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Sensitivity analysis of scanning near-field optical microscope probe

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Abstract

In this paper, we study the dynamic modes of a scanning near-field optical microscope (SNOM) which uses an optical fiber probe; and the sensitivity of flexural and axial vibration modes for the probe were derived and the closed-form expressions were obtained. According to the analysis, as expected each mode has a different sensitivity and the first mode is the most sensitive mode of flexural and axial vibration for the SNOM probe. The sensitivities of both flexural and axial modes are greater for a material surface that is compliant with the cantilever probe. As the contact stiffness increases, the high-order vibration modes are more sensitive than the lower-order modes. Furthermore, the axial contact stiffness has a significant effect on the sensitivity of the SNOM probe, and this should be noted when designing new cantilever probes.

Keywords: Scanning near-field optical microscope; Optical fiber probe; Sensitivity

1. Introduction

During the last decade the atomic force microscope (AFM) has become a very powerful and indispensable tool for studying the nature of the surface topography of diverse samples on a nanometer scale [1–5]. Although AFM possesses excellent imaging capabilities, it only provides mechanical information about the material surface. To simultaneously yield the information about the mechanical and optical properties of nanometer scale surfaces, the scanning near-field optical microscope (SNOM) has been developed [6,7]. The SNOM usually achieves high resolutions beyond the optical diffraction limit by using an optical fiber to scan a few nanometers above the sample material surface.

In a typical SNOM, the optical fiber probe is normal to the sample. The cantilever probe allows simultaneous measurement of the topography and the optical transmission of samples with high lateral resolution [8–10]. In general, the nonlinear interaction forces occur between tip and sample surface. The dynamic responses of the cantilever probe to these surface forces include axial and flexural modes. Each mode has a different mode shape and a different sensitivity, affected by the local sample surface conditions. To obtain the highest contrast for imaging, the most sensitive modes in the system should be found and used.

In this paper, the dynamic responses of the optical fiber probe of a SNOM are considered in terms of both axial and flexural vibrations. For the simple analysis, the amplitude of the surface motion is not very large, so a linearized response can be assumed. The modal sensitivities for axial and flexural vibrations are derived, and the closed form expressions are obtained.

2. Analysis

An optical fiber probe is cantilevered at one end as depicted in Fig. 1. The probe is assumed to have a uniform circular cross section. For simplifying the problem, the cladding of an optical fiber probe is not taken into account in this paper. The interaction with the sample is modeled by an axial spring stiffness, K_a, and a lateral spring stiffness, K_l, and is shown as Fig. 2. The probe experiences flexural and axial vibrations during contact with the probe–sample.

2.1. Flexural vibration

If the sample surface vibrates normal to the probe, the SNOM probe will vibrate flexurally. The linear differential

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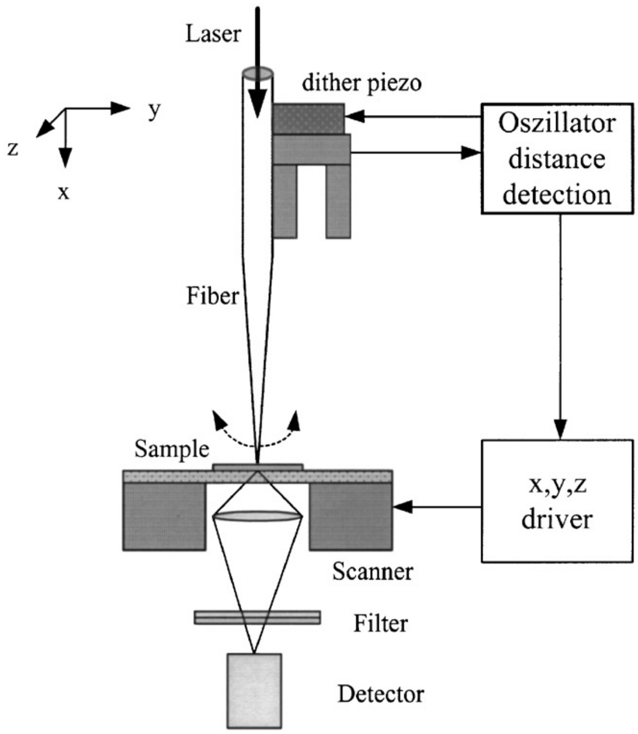

Fig. 1. Schematic diagram of the SNOM apparatus.

