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Analyses of vibration responses on nanoscale processing in a liquid using tapping-mode atomic force microscopy

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ABSTRACT

An analytical solution of the vibration responses of biological specimens using atomic force microscopy (AFM), which often requires operation in a liquid, is developed. In this study, the modal superposition method is employed to analyze the vibration responses of AFM cantilevers in tapping mode (TM) operated in a liquid and in air. The hydrodynamic force exerted by the fluid on AFM cantilevers is approximated by additional mass and hydrodynamic damping. The tip–sample interaction forces were transformed into axial, distributed transversal, and bending loading, and then applied to the end region of the AFM through the tip holder. The effects of transverse stress and bending stress were adopted to solve the dynamic model. With this model, a number of simulations were carried out to investigate the relationship between the transient responses of the cantilever in a liquid and the parameters considered in nanoscale processing. The simulations show that the vibration of AFM cantilevers in a liquid has dramatically different dynamic characteristics from these of that in air. The liquid reduces the magnitude of the transversal response and reduces the cantilever resonances. Moreover, the magnitudes of response become larger with increasing intermolecular distances and smaller with decreasing tip length. The cantilever vibration amplitudes significantly depend on the damping constant and the mass proportionality constant.

1. Introduction

In this investigation, the solution of the vibration response on nanoscale processing in a liquid using tapping-mode atomic force microscopy was obtained using the modal superposition method. The atomic force microscope (AFM) was developed for producing high-resolution images of surface structures of both conductive and insulating samples in both air and liquid environments [1–4]. AFM can be used as a cutting tool for nanolithography work [5] and as a nanoindentation tester for evaluating mechanical properties. Operating AFM in a liquid allows the investigation of the morphology and mechanical properties of biological samples in their native environment. Other advantages include the elimination of capillary forces, a significant reduction of van der Waals forces, and reduced tip and sample contamination [6]. The pioneering images of biological samples in a liquid were acquired using contact mode AFM and tapping mode measurements were performed on biological samples in a liquid using a different design [7]. In contact-mode AFM, the cantilever tip is in constant contact with the surface; the resulting lateral force can be destructive to soft samples. Tapping-mode (TM) AFM in a liquid was first implemented by Putman et al. [8]. They successfully measured the frequency responses and tip–sample approach curves of V-shaped silicon nitride cantilevers in both air and liquid. If the vibration amplitude is kept at a constant value using a feedback loop, TM can be used to obtain the surface topography.

The vibration behavior of TM depends on the excitation forces, which are composed of the transverse stress and bending stress acting on the tip holder, transmitted from the tip–sample interaction forces. TM operated in either air or in a liquid utilizes the changes of the cantilever vibration amplitude, phase, or resonance frequency caused by the tip–sample interaction to reveal surface properties. Therefore, analytical models that can accurately simulate the surface-coupled dynamics of the cantilever are essential for the qualitative and quantitative interpretation of scanning images, the selection of AFM operating conditions, and the evaluation of the sample's mechanical properties. Modeling cantilever vibration for TM operated in a liquid is a more difficult task than it is for TM operated in air. In a liquid environment, the cantilever behavior is dominated by large hydrodynamic damping and the additional mass from the liquid.

Horng [9] developed an analytical solution to deal with the flexural vibration problem during a nanomachining process which involves an atomic force microscope (AFM) cantilever; in his study, the axial and damping force were neglected. Chen et al. [10] studied the frequency and transient responses of AFM cantilevers

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immersed in a liquid by representing the cantilevers as spheres oscillating in a viscous liquid. Using a point-mass model, Burnham et al. [11] obtained the tip–sample approach curves. Their results in air agree well with the experimental results, but their results in a liquid did not match the unsymmetric amplitude change in the tapping region. Sader [12] gave a general theoretical model for frequency response analysis of a cantilever immersed in a viscous liquid. This model is valid for beams that vibrate with small amplitudes and whose lengths are much larger than their widths. Yaxin [4] presented an FE beam model to simulate the cantilever dynamics in TM operated in air or liquid. Ashhab et al. [13] analyzed the dynamic behavior of a microcantilever–sample system in order to control the cantilever–sample interaction and to avoid the possibility of chaos. Based on calculations of the contact radius and radiation impedance, Yaralioglu et al. [14] proposed an algorithm to calculate the contact stiffness between an AFM tip and a layered material as a function of layer thickness. Due to the nonlinear nature of the tip–sample interaction, numerical methods, e.g., the finite element (FE) method [4,13], are often needed to obtain the solutions of the beam models. Moreover, Sokolov et al. [15] proposed a method to imitate non-contact mode while scanning in the presence of an electric double layer. The combination of minimal tip–sample deformation and repulsive force interaction, are responsible for the observation of the single atom defects. The method decreases the tip–sample interaction by eliminating the attractive forces between the tip and sample. The surfactant solution induces an electrical double-layer (EDL) on the surface of the tip and sample. The solution in a liquid induces an electrical double-layer (EDL) on the surface of the tip and sample, and enhances tip stability during the image scan. Nevertheless, the analytical solution to vibration responses on nanoscale processing in a liquid that result from the tip–sample interaction forces and the damping force applied to the AFM is absent from the literature.

