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Dynamic behavior of the tuning fork AFM probe

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Abstract

We recently introduced a new self-actuating and self-sensing atomic force microscope (AFM) probe based on a quartz tuning fork and a micro-fabricated cantilever. This system has two degrees of freedom, associated with its two components. We developed a model for describing how the sample-tip interaction is transduced to the tuning fork. It is based on two coupled spring-mass systems. In a first step, the coupling between the tuning fork and the cantilever was investigated to reveal the influential factors. The analysis of these factors enabled us to deduce their effect on the whole system and to optimize the sensitivity of this novel probe. The theoretical analysis was compared with experimental results and it was found that the model appropriately describes the probe in a qualitative manner while further refinement will be needed for achieving a correct quantitative description.

Keywords: Atomic force microscope; 2DOF system; Tuning fork

1. Introduction

The application of quartz tuning forks (QTF) in atomic force microscopy (AFM) probes has been demonstrated in the past [1,2]. QTFs are attractive due to their high quality factor Q, which makes them a stable source for small vibration amplitudes. Moreover, changes in their vibration state can be electronically detected, which makes them a self-sensing and self-actuating probe. The high stiffness of the quartz prongs, on the other hand, appears as a drawback when working on soft samples. A new design, based on a soft cantilever coupled to a QTF was proposed by Akiyama et al. [3] to overcome this limitation. A schematic view of that probe is depicted in Fig. 1. The QTF vibrates in a horizontal plane. This induces stress in the U-shaped cantilever leading to an excitation in a perpendicular plane. This stress may also induce a nonlinear change in the spring constant of the cantilever, that however is believed to be negligibly small as long as the vibration amplitude of the prongs is much smaller than the length of the cantilever [3].

This probe can be understood as a coupled system with two degrees of freedom (2DOF). We present a model for this 2DOF system, which enabled us to explain how the interaction between the tip of the cantilever and the sample is coupled back to the tuning fork. This should allow the optimization of the probe's sensitivity.

2. Theory and model approximations

The tuning fork and the cantilever were considered as two independent masses (m_1 and m_2) that are connected to each other by two mass-less springs (k_1 and k_2). Considering the high Q of the tuning fork, only the internal damping of the cantilever (c_2) was accounted for. Since the nonlinear changes in the spring constant of the cantilever were considered to be negligible [3], the presence of a simple spring in the model was assumed. Due to the self-actuating properties of quartz, the driving force $F = F_0 \cos(\omega t)$ could be directly applied to the tuning fork. The frequency response of the system was found from the system's equations of motion:

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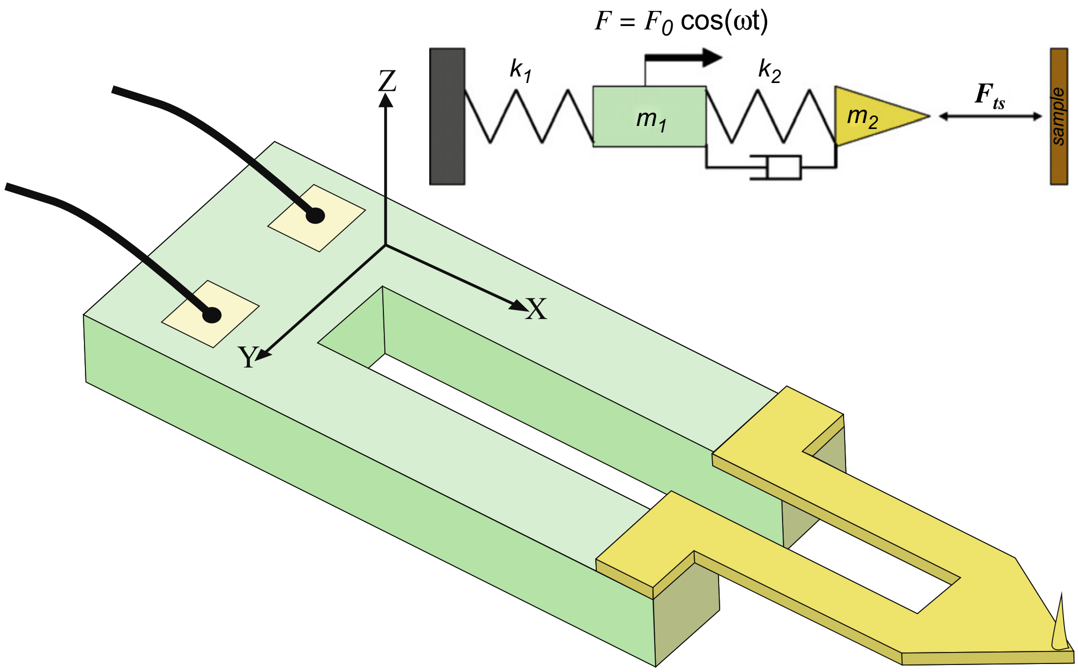

