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Piezoelectrically actuated microcantilevers: An experimental nonlinear vibration analysis

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ABSTRACT

With daily growth of using microcantilevers in microelectromechanical systems, comprehensive analysis on their dynamical behavior is necessary since they are mostly utilized as the main sensing device. In this paper, out-of-plane vibrations of a piezoelectrically actuated microcantilever are experimentally investigated. The microcantilever's top layer is covered with a piezoelectric material (here, ZnO) through which it can be excited. The nonlinear frequency response of the microcantilever is studied and the resulting shift in natural frequency due to nonlinearity is examined. By observing the subharmonics of the fundamental frequencies at second and third order, it is experimentally shown that there exist cubic and quadratic nonlinearities in the microcantilever. Mathematical models based on these experimental tests are then proposed and verified. The out-of-plane measurements provide the experimental ability to observe both transversal and torsional modes. In addition, the modes in which the microcantilever acts like a plate are observed and discussed.

1. Introduction

Microcantilevers are finding applications in many nanomechanical sensors and actuators. More specifically, piezoelectrically actuated microcantilevers have recently received considerable attention since they have the capability of better actuation, while also possessing self-sensing features. The sensing/actuating operation is based on static and dynamic deflections of the microcantilevers. However, measurement of the dynamic vibrations of the microcantilever is the basis for sensing strategy. Therefore, a nonlinear comprehensive experimental study on the frequency response of these microcantilevers seems to be essential since in such small scale even very small excitations can provide large amplitude and consequently nonlinear vibrations [1,2]. Applications of this research can be expanded to several nanomechanical instruments, such as scanning force microscopy [3,4], chemical/biological mass and surface stress sensing [5–7], precise optical sensing [8] and other applications [9].

Piezoelectric composite microcantilevers were first utilized for sensing purposes [10] and then utilized as actuators [11]. The structure of the microcantilever considered here consists of two layers: a main metallic layer which is usually silicon-based layer such as Si or SiO_2, and the piezoelectric layer usually covers a part of one side of the microcantilever (monolayer piezoelectric microcantilever), e.g., ZnO. Fig. 1 shows microscopic image of the piezoelectrically actuated microcantilever and its components considered here.

The nonlinear-flexural vibrations of piezoelectrically actuated microcantilever for fundamental resonance were studied [2,12,13], and it was shown that, as expected for cantilevers, there are cubic nonlinearities due to inertia and stiffness in the model. In addition, for large excitations jump phenomenon is observed. It is shown in this paper that these cubic nonlinearities generate subharmonic resonance. It is also expected to observe subharmonic in the response due to quadratic nonlinearity. This type of nonlinearity is predicted to be added to the system due to nonlinearity of the piezoelectric material which is induced in the response through the electromechanical coupling into the piezoelectric actuator [14,15]. Therefore, by experimentally investigating the response of the microcantilever, a general theoretical model can be obtained and verified. The results are valuable not only for modeling the systems but also for control purposes [16].

In this paper, vibration and frequency response of the microcantilever are investigated. First, three natural frequencies of the microcantilever are obtained and linear and nonlinear phenomena occurred during frequency response sweep are studied to obtain the nonlinearities in the system to present a general model for the microcantilever. In addition, the mode shapes of the microcantilever are experimentally obtained and presented.

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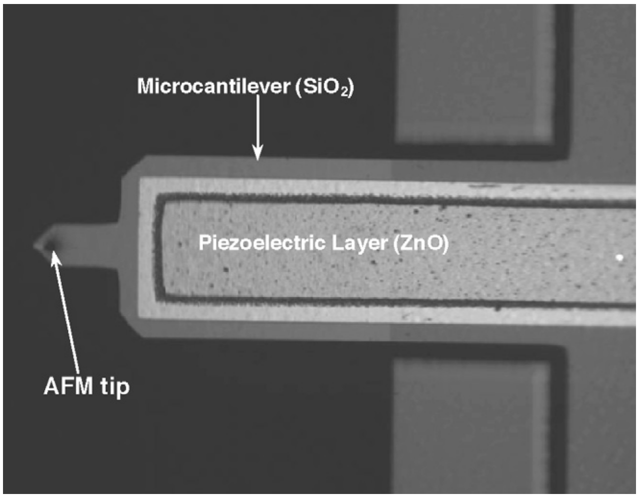

Fig. 1. Microcantilever with piezoelectric layer for atomic force microscopy (AFM) applications.

Table 1
Geometrical and mechanical properties of the microcantilevers.

