Measurement and visualization of dynamics of piezoelectric microcantilever

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Abstract

Methods for measuring the resonant frequencies and visualizing the motion of the $Pb(Zr_{0.5}Ti_{0.5})O_3$ microcantilever are investigated. Considering the two-segment structure of the microcantilever, a self-exiting self-sensing method is proposed to obtain the fundamental resonant frequency. An optical system consisting of light microscope, CCD camera and video card is established to visualize the first two vibration mode shapes. The theoretical, measured and visualized first resonance of one micocantilever is 17.28 kHz, 17 kHz and 17.8 kHz, respectively. A theoretical second resonance of 84.16 kHz is seen at 71.9 kHz. The proposed method is valid for measuring and visualizing low resonances of active micro structure.

Keywords: Piezoelectric, microcantilever, dynamics, natural frequency, visualization

1. Introduction

Advanced testing methods for the dynamics of mechanical microdevices are necessary to develop reliable micro electro-mechanical systems. However, microdevices often present a measurement challenge. Small feature sizes and submicrometer deflections make the detection of microdevices motion particularly difficult [1].

Laser Doppler Vibrometer is widely used in non-contact measuring the dynamic response of microstructure [2]. Resonances of piezoelectric microcantilever can be determined by impedance analysis [3]. Xie *et al.* proved that Laser Doppler Vibrometer (Polytec, model PSV-300F) and impedance analyzer (SI 1260) can provide first resonant frequency at 223 kHz level very closely [4]. Hart *et al.* described a computer-controlled stroboscopic phase-shifting interferometer system, which can measure tens of micrometers out-of-plane deformations at multiple points on micro mirror and determine the resonant modes [5]. 3D visualization of microdevices involves a complicated and expensive system that is capable of stroboscopic imaging, interferometry and digital interference image processing [6, 7], requiring careful optical alignment and meticulous operation.

The purpose of this research is to find a low cost and direct viewing method to measure the dynamics of piezoeletric mirocantilever, needless of any digital post-processing. The fabrication and structure of PZT microcantilever is briefly introduced. Then two measurement techniques for first and second resonance are explained. One involves lock-in amplifier and charge amplifier by integrating piezoelectric sensing and actuating capability, and the other one is optical technique involves microscope and CCD camera.

2. Piezoelectric microcantilevers under test

$Pb(Zr_{0.5}Ti_{0.5})O_3$ thin film was deposited by sol-gel method. The PZT microcantilevers were fabricated using wet and dry combined bulk micromachining techniques. The process details can be found in [8]. One type of microcantilever as shown in Fig. 1 is heterogeneous bimorph. The PZT layer was deposited on the substrate $Pt/Ti/SiO_2/Si$, Pt/Ti acts as bottom electrode. Another Pt layer was deposited on PZT layer as top electrode but separated into two equal parts with length of 450μm. The other type of cantilever has two layers of PZT thin film with a whole top electrode. The microcantilever chip is glued to a small printed circuit board (PCB) and contacted by wire bonding.

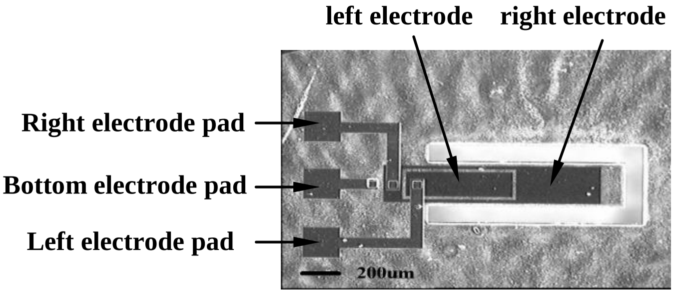


Fig. 1. SEM picture of PZT microcantilver.

Fig. 2. Picture of PZT microcantilvers on PCB.

For fixed-free cantilever, the flexural modal frequencies were theoretically derived as following in [9].

$$f_i = \frac{\beta_i^2}{2\pi l^2}\sqrt{\frac{EI}{\rho A}} \tag{1}$$

where i is mode order, β_i is mode constant, l is length, E is effective Young's modulus, I is inertial moment, A is cross section, ρ is density of the beam material. These parameters and theoretical resonant frequencies are listed in Table 1.

Table 1. Parameters of PZT microcantilever.

	l, μm	w, μm	h, μm	E, GPa	ρ, kg/m^3	f_1, kHz	f_2, kHz
specimen #1	1160	240	17	165	2300	17.28	108.30
specimen #2	1240	280	17	130	2300	13.43	84.16

3. Measurement system and techniques

3.1 Measurement of first resonant frequency

Although complex impedance analysis can provide an effective and convenient way to evaluate the dynamics of piezoelectric cantilever [4], we are trying to develop alternative method by using the same hardware setup during the research of sensing and actuation characteristics. We have demonstrated that each part of the microcantilever sample #1 can be used as sensor or actuator [8]. The integration of a sensing part on the cantilever may eliminate the need for external deflection detectors like Laser Doppler Vibrometer.

