Journal of Novel Applied Sciences
Available online at www.jnasci.org
©2013 JNAS Journal-2013-2-S/806-811
ISSN 2322-5149 ©2013 JNAS

Vibration Studying of AFM Piezoelectric Microcantilever Subjected to Tip-Nanoparticle Interaction

R. Ghaderi[1*], M. H. Korayem[2] and M. Haghpanahi[2]

1- Department of Mechanical Engineering, Faculty of Technical and Engineering, Shahrekord Branch, Islamic Azad University, Shahrekord, Iran
2- Robotic Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

***Corresponding author*: R. Ghaderi**

ABSTRACT: Piezoelectric microcantilevers (MCs) are a set of MCs that can be used in atomic force microscope (AFM) to measure the force between tip and surface of sample, nanotribological description of particles and nanomanipolation. In this paper, the vibrating motion of AFM piezoelectric MCs is studied nearby nanoparticle with consideration of the Van der Waals force. The effect of nanoparticle on vibrating motion is investigated. Studying the vibration response of the piezoelectric MC in higher vibration modes indicates that the first vibration mode has the most sensitivity to the nanoparticle interaction. Therefore, this mode is the best operating mode for this type of MC in the non-contact state and in interaction with nanoparticle.

***Keywords*:** Nanoparticle, Piezoelectric MC, AFM, Van der Waals

INTRODUCTION

Recently, MCs are used extensively in many micro and nano systems. MCs can be used in AFM for measurement of force between tip and surface of sample, nanotribological description of nanoparticles (Sitti, 2001) preparation topographical images of surface (Rogers et. al., 2004) and measurement of biological induced surface stress (Mahmoodi et. al., 2008). Among common cantilevers in AFM, piezoelectric MCs are introduced as another type of AFM beams with self-actuator and self-sensing feature. Piezoelectric MCs are one the most commonly utilized microelectro-mechanical systems in a variant of the ultra-precise scanning and characterization application. The MC is covered by a piezoelectric layer on the top surface. The piezoelectric layer is utilized as a potential source of actuation, or as an alternative transduction for the laser interferometer in the AFMs. Through elimination of laser, these types of MCs make it possible to miniaturize AFM and facilitate its calibration.

Itoh and Suga (1994) presented a piezoelectric MC for determination of force gradients as self-sensing and self-actuating. Adams et al. (2005) presented a simple electrical circuit to make possible the commercial use of piezoelectric MC as a self-sensing mode in AFM tapping mode. Lee et al. (1997) introduced a microcantilever with PZT piezoelectric layer in order to be used in the AFM in dynamic mode and employed it as three building blocks of AFM namely, microcantilever, actuator and deformation sensor. They then succeeded in capturing high-contrast images from the selected sample in the amplitude mode. Mahmoodi et al. (2007, 2009) theoretically investigated the flexural vibration of the piezoelectric MC in the absence of the sample force for non-AFM applications using the theory of nonlinear uniform beam and compared the flexural responses with experimental results.

MCs can be used in nanomanipulation (2011) and surface lithography (Sitti, 2001) as a robot arm or for determination of position and characteristics of nanoparticle. Nanomanipulation systems have two different operating modes: (i) *static mode (contact mode)* in which the MC deforms under the particle force without any vibrating motion force; (ii) *dynamic mode (noncontact or semi-contact mode)* in which cantilever vibrate near particle with its natural frequency or near to it. Most of manipulation systems are operated in contact mode. In this operating mode, sharp tip is pushed into sample surface that may lead to destruction of sample surface. This is more serious for soft samples such as biomaterial samples. So nanomanipulation based on dynamic mode has more advantages than contact mode (Martin et. al., 1998; Yang et al., 2008). Although the MC subjected to the tip-nanoparticle interaction has been widely investigated in contact mode (Korayem and Zakeri, 2009; Korayem et. al., 2009) but there are a few studies in non-contact mode (Raifi et. al., 2005; Delnavaz et. al., 2010) that is only for MC without piezoelectric layer and vibrating response of piezoelectric MC interacting with nanoparticles hasn't studied yet.

In this paper, the vibration response of piezoelectric MC interacting with nanoparticle is analyzed. With respect to the discontinuities of the MC (Mahmoodi et. al., 2007), due to the present of the piezoelectric layer and tip zone (Figure 1), non-uniform beam model is used for analysis. MC vibration studying is done near the surface of the nanoparticle in non-contact mode using the Van der Waals model. We will study the effect of the spherical nanoparticle on the motion parameters of a MC (amplitude, resonance frequency) and the way the nanoparticle affects the vibration response of a MC in different vibration modes.

