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The effect of fluid properties and geometrical parameters of cantilever on the frequency response of atomic force microscopy

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ABSTRACT

Nowadays, the atomic force microscopy plays an indispensable role in imaging and manipulation of biological samples. To observe some specific behaviors and biological processes, fast and accurate imaging techniques are required, and one way to speed up the imaging process is to use short cantilevers. For short beams, the Timoshenko model seems to be more accurate compared to other models such as the Euler–Bernoulli. By using the Timoshenko beam model, the effects of rotational inertia and shear deformation are taken into consideration. In this paper, the frequency response of a rectangular atomic force microscope (AFM) in liquid environment has been analyzed by using the Timoshenko beam model. Afterward, since the dynamic response of AFM is influenced by the applied medium, the effects of physical and mechanical properties (e.g., fluid density and viscosity) on the frequency response of the system have been investigated. The frequency responses of the AFM cantilever immersed in various liquids have been compared with one another. And eventually, to study the influence of geometry on the dynamic behavior of AFM, the effect of the cantilever's geometrical parameters (e.g., cantilever length, width and thickness) on the frequency response of the system has been studied.

1. Introduction

The atomic force microscope (AFM) can be used in different environments such as vacuum, air and liquid. The use of atomic force microscopy in biological research enables the examination of the morphology and mechanical properties of biological samples in their natural environment, as the liquid medium allows the samples to stay alive during the research. The other advantages of conducting research in this environment include the elimination of capillary forces [1], reduction of Van Der Waals forces by tenfold [2], and the reduction of contamination between tip and sample [3]. Because the sample molecules that usually stick to cantilever tip and cause low-resolution images escape from the tip in a liquid environment, the quality of images taken by AFM in liquid improves as a consequence. The initial images of biological samples in liquid environments were acquired using the contact mode AFM. In contact mode AFM, the cantilever tip is in constant contact with the surface, and the resulting lateral force could be destructive to soft biological samples. Tapping-mode (TM) atomic force microscopy in liquid was carried out for the first time by Putman et al. [4]. In this mode, problems such as friction and adhesion that lead to low quality images are eliminated.

The tapping mode (either in air or liquid) uses the changes of cantilever vibration amplitude, phase, or resonant frequency caused by tip–sample interaction to reveal the surface properties. Therefore, analytical or numerical models that can accurately simulate the surface-coupled dynamics of the cantilever are so essential [4]. Research suggests that the discrete model (point-mass model) can only approximate the low-harmonic behavior of the system, and that in the stimulation of higher harmonics, there is a major difference between the experimental results and the outcomes of this model [5]. Furthermore, point-mass models provide solutions that correspond to the cantilever's vertical displacement, while in experiments, the detecting system of AFM measures the rotation angle of the cantilever; so to eliminate this problem, the Euler–Bernoulli theory has been used to model the cantilever [6]. Due to the existence of nonlinear forces between tip and sample, analytical solution is too complex or even impossible; so for the dynamic analysis, numerical approaches such as the finite element and superposition methods are usually needed [7]. To investigate the effects of rotational inertia and shear deformation, the modeling of atomic force microscopy by Timoshenko model, which is more accurate than the Euler–Bernoulli model, seemed so necessary, and this research has been implemented recently in an air environment [8].

The modeling of cantilever vibrations in tapping mode, in a liquid environment, is more complicated than that in air. In liquid environments, the cantilever behavior is dominated by large

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hydrodynamic damping and the additional mass from the liquid. Chen et al. studied the frequency and transient responses of AFM cantilevers immersed in liquid by representing the cantilevers as spheres oscillating in viscous liquid [9]. Burnham et al. simulated the behavior of AFM in liquid environment by using a point-mass model [10]. Their results in air had good agreement with the experimental findings, but their results in liquid could not demonstrate the unsymmetrical amplitude changes in the tapping region. The possible reasons for this discrepancy include an inaccurate point-mass model, which was discussed above, and the fact that the hydrodynamic force exerted on a cantilever may not be well represented by the drag force on a sphere. Sader offered a general mathematical model for cantilevers immersed in viscous fluids [11]. Song et al. applied the Euler–Bernoulli beam theory and used the finite element method to simulate the behavior of AFM cantilever in liquid under the tapping mode [12]. They approximated the hydrodynamic force of fluid by using Sader's experimental model, and derived the frequency and transient response of the system. Korayem et al. analyzed the frequency response of AFM cantilever in liquid environment by Euler–Bernoulli beam theory, and used the forward-time method for the simulation [13].

In dynamic mode, the frequency response of atomic force microscope is a function of the cantilever's geometrical parameters and the drag force which is applied on the cantilever by the medium. Since drag force is dependent on fluid viscosity and density, these two parameters have significant effects on system response. By the way, some research works have been performed that demonstrate the effect of fluid viscosity on the quality of images taken from biological samples by AFM [14,15]. The obtained results confirm this important finding that with the increase of kinematic viscosity, image quality drops sharply. More research works have been carried out to determine fluid viscosity and density from the frequency response of the system. Measuring these two properties by other means is impossible [16].