Fig. 1. Schematics of the 2DOF tuning fork AFM. A U-shaped cantilever is symmetrical attached to a tuning fork such that each leg of the cantilever is fixed to one of the two prongs of the tuning fork. In operation, the tuning fork moves in the x–y plane which makes the cantilever move in the z direction. In return, the movements of the cantilever are coupled back to the tuning fork. The proposed linear model of two coupled spring-mass systems is shown in the upper right corner; m_1 and k_1 are the tuning fork's mass and spring constant, m_2 and k_2 the mass and spring constant of the cantilever, respectively. Only the damping of the cantilever c_2 is considered.

$$H_{\mathrm{TF}} = \frac{k_2 + jc_2\omega - \omega^2}{k_1k_2 + jc_2k_1\omega - (k_2m_1 + k_1m_2 + k_2m_2)\omega^2 + jc_2(m_1 + m_2)\omega^3 + m_1m_2\omega^4},$$

$$H_{\mathrm{CL}} = \frac{k_2 + jc_2\omega}{k_1k_2 + jc_2k_1\omega - (k_2m_1 + k_1m_2 + k_2m_2)\omega^2 + jc_2(m_1 + m_2)\omega^3 + m_1m_2\omega^4}.$$

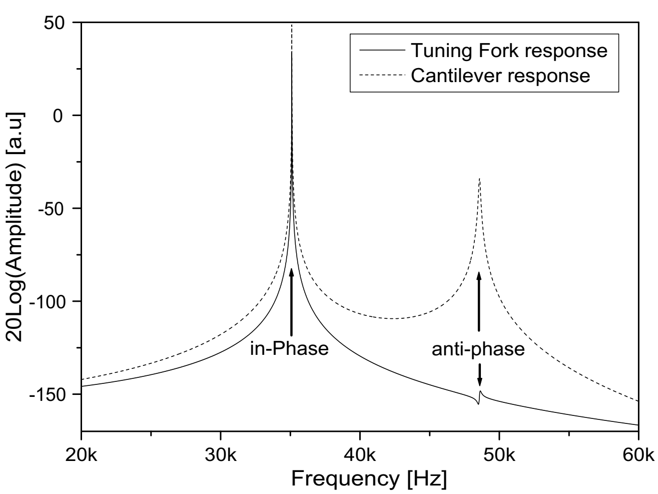

Fig. 2. Transfer function of the cantilever (dashed line) and the tuning fork (solid line). Both of the transfer functions have two resonance frequency peaks, due to the system's 2DOF. The in-phase and anti-phase resonance frequency peaks are indicated.

H_{TF} and H_{CL} are transfer functions of the system for the tuning fork and the cantilever, respectively. Using these transfer functions, we found two distinct resonance frequencies of the system (Fig. 2). We related them to the coupling between the two components. The QTF had a much bigger mass in comparison to the mass of the cantilever, which explained the smallness of the second peak of the tuning fork in comparison to that of the cantilever. The two resonance peaks were named in-phase and anti-phase peaks, due to their relative phase shift, which were zero degree for in-phase and 180 degrees for anti-phase. It was observed in previous experiments that the relative phase shift of "anti-phase" peaks made AFM feedback operation more difficult [3]. Thus it is preferred to work in the "in-phase" region and the "anti-phase" option is no longer pursued in this report.

3. Sensitivity

Through the rest of this report we will use the harmonic approximation method [4]. In this method the gradient of

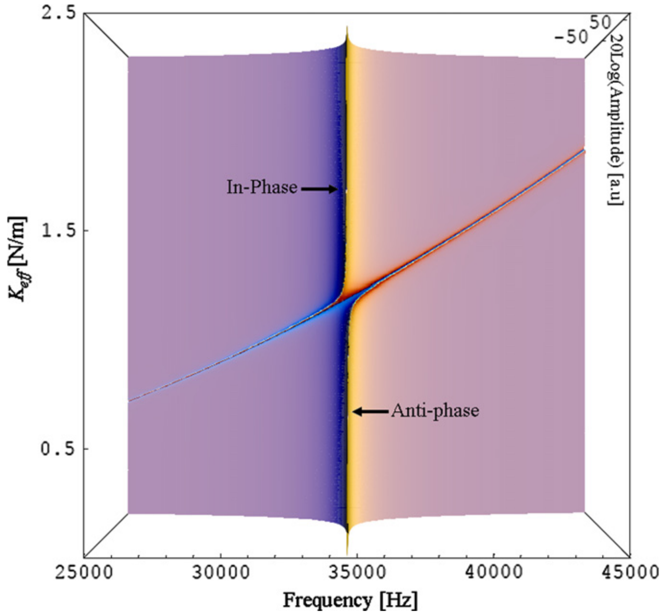

Fig. 3. A top view of the 3D plot of the transfer function variations, due to changes of k_{eff} (y-axis). The transition point where the frequency variations of one peak stops and the other starts to vary is clearly visible. It is illustrated that as k_{eff} changes, the frequencies of the two peaks never shift together. The amplitude (z-axis of the plot) is drastically decreased as k_{eff} moves away from the transition point but stabilizes further away from that point.

