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Analyzing the effect of the forces exerted on cantilever probe tip of atomic force microscope with tapering-shaped geometry and double piezoelectric extended layers in the air and liquid environments

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ABSTRACT

The aim of the present study is to assess the force vibrational performance of tapering-shaped cantilevers, using Euler–Bernoulli theory. Tapering-shaped cantilevers have plan-view geometry consisting of a rectangular section at the clamped end and a triangular section at the tip. Hamilton's principle is utilized to obtain the partial differential equations governing the nonlinear vibration of the system as well as the corresponding boundary conditions. In this model, a micro cantilever, which is covered by two piezoelectric layers at the top and the bottom, is modeled at angle α. Both of these layers are subjected to similar AC and DC voltages. This paper attempts to determine the effect of the capillary force exerted on the cantilever probe tip of an atomic force microscope. The capillary force emerges due to the contact between thin water films with a thickness of h_c which have accumulated on the sample and the probe. In addition, an attempt is made to develop the capillary force between the tip and the sample surface with respect to the geometry obtained. The smoothness or the roughness of the surfaces as well as the geometry of the cantilever tip have significant effects on the modeling of forces applied to the probe tip. In this article, the Van der Waals and the repulsive forces are considered to be the same in all of the simulations, and only is the capillary force altered in order to evaluate the role of this force in the atomic force microscope based modeling. We also indicate that the tip shape and the radial distance of the meniscus greatly influence the capillary force. The other objective of our study is to draw a comparison between tapering-and rectangular-shaped cantilevers. Furthermore, the equation for converting the tip of a tapering-shaped cantilever into a rectangular cantilever is provided. Moreover, the modal analysis method is employed to solve the motion equation. The mode shape function for the two tapering-shaped sections of the first and the second kind of Bessel functions is utilized. The nonlinear governing equation is solved by employing the Forward Time Simulation (FST). As the Atomic Force Microscopy cantilever switches from the attractive mode to the contact repulsive mode upon proximity to the surface and the reverse occurs during the departure from the sample surface, a hybrid mode is developed which is illustrated in the graphs.

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1. Introduction

Beams, whose geometry and/or material properties vary along the length, have practical importance in engineering design for instance they are used to reduce weight or volume and increase strength and stability of structures [1]. The vibrations of a class of linearly tapered beams were first studied by Kirchkoff. The large displacement response of tapered cantilever beams made of axially and functionally graded materials is investigated by the finite element method, which has been deduced in [3]. The free vibration of elastically restrained cantilever tapered beams with concentrated viscous damping and mass was investigated by De Rosa et al. [4]. Baghani et al. presented the efficient and accurate analytical expressions for large amplitude free vibration analysis of single- and double-tapered beams on elastic foundation [5]. Ghahalfian and Ariaei determined the natural frequencies and the mode shapes of a system of elastically connected multiple rotating tapered beams through a differential transform method [6]. In addition, Auciello and Ercolano calculated the free vibration frequencies of tapered beams in the most general possible boundary conditions by means of direct method [7]. Zhou and Cheung studied the vibrational characteristics of tapered beams with continuously varying rectangular cross-section of depth and breadth proportional to x^s and x^t respectively, where both s and t represent arbitrary real numbers for a truncated beam and arbitrary positive numbers for a sharp ended beam, and x is the axial coordinate measured from the sharp end of the beam [8]. The dynamic stiffness method for free vibration analysis of a rotating tapered Rayleigh beam was developed by Banerjee and Jackson to investigate its free vibration characteristics [9]. A 3D finite element beam element model was investigated by Mohri et al. for the behavior, the buckling and the post-buckling analyses of thin-walled tapered beams with open cross-sections. For this purpose, a nonlinear model was performed in large torsion context according to a new kinematics that accounts for large torsion, flexural torsional coupling and the presence of tapering terms in bending and torsion [10]. The expression describing a cross area linear variation for a tapered beam vibrating axially was considered by Chalah et al. [11]. The structural performance of thin walled multicell multitapered (discrete variation of tapered angles at any point along the beam length) composite beams subjected to constrained torsional loading was examined by Ahmed and Ahmed [12]. Wang et al. investigated the boundary condition identification method for tapered beams with the specific flexible boundaries using static flexibility measurements [13]. Additionally, Banerjee and Williams [14] applied the Euler–Bernoulli theory and Bessel functions to obtain explicit expressions for the exact static stiffness for axial, torsional and flexural deformations of an axially loaded tapered beam. Sadeghi and Zohoor studied the resonant frequency of flexural vibration for a taper-shaped atomic force microscope (AFM) cantileve using the Timoshenko beam theory. The effects of contact position, contact stiffness, height of the tip, thickness of the beam, height and breadth taper ratios of cantilever and the angle between the cantilever and the sample surface were studied based on Timoshenko beam theory on the non-dimensional frequency and sensitivity to the contact stiffness [15]. Korayem and Ghaderi investigated the effect of the interactionof forces on the AFM probe tip. To achieve a higher precision, they divided the thickness of the piezoelectric layer into three sections and examined the effect of each layer [16].

Our study considers the vibrational performance of the tapering cantilever of atomic force microscope in tapping mode. The cantilever actuation is performed using continuous piezoelectric layer. Here instead of nonlinear spring force, three forces are used in the probe tip (Van der Waals, capillary force, and repulsive force). When the tip and the sample are in contact, the water in the overlapping region is accumulated at the edge of the contact area. This volume of water forms a meniscus when the tip-sample separation is less than a specific value. The capillary force arises from the interactions between thin films of water of depth h that cover the sample and cantilever tip due to ambient humidity. This force is dependent on the geometry between the probe tip and the sample surface. In this study, we calculate the capillary forces for different geometries. We also assess the influence of surface roughness. When considering the type of geometry, the capillary force can change fundamentally. Furthermore, depending on the roughness and the smoothness of the surface, the Van der Waals force will change, and it would be possible to model the surface roughness using Rumpf and Rabinovich models. During the proximity of the probe tip to the surface, the contact repulsive force will draw away the probe from the sample surface. For this type of force a number of models have also been predicted which consider the type of the sample surface. Correct modeling of the hybrid dynamic systems constitutes the correct basis for the analysis of tapping mechanical systems. Hybrid in formulation is properly capable of solving the variations in the system response which directly depends on the quick changes of the system% status. In long distances the cantilever fluctuates like a oscillator; however, by reducing the distance of the nonlinear forces the cantilever potential increases. Due to the entry of such nonlinear forces into calculations, determining the material properties, including surface cohesion, elasticity and viscoelasticity is influenced by then on-linear dynamic effect of the cantilever. By describing the physical model as a hybrid dynamic system it could be possible to analyze the hybrid feature during the taping mode. Hence for illustrating this hybrid state the Forward Time Simulation (FTS) is used. Moreover, the solution procedure of the numerical method is referred to in this paper. The relevancy of the solutions of cantilever equations is compared to that of the rectangular cantilever studies in [17]. In addition, we evaluate two hydrodynamic force models for analyzing the mass and the damping added to a cantilever in liquid medium.

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