In this paper, the flexural vibration responses of a rectangular Tapping-Mode AFM cantilever subjected to tip–sample interaction forces with the axial force effect, which can be arbitrarily chosen, are studied analytically using the modal superposition method. In this study, the effects of transverse stress, bending stress, and the axial force are used to solve the dynamic model. The results reveal that the vibration of AFM cantilevers in a liquid has dramatically different dynamic characteristics from that in air. The liquid reduces the magnitude of the transversal response and shifts the cantilever resonances to smaller values. Moreover, the vibration phases in liquid and air are always different. The magnitude of response in a liquid stabilizes rapidly and then levels off due to the viscous damping effect, and can improve significantly tip stability during the image scan in the presence of the EDL.

2. Analysis

2.1. Differential governing equations

In this paper, the AFM cantilever moves down vertically with a small amplitude (1–5 nm) when the cantilever tip processes a sample surface in contact mode. Therefore, the linear model can be used to describe the tip–sample interaction. The atomic force microscope cantilever, shown in Fig. 1, is a small elastic beam with a length L, thickness $\bar{h}$, width b, a tip with length l and a tip holder with width of w. x is the coordinate along the cantilever and $v(x,t)$ is the vertical deflection in the x-direction, as shown in the figure. One end of the cantilever, at $x = 0$, is clamped, while the other end, at $x = L$, has a conical tip.

In TM, an AFM cantilever oscillates up and down and touches the sample surface intermittently. As shown in Fig. 2, in the operating condition, the AFM cantilever is usually tilted to the sample surface with a tilt angle $\bar{\alpha}$.

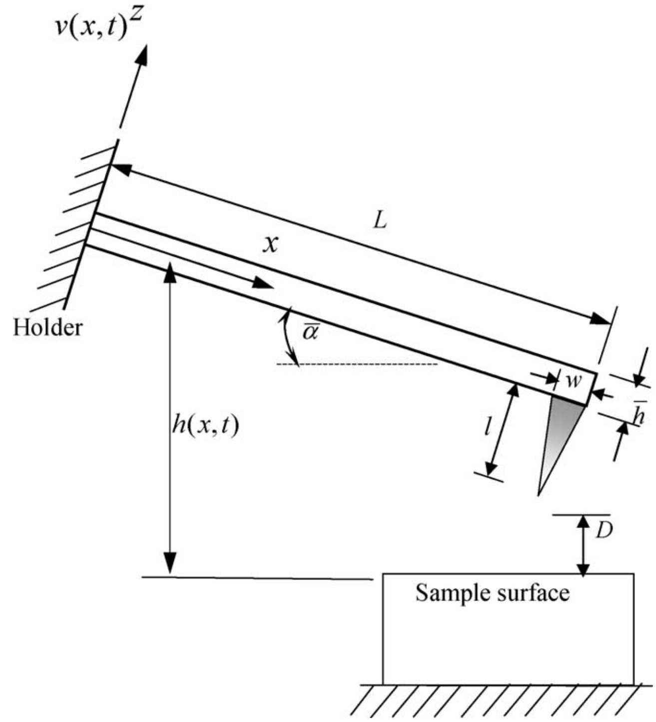

Fig. 1. Schematic diagram of a tip–cantilever system tilted to the sample surface with angle $\bar{\alpha}$ and equilibrium tip–sample separation D.

It is assumed that the damping stress develops in proportion to the strain velocity, and that the bending behavior of a beam vibrating in air (or vacuum) is governed by the following ordinary differential equation [16]:

$$\rho A \frac{\partial^2 v(x,t)}{\partial t^2} + c(x)\frac{\partial v(x,t)}{\partial t} + \frac{\partial^2}{\partial x^2}\left[EI\left(r_1 \frac{\partial^3 v(x,t)}{\partial x^2 \partial t} + \frac{\partial^2 v(x,t)}{\partial x^2}\right)\right] + \frac{\partial}{\partial x}\left[N(t)\frac{\partial v(x,t)}{\partial x}\right] = 0 \quad (1)$$

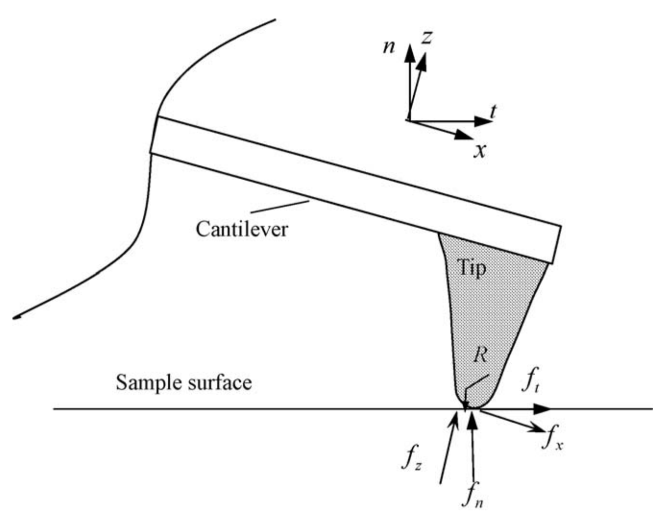

Fig. 2. Schematic diagram of a tip–cantilever system tilted to the sample surface with tip–sample interaction.