signal using the same tip resulted in a too unstable feedback to generate an image of comparable quality.

It can be concluded that by using feedback on the phase of the oscillation of the tuning fork an increased bandwidth in the feedback system can be applied as compared to feedback on the rms signal resulting in higher applicable scan speeds. The experiments on DNA show that using the shear-force microscope a more realistic height of the DNA is measured as compared to regular tapping mode AFM.

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