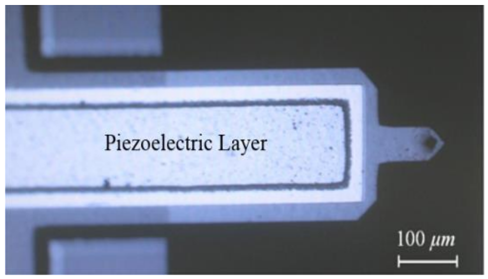

Figure 1. Piezoelectric MC with cross-sectional discontinuity (Mahmoodi et al., 2007)

2. Numerical Simulation

In order to numerically investigate the vibrating motion, a system involving MC and nanoparticle is considered as Figure 2. A dynamic micro actuated silicon probe (DMASP) MC beam from Bruker AFM Probes® series (Mahmoodi et. al., 2007) is selected (Fig. 1). MC specifications are listed in Table 1. The probe tip radius of this MC is 50nm. Nanoparticle is also selected from Thermo Scientific 3200® series that is made from polystyrene.

Table 1. Parameters of simulated piezoelectric MC

	E (Gpa)	ρ (Kg/m^3)	h (μm)	W (μm)	L (μm)
Base Layer	185	2330	3.5	250	375
Lower Electrode	78	19300	0.25	130	330
Piezoelectric Layer	104	6390	3.5	130	330
Upper Electrode	78	19300	0.25	130	330
Tip	185	2330	3.5	55	125

Figure 3 shows the time response of piezoelectric MC near the nanoparticle surface. The excitation voltage is 0.5mV and the equilibrium distances are selected 200, 170, 165 and 160 nm. As seen in Figure 3(a), at large equilibrium distance, the time response of MC is very close to its free time response due to negligibility of the Van der Waals force. However, by closing the probe tip to the nanoparticle and therefore increasing the Van der Waals attraction force, the amplitude of vibrating motion will decrease. This phenomenon can be seen in Figures 3(b) – 3(d).

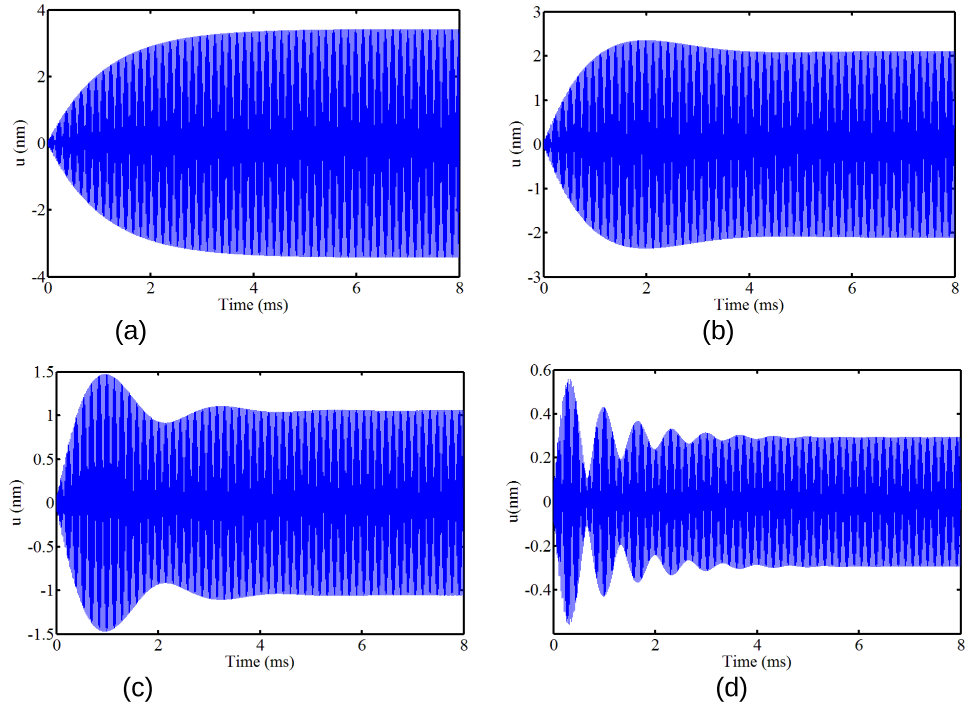

Figure 3. Time response of piezoelectric MC near the nanoparticle (a) d=200 nm, (b) d=170 nm, (c) d=165 nm, (a) d=160 nm

In piezoelectric MCs, piezoelectric layer is used as an actuator. According to Eq. 12, the more applied voltage (P_d *(t)*) is, the more amplitude of vibrating motion will be. According to Figure 4, this increase in amplitude is linear in small vibrations and absence of force between tip and nanoparticle. But as tip approaches to nanoparticle and the Van der Waals force is intensified, increase of amplitude will be nonlinear. According to this Figure, by approaching the MC tip to the nanoparticle and thus intensification of the Van der Waals force, deviation from linear state will increase.

