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Sensitivity of flexural vibration mode of the rectangular atomic force microscope micro cantilevers in liquid to the surface stiffness variations

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ABSTRACT

In this paper, the resonance frequencies and modal sensitivity of flexural vibration modes of a rectangular atomic force microscope (AFM) cantilever immersed in a liquid to surface stiffness variations have been analyzed and a closed-form expression is derived. For this purpose, the Euler–Bernoulli beam theory is used to develop the AFM cantilever model in liquid. Then, an expression for the resonance frequencies of AFM cantilever in liquid is derived and the results of the derived expression are compared with the experimental measurements. Based on this expression, the effect of the surface contact stiffness on flexural mode of a rectangular AFM cantilever in a fluid is investigated and compared with the case that AFM cantilever operates in the air. The results show that in the low surface stiffness, the first mode is the most sensitive mode and the best image contrast is obtained by excitation this mode, but by increasing the sample surface stiffness the higher modes have better image contrast. In addition, comparison between modal sensitivities in air and liquid shows that the resonance frequency shifts in the air are greater than the shifts in the fluid, which means that for the similar surface stiffness the image contrast in air, is better than liquid.

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1. Introduction

Dynamic analysis of AFM cantilever beams immersed in fluids is of fundamental importance to the resolution of the nanoscale imaging in liquids. In comparison with the air or vacuum environments, AFM cantilever dynamics in liquids remains much less understood and requires further investigations [1]. Certainly, the viscosity plays an important role in this case and must be considered in the modeling of the dynamic behavior of the immersed cantilevers. The viscosity changes the natural resonance frequencies and the damping parameters of each mode of the AFM cantilever. Several theoretical models have been proposed for the AFM cantilevers immersed in the liquid which consider the effect of the viscosity [2–11]. Chu [9] presented an expression for the flexural resonance frequency of a cantilever immersed in the fluid. However, Chu's analysis [9] is inapplicable at small scales where the effect of fluid viscosity is increased. Other formulas for the resonance frequency of the cantilever immersed in the fluid are proposed by [10]. However these expressions are directly applicable for macroscopic cantilevers and may introduce error once used for the analysis of the AFM micro-cantilevers [10]. To calculate the resonance frequencies, in [11–13], the hydrodynamics force is considered as a function of added mass and damping and the expressions for cantilever dynamics are developed.

Imaging the surface topography of the sample has been one of the main goals for developing atomic force microscope.

Resonance frequency and sensitivity of the AFM have significant impact on the image contrast. Several research works have been carried out to analyze the effect of surface stiffness on the modal sensitivity of AFM cantilever [14–19].

However, all of these studies concentrate on the operation of AFM in the air and analyze the modal sensitivity of the AFM cantilever in liquid has not been carried out yet.

In [20–22] inclusion of the dissipative terms and stochastic forces excitation is considered and the behavior of micro-cantilever is described by theory and experiments. These factors make challenges in the modeling and analysis of cantilever dynamics in fluids, in particular with respect to the sensitivity of the modes.

In this paper, the modal sensitivity of a rectangular AFM cantilever immersed in the fluid has been studied. For this purpose, the Euler–Bernoulli beam theory is used and by considering the hydrodynamic force in terms of added mass and viscosity damping parameters, the dynamics of the AFM rectangular cantilever immersed in the liquid is modeled.

Then the natural resonance frequency of each mode is calculated. Using the expression developed for the resonance frequencies of the AFM cantilever in liquid, a closed form analytical expression for the modal sensitivity of the AFM rectangular

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cantilever to the surface stiffness variations is derived. Then, using numerical simulation, at first the results of the derived expression for resonance frequencies are compared with other theoretical model and experimental measurement [8]. Secondly, the modal sensitivity of the AFM rectangular micro-cantilever in liquid is studied and its behavior with that of the AFM cantilever operating in the air is compared.

The method proposed in this paper not only increases the precision of the calculated resonance frequency for the lower eigen modes, but also provides a new expression for the analysis of the sensitivity of AFM cantilever to the surface stiffness. To calculate the resonance frequency and sensitivity, the hydrodynamic force is directly considered in deriving the expressions by taking into account the fluid environment by modeling added mass and added viscous damping. This results in a simpler and more accurate analytical method as compared with those in literatures [2–11].

This precision especially for low eigen modes allows for the sensitivity analysis and selection of proper excitation mode which leads to the better image contrast.

2. Modal sensitivity of flexural vibration of AFM in liquid

The Euler–Bernoulli equation for a continuous and uniform cantilever shown in Fig. 1 with external force in liquids is written as:

$$EI\frac{\partial}{\partial x^4}\left[W(x,t)+a_1\frac{\partial W(x,t)}{\partial t}\right]+\rho bh\frac{\partial^2 W(x,t)}{\partial t^2}=F_h+F_{ext}+\delta(x-L)F_{ts}(d), \quad (1)$$

where E is Young's Modulus, I is the area moment of inertia, a_1 is the internal damping coefficient, b, h and L are width, height and length of the cantilever, respectively.