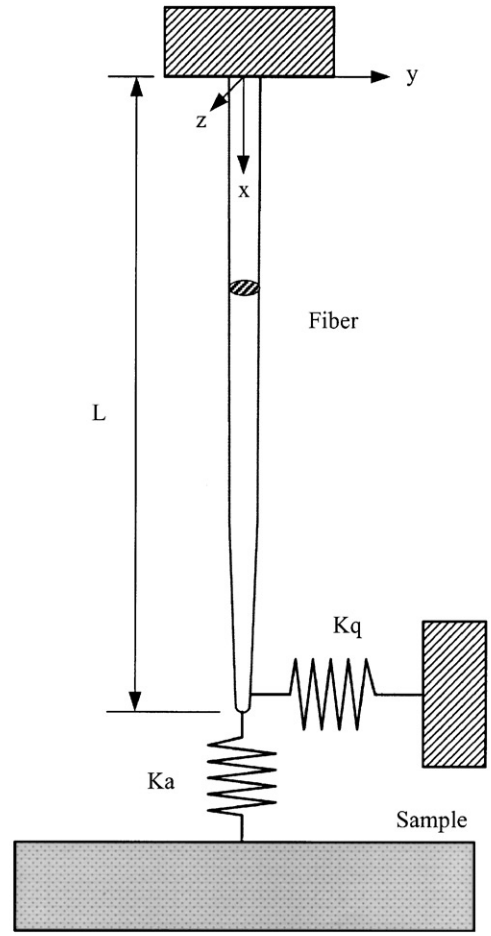

Fig. 2. Schematic diagram of flexural and axial contact with sample for an optical fiber SNOM probe.

equation of motion for the free vibration of the cantilever beam is [11,12]

$$EI\,\frac{\partial^4 y(x,t)}{\partial x^4} + \rho A\,\frac{\partial^2 y(x,t)}{\partial t^2} = 0, \tag{1}$$

where E is the modulus of elasticity, I is the area moment of inertia, ρ is the volume density, and A is the circular cross-sectional area of the cantilever.

The corresponding boundary conditions are

$$y(x,t)|_{x=0} = 0, \qquad y(x,t)|_{x=0} = 0, \tag{2}$$

$$y''(x,t)|_{x=L} = 0, \qquad EIy'''(x,t)|_{x=L} = K_1 y(x,t)|_{x=L}. \tag{3}$$

The boundary condition of the probe at $x = 0$ is assumed fixed end; then the boundary conditions given by Eq. (2) correspond to conditions of zero displacement and zero slope. The boundary conditions given by Eq. (3) correspond to zero moment at $x = L$ and the force is balanced between the beam and the linear tip–sample stiffness. Because a linear model is used to describe the tip–sample interaction force, the probe is restricted to small displacements. The linear spring constant, K_1, depends on the shear rigidity between the probe tip and sample [13,14].

The governing equation, Eq. (1), is a partial differential equation. The equation can be solved by the method of separation of variables and be divided into the two ordinary linear differential equations. Each equation depends only on one of the variables x and t. For satisfying the behavior of the vibration, they must be an eigenvalue problem in space domain and a harmonic function in time domain. Therefore, a general solution of Eqs. (1)–(3) can be expressed as

$$y(x,t) = (a_1 \cos kx + a_2 \sin kx + a_3 \cosh kx + a_4 \sinh kx)e^{i\omega t}, \tag{4}$$

where a_i, $i = 1-4$, are constants determined from the boundary conditions, ω is the angular frequency, k is the flexural wave number.

From the above equations, the characteristics equation can be found:

$$C(\gamma, K_1) \equiv \gamma^3(\cos\gamma\cosh\gamma + 1) - \frac{K_1 L^3}{EI}(\sinh\gamma\cos\gamma - \sin\gamma\cosh\gamma) = 0, \tag{5}$$

where $\gamma = kL$ is the normalized wave number or a frequency parameter.

Substituting Eq. (4) into Eq. (1), we have

$$EIk^4 - \rho A\omega^2 = 0. \tag{6}$$