Therefore, considering the significance of performing atomic force microscopy in liquid environments in biological sciences, and the need for high-speed imaging techniques in order to avoid possible chemical reactions in these environments necessitates the use of short cantilevers. In this paper, the behavior of AFM cantilever, modeled by using the Timoshenko beam theory in liquid environment, has been dynamically analyzed; and for this short beam, Timoshenko model is more accurate, compared to other models. Then, the obtained model has been simulated by using the finite element method and MATLAB software. The results in the two environments have been analyzed and compared with the experimental results, indicating good agreement. Since the medium has a non-negligible effect on system response, the effects of mechanical and physical parameters, such as fluid density and viscosity, on the frequency response of the system have been studied. Finally, the influences of the geometrical parameters of cantilever, including the length, width and thickness, on the frequency response of the system have been considered. The results indicate that geometrical parameters affect the frequency response of the system more in a liquid medium than in air. Since hydrodynamic forces in liquid environments are influenced by cantilever dimensions, a more dimensionally appropriate cantilever design would be necessary for these environments.

2. Mathematical modeling of the micro-cantilever

For the mathematical model, a rectangular beam, clamped at one end has been considered, as shown in Fig. 1.

Based on the Timoshenko beam theory for a rectangular cantilever with constant cross section, two coupled governing differential equations of motion that include the transverse deflection and the corresponding bending angle are written as [17]:

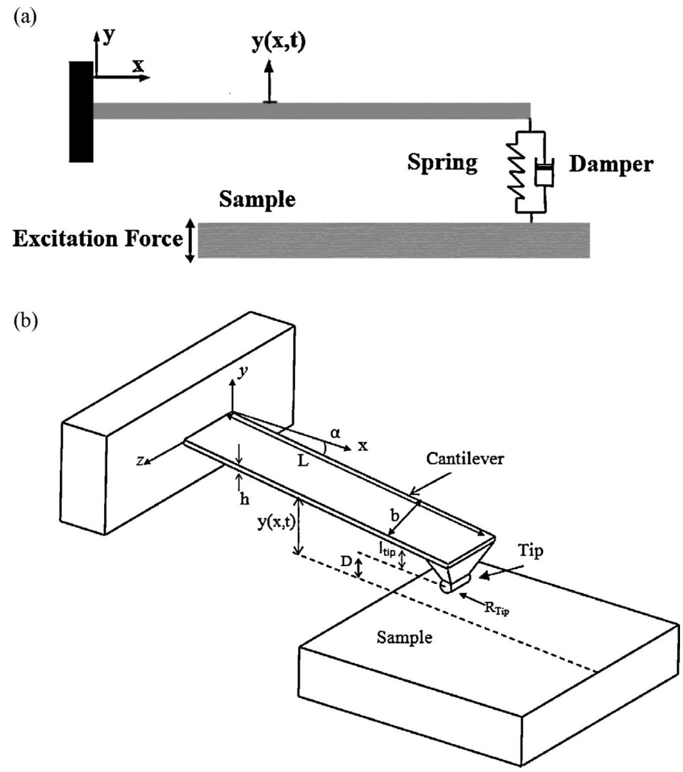

Fig. 1. Schematics of an AFM cantilever: (a) cantilever is clamped at one end and affected by linear interaction forces and (b) geometrical parameters of cantilever.

$$P.D.Es: \quad \begin{cases} \dfrac{\partial}{\partial x}\left[KGA(\dfrac{\partial y(x,t)}{\partial x} - \phi(x,t))\right] - c\dfrac{\partial y(x,t)}{\partial t} - \rho A\dfrac{\partial^2 y(x,t)}{\partial t^2} + f_h(x,t) = 0 \\ \dfrac{\partial}{\partial x}\left(EI\dfrac{\partial \phi(x,t)}{\partial x}\right) + KGA\left(\dfrac{\partial y(x,t)}{\partial x} - \phi(x,t)\right) - \rho I\dfrac{\partial^2 \phi(x,t)}{\partial t^2} = 0 \end{cases} \tag{1}$$

where K, G, A, $y(x,t)$, $\phi(x,t)$, ρ, I, E, c and $f_h(x,t)$ are the shear coefficient, shear modulus, area of cross section, transverse deflection of beam, bending angle of beam, mass density of beam, moment of inertia of cross section, Young's modulus, internal damping of cantilever and the hydrodynamic force exerted on cantilever by the liquid environment, respectively.

The calculation of internal damping coefficient C is generally complex. In this paper, we use the proportional damping method.

$$C = \Phi^{-T} C_\Lambda \Phi^T$$
$$C_\Lambda = diag\left[2\xi_1\omega_1, 2\xi_2\omega_2, \ldots, 2\xi_n\omega_n\right] \tag{2}$$

In the above relations, Φ, ξ_n and ω_n are the matrix of Eigen vectors, nth damping ratio and nth natural circular frequency of the system. In the simple simulation case, the cantilever has been considered as parallel to sample, and the interaction forces between sample and tip have been approximated by a spring and a linear damper.

$$B.Cs: \quad \begin{cases} y(x,t) = \phi(x,t) = 0 & x = 0 \\ -KGA\left(\dfrac{\partial y(x,t)}{\partial x} - \phi(x,t)\right) = F_{int} = k_n y(x,t) + c_n\dfrac{\partial y(x,t)}{\partial t} & x = L \\ EI\dfrac{\partial \phi(x,t)}{\partial x} = 0 & x = L \end{cases} \tag{3}$$