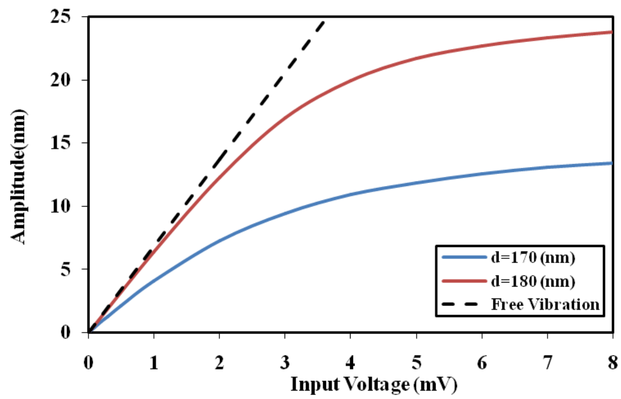

Figure 4. Influence of applied voltage on amplitude

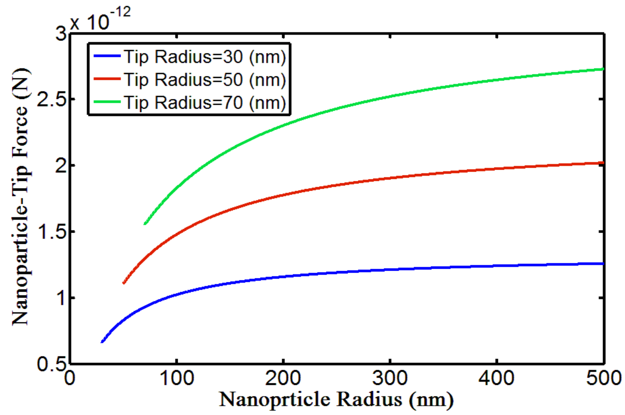

Figure 5. Influence of nanoparticle radius on the Van der Waals force

According to Eq. 8, the Van der Waals force between tip and nanoparticle depends on tip and nanoparticle radius as well as distance. Figure 5 indicates relation of this force with on tip and nanoparticle radius. As it is apparent, the Van der Waals force decreases with increment of tip and nanoparticle radius. According to results of Figure 5, it is evident that ratio of force increment in low radius is high and decrease with increment of radius.

Decrement of the Van der Waals force has inverse result on amplitude of vibrating motion, i.e. decrement of the Van der Waals force leads to increment of amplitude of MC. This is verified in Figure 6. As can be seen in this Figure, rate of amplitude increment is higher in low radius of nanoparticle in which rate of force decrement is higher and rate of amplitude increment is lowered in high radius in which rate of force decrement is lowered. Comparison of obtained results in Figures 5 and 6 indicates high dependency of vibrating motion amplitude on variation of the Van der Waals force.

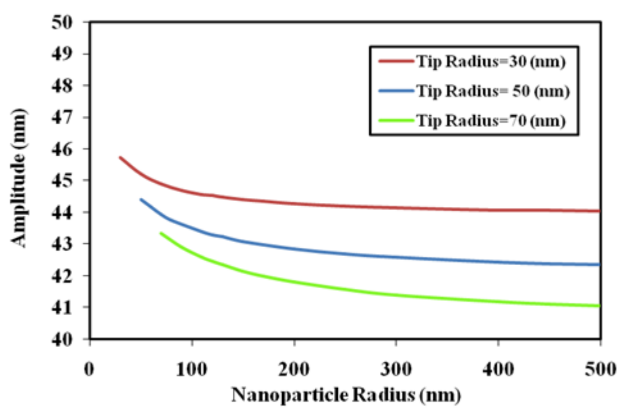

Figure 6. Influence of nanoparticle radius on the amplitude of MC vibrating motion

Figure (7) shows the sensitivity of the amplitude to the tip-nanoparticle Van der Waals force in higher vibration modes. With respect to the results of this Figure, it can be concluded that contrary to the first mode of vibration, the sensitivity of the amplitude to the intensity of the Van der Waals force (the size of nanoparticle) decreases in higher vibration modes. Therefore, regarding the high sensitivity of the first mode to the changes of Van der Waals force, we can conclude that the best operating mode of vibration for the topography of the nanoparticle would be the first mode of vibration.

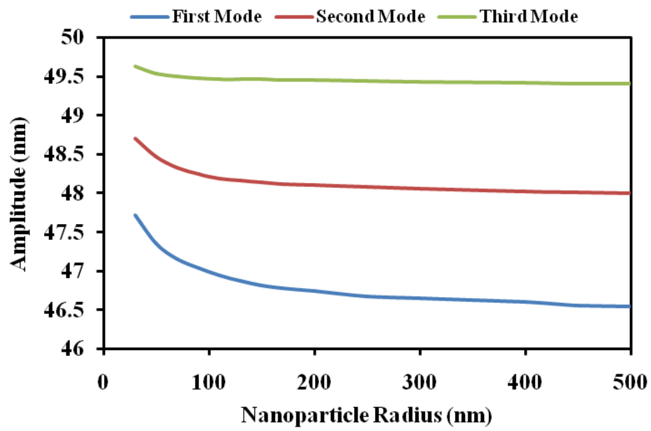

Figure 7. Influence of nanoparticle radius on the amplitude of MC vibrating motion in higher modes of vibration

Figure (8) shows the microcantilever frequency response near the nanoparticle. The curve of microcantilever frequency response consists of two branches: FR^- and FR^+. The two branches approach each other very much near the resonance frequency. Due to the instability of the FR- branch, an abrupt jump from the FR^+ to the FR^- branch