$W(x,t)$ is the time-dependent displacement of the cantilever, $F_{ext}(t)$ is the excitation force and $F_{ts}(d)$ is the tip-sample force, where:

$$d=W(L,t)+Z_c, \quad (2)$$

F_h is the hydrodynamic force and can be described by a separate added mass and viscose damping and is given by [12,13,23]:

$$F_h(t)=-m_h\frac{\partial^2}{\partial t^2}W(x,t)-c_h\frac{\partial}{\partial t}W(x,t), \quad (3)$$

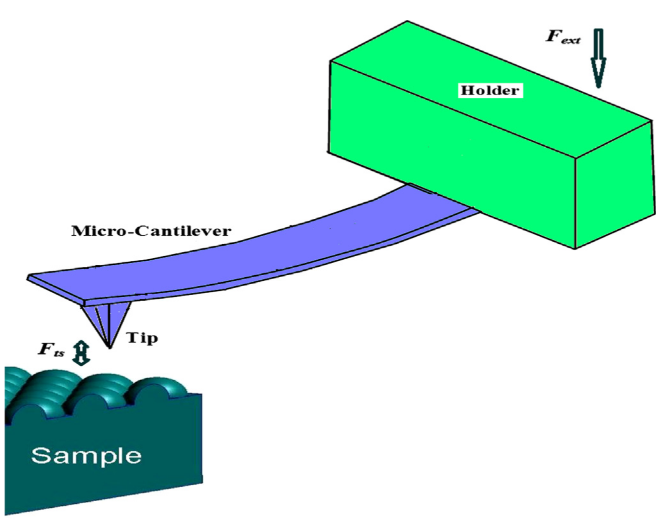

Fig. 1. Schematic of rectangular cantilever.

m_h and $c_h$are defined later in Eqs.(14) and (15). The boundary condition of the cantilever beam is given by:

$$W(0,t)=\frac{\partial W(0,t)}{\partial x}=\frac{\partial^2 W(L,t)}{\partial x^2}=0,$$

$$EI\frac{\partial^3 W(L,t)}{\partial x^3}=K_f W(L,t), \quad (4)$$

where K_f is the normal contact stiffness which is calculated by linearizing the interaction force around equilibrium point and expressed as effective spring constant.

The cantilever is clamped at $x=0$ and is free at $x=L$. The displacement of the cantilever can be written as:

$$W(x,t)=\sum_{n=1}^{\infty}\varphi_n(x)Y_n(t), \quad (5)$$

Based on the method presented in [24,25], $\varphi_n(x)$can be defined as:

$$\varphi_n(x)=A_n\left[\sin k_n x-\sinh k_n x-\frac{\sin k_n L+\sinh k_n L}{\cos k_n L+\cosh k_n L}(\cos k_n x-\cosh k_n x)\right],\ k_n=\frac{\kappa_n}{L}, \quad (6)$$

Normalization of the natural modes requires:

$$A_n=\frac{1}{2}\sqrt{\frac{1}{\int_0^L\left[(\sin k_n x-\sinh k_n x)-\frac{\sin k_n L+\sinh k_n L}{\cos k_n L+\cosh k_n L}(\cos k_n x-\cosh k_n x)\right]^2 dx}}, \quad (7)$$

Such that $\varphi_n(L)=1$, with the characteristics equation given as:

$$C(k_n,\beta)=\kappa_n^3(1+\cos\kappa_n\cosh\kappa_n)-\beta(\sinh\kappa_n\cos\kappa_n-\sin\kappa_n\cosh\kappa_n)=0, \quad (8)$$

where $\beta=\frac{K_f}{EI/L^3}$ is the normal stiffness ratio between the normal contact stiffness and that of the cantilever. Also,

$$\int_0^L\varphi_n(x)\varphi_m(x)dx=\begin{cases}0 & n\neq m\\ 0.25 & n=m\end{cases},\ \varphi_n(0)=0,\ \varphi_n(L)=1, \quad (9)$$

After some mathematical calculations given in the Appendix, the AFM cantilever dynamics equation is obtained as:

$$\ddot{Y}_n(t)+\frac{\omega_n}{Q_n}\dot{Y}_n(t)+\omega_n^2 Y_n(t)=\frac{F_n(t)}{m_n}, \quad (10)$$

where $F_n(t)$ is the external force applied to the cantilever which is calculated in the appendix (F_i) and

$$m_n=M_i=0.25(m_h+\rho bh)L, \quad (11)$$

$$\omega_n^2=k_n^4\frac{EI}{m_h+\rho bh}, \quad (12)$$

$$Q_n=\frac{\omega_n}{c_h/(\rho bh+m_h)+a_1\omega_n^2}, \quad (13)$$

The added mass and damping stiffness of hydrodynamic force are given by [12,13]

$$m_h=\frac{\pi}{4}\rho_f b^2\mathrm{Re}[\Gamma(\omega)], \quad (14)$$

$$c_h=\frac{\pi}{4}\rho_f\omega b^2\mathrm{Im}[\Gamma(\omega)], \quad (15)$$

where

$$\Gamma=\Gamma_r+j\Gamma_i, \quad (16)$$

$$\Gamma_r=a'_1+\frac{a'_2}{\sqrt{\mathrm{Re}}},\Gamma_i=\frac{b'_1}{\sqrt{\mathrm{Re}}}+\frac{b'_2}{\mathrm{Re}}, \quad (17)$$

where $a'_1=1.0553, a'_2=3.7997, b'_1=3.8018, b'_2=2.73642$ [13]. The Reylonds number is calculated by [26]

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