The schematic is shown in Fig. 3. Lock-in amplifier (SR830) generates accurate sinusoidal voltage as inner referece signal. Here, this voltage is output and applied to the left electrode to drive the microcantilever. Due to the direct piezoelectric effect, charge appears on the right electrode. The charge is collected by a charge amplifier (YE-5850). Denote the output of the charge amplifier as V_{sen}. V_{sen} is then transfered to the lock-in amplifier. The lock-in amplifier extracts the amplitude of V_{sen} at referece/driving frequency. By changing the frequency in steps and observing the amplitude changes of V_{sen}, resonant peak can be found.

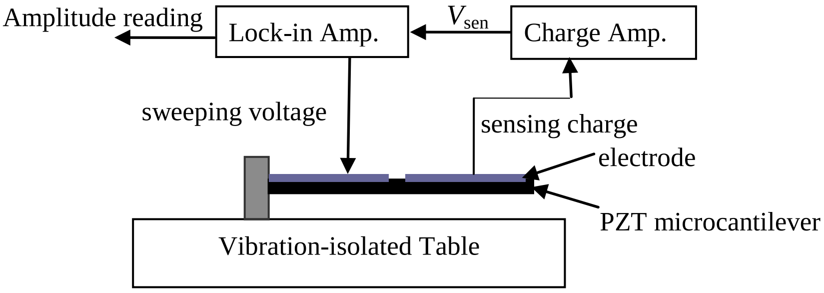


Fig. 3. Schematic for measuring first resonance by integration of sensing and actuation.

3.2 Visualization of first two resonances

We also developed an optical system in order to intuitively observe how the micro cantilever vibrates. As shown in Fig. 4, it consists of light microscope, CCD camera and computer with video card. The microcantilever is placed on microscope stage with a tiny slope. We utilized the light source of 12 LEDs in Scanning Probe Microscope (CSPM 3000). These LEDs produce a continuous white focused beam to illuminate the microcantilever surface. Make sure that there is only a small light spot shinning on tip of the microcantilever in initial state. The microcantilever is applied a sine sweeping voltage by lock-in amplifier (SR830). The transient shapes of microcantilever with different size of reflected light spot are captured by CCD camera and shown on the monitor of PC simultaneously, from which, the approximate vibration mode can be determined subjectively. The whole system is mounted on a vibration-isolation optical table.

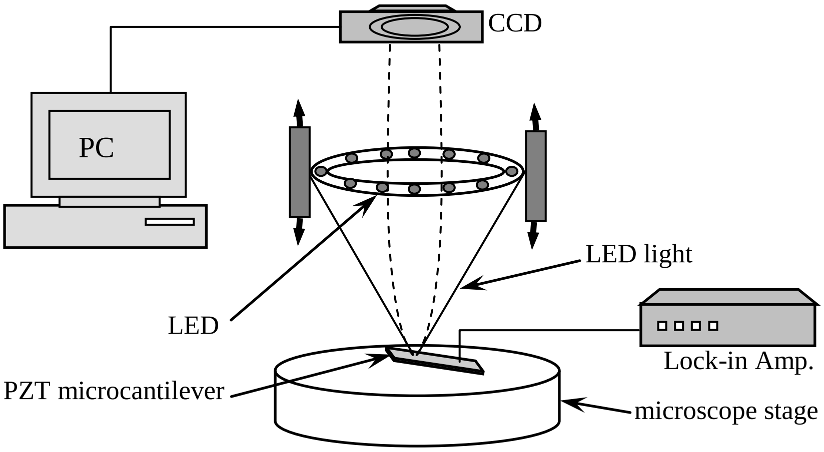


Fig. 4. Schematic for visualizing dynamics of microcantilever.

4. Measurement results

4.1 First resonant frequency determination

The amplitude of the sweeping voltage is fixed at 5 V, which is the maximum value that SR830 can generate. Due to the theoretical first resonance of 17.28 kHz, the sweeping frequency range was set from 10 kHz to 25 kHz at step of 1 kHz. The charge amplifier was at resolution of 2 mV/pC. The method for measuring the first resonance by integration of sensing and actuation is only available to microcantilever sample #1. The measured amplitude of V_{sen} versus frequency is shown in Fig. 5. The first resonant frequency is observed at 17 kHz, which is close to the theoretical value of 17.28 kHz.

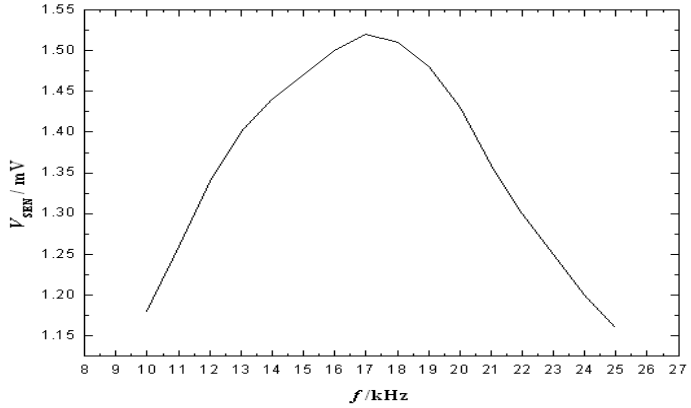
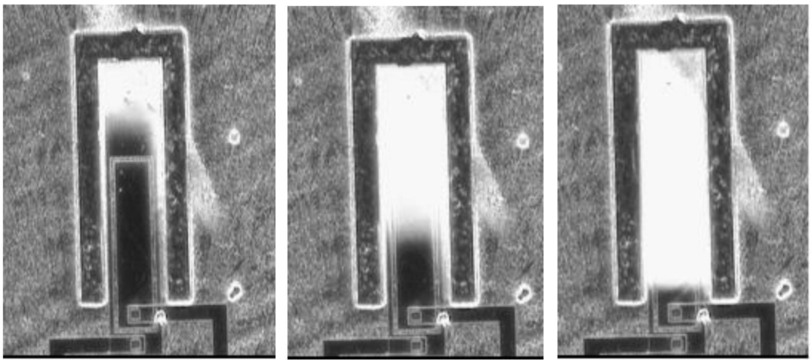


Fig. 5. Measured relation between amplitude of V_{sen} and frequency.

Fix the amplitude of driving voltage and increase frequency at step of 0.1 kHz. In the process, capture pictures of the microcantilever. Three typical pictures of sample #1 are shown in Fig. 6. The light spot was getting bigger along with the increase of frequency, the largest light spot was observed in Fig. 6 (c) when frequency was 17.8 kHz. After that, as frequency was bigger than 17.8 kHz, the size of light spot became smaller. So the visualized first resonance of sample #1 was 17.8 kHz. Because the upper frequency limit of SR830 is 102 kHz, we did not try second resonance at theoretical value of 108.3 kHz.



(a) far from resonance (b) near to resonance (c) at resonance

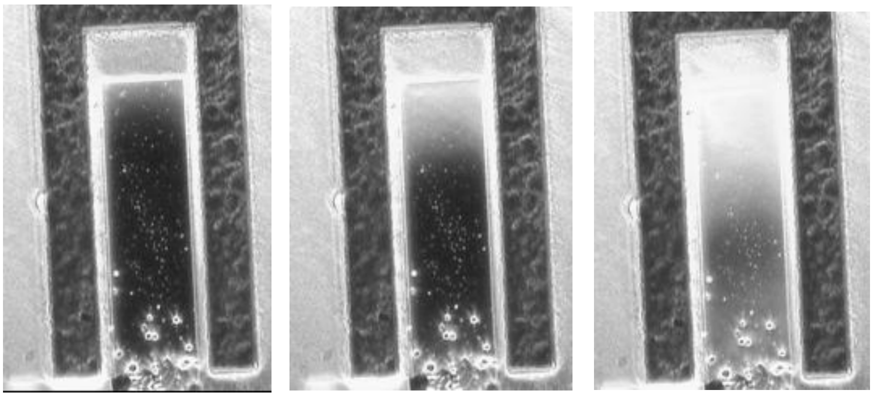
Fig. 6. Pictures of microcantilever sample #1 at frequency approaching first resonance.

4.2 Second resonant frequency determination

Microcantilever sample #2 was chosen to demonstrate the proposed method in visualizing high resonance. The test process was the same as above, but the sweeping frequency reached 90 kHz. Three typical pictures are shown in Fig. 7, from which two distinct resonances can be seen, at 12.6 kHz and 71.9 kHz.

5. Conclusion

Two methods for measuring and visualizing the first and second resonances is described. For microcantilever sample #1, the measured and visualized first resonance was 17 kHz and 17.8 kHz versus the theoretical value of 17.28 kHz. For sample #2, the visualized first two resonances was 12.6 kHz and 71.9 kHz versus theoretical value of 13.4 kHz and 84.2 kHz. As piezoelectric charge is proportional to the average deflection, the sensing and actuation combined method may not get accurate result in measuring second mode above. The dynamics visualization results are intuitive and vivid, but may be not accurate due to manipulator's judgment. So the proposed method is only valid for measuring and visualizing low resonances of active micro structure.



(a) initial state (b) at first resonance (c) at second resonance

Fig. 7. Pictures of microcantilever sample #2 at different frequency.

6. Acknowledgements

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