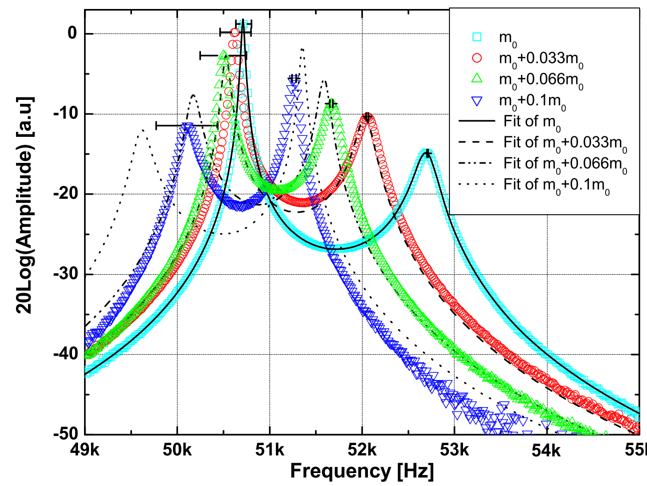

Fig. 4. Experimental results showing that the response of the cantilever always featured two peaks, in agreement with the theory. Increasing the mass loading of the cantilever in equal steps led to a decreased amplitude and a frequency shift of the "in-phase" peak to lower values. The anti-phase peak increased its amplitude and also shifted to lower frequencies, as predicted by theory. The transition point was observed within the error margins of the experiments. The error bars are shown only for the peak values.

the tip-sample interaction forces F_{ts} (Fig. 1) can be thought of as an extrinsic spring constant which changes k_2 to an effective spring constant k_{eff}. This in turn shifts the resonance frequency of the whole system. This approach showed that our focus should be on the spring constant of the cantilever. There are two points to consider: (1) The resonance frequency changes and (2) the amplitude changes due to changes of k_{eff}. An intuitive way to address these points is to investigate a 3D plot of the amplitude and frequency changes as function of variations of k_{eff}. Fig. 3 shows a color coded top view of such a plot. It can be seen that as k_{eff} is increased, the in-phase resonance frequency peak increases in amplitude and reaches a nearly-constant value. The anti-phase peak shows exactly the opposite behavior and starts to vary as the other becomes nearly constant. The point within which this transition occurs is called the transition point.

The best working point for frequency shift measurements, based on these findings, is at an initial k_2 sufficiently below the transition point. The frequency shift is at its maximum for such a configuration. If k_2 is sufficiently away from the transition point, the amplitude was found to be small and its variations minimal. However it should be kept in mind that the small amplitude next to the much bigger anti-phase peak may be hard to detect. Therefore the use of a digital feedback system might become necessary. Regarding these characteristics; frequency modulation is the preferred scheme of operation for the tuning fork AFM.

4. Experiments

In order to test our model, we conducted experiments with cantilevers featuring different added masses. The mass was deposited by incrementally depositing a thin film of gold onto the free end of the cantilever. The mass was added in steps of 3%. It was supposed that this added mass did not affect either the spring constant or the damping. The cantilever was exited by the tuning fork and its deflection was optically detected. The measured frequency response to the added mass is depicted in Fig. 4. The transition point, where all the graphs in Fig. 4 intersect, could be observed within the error margins of the measurement. We also observed that the amplitude did shift to lower values and the frequency shifts increased as the peak moved away from the transition point. Thus we concluded that the behavior of the system is qualitatively described by the above outlined theory. However, Fig. 4 also shows the fitted curves of the frequency response for an increased mass. It can be seen that the theoretically predicted frequency shifts were bigger than the real, experimental observations.

One possible explanation for this discrepancy could be that the assumption of a linear coupling between the in-plane vibrations of the tuning fork to the out-of-plane oscillation of the cantilever has not been fulfilled in these experiments. This in turn, implies that a more elaborated model may need to be developed in order to predict the exact variations of the resonance frequencies.

5. Summary and outlook

We have developed a semi-analytical model for the QTF-AFM probe. It was shown that a reasonable sensitivity can be achieved by this probe. The presented model can qualitatively predict the behavior of this system. The stable mode of operation of the probe is the frequency modulation mode, using the "in-phase" peak. The use of a digital feedback system might be inevitable. Further investigation of the nonlinearities of the coupling and the spring constants should be pursued and complemented by further experiments for validating a refined model.

Acknowledgment

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