Property	Value
Density of the piezoelectric layer	6390 kg/m^3
Density of the Si	2330 kg/m^3
Length of the piezoelectric layer	375 ± 5 μm
Length of the Si microcantilever	500 ± 5 μm
Thickness of the piezoelectric layer	4 ± 0.5 μm
Thickness of the Si microcantilever	4 ± 0.5 μm
Width of the microcantilever tip part	55 ± 2 μm
Width of the piezoelectric layer	130 ± 5 μm
Width of the Si microcantilever	250 ± 5 μm
Young's modulus of the piezoelectric layer	130 ± 5 GPa
Young's modulus of the Si	180 ± 5 GPa

2. Experimental setup and method

The experimental investigation is performed using the state-of-the-art microsystem analyzer, the MSA-400, which is equipped with laser interferometry measurement system to provide both in-plane and out-of-plane displacement and velocity measurements at the nanoscale. Eight identical (in shape) microcantilevers are used for the test as shown in Fig. 1. The piezoelectric layer is made of one 3.5 μm Zinc Oxide (ZnO) layer and two 0.25 μm titanium–gold (Ti/Au) layers [2]. The mechanical and geometrical properties of all specimens slightly vary that cause some changes in natural frequencies from one microcantilever to the other one. However, the overall response properties show similar behavior. These properties are listed in Table 1.

Each microcantilever is installed in a holder as shown in Fig. 2. The holder provides the sockets for connecting the piezoelectric layer to a voltage source for actuation of the microcantilever. The voltage source for experiments is provided by the microsystem analyzer which can produce different signal types in the range of 0–10 V and up to 20 MHz. The piezoelectric layer of the microcantilever is also limited to 10 V input. In the experiments presented here, the excitation voltage is kept in the range of 2–9 V.

The holder is then assembled on a goniometer that can provide the ability to rotate the microcantilever to make it completely horizontal under the laser and microscope. Fig. 3 demonstrates the microcantilever holder installed in the goniometer.

The complete setup including microcantilever, the holder and the goniometer is then placed on a microstage under the laser sensor of the MSA-400 as shown in Fig. 4. The microstage system provides the 3D motions to place the microcantilever tip in proper range and position under the laser sensor for vibration measurement.

The experimental data are captured using MSA-400 compatible software. The excitation voltage for the piezoelectric layer is generated by the MSA-400 in different formats and amplitudes. For these experiments, periodic chirp signals with 2–9 V amplitudes are applied to the piezoelectric layer. Once the microcantilever is placed under the laser, the piezoelectric layer is connected to the excitation voltage through connection cables. Scanning points on the microcantilever for measuring the vibration can be defined for the MSA-400 software; then the laser automatically reads the vibra-

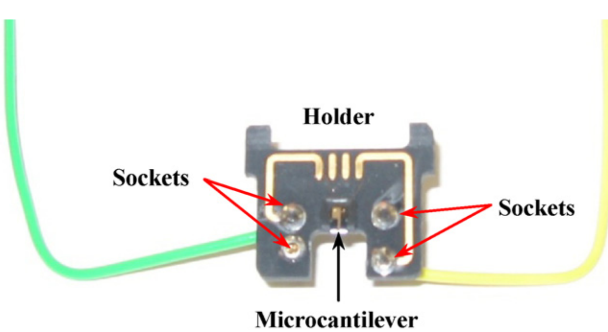

Fig. 2. Piezoelectric actuated microcantilever on the holder.

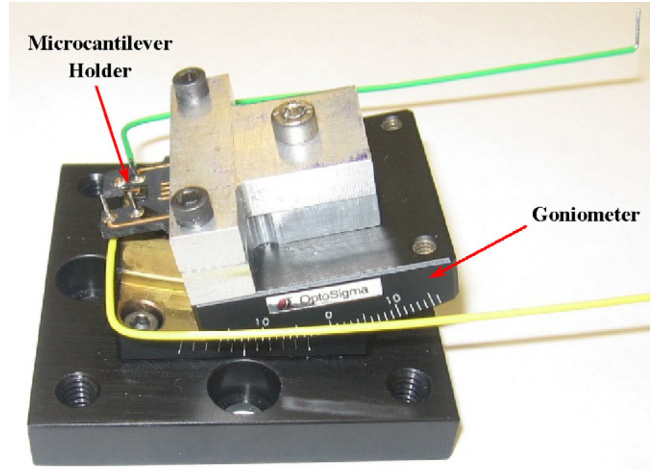

Fig. 3. Microcantilever holder on the goniometer.

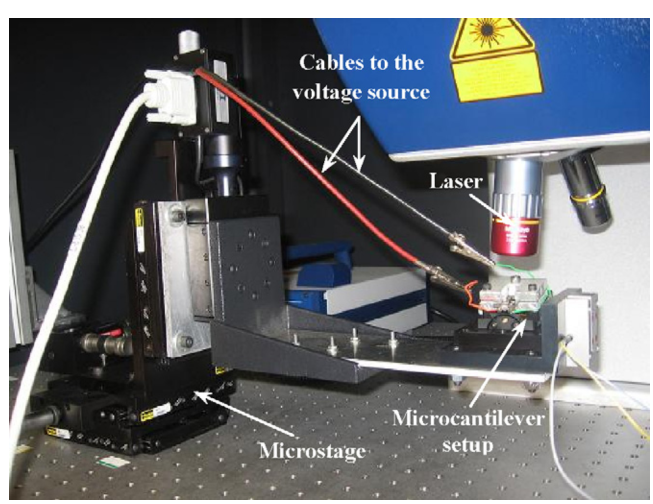

Fig. 4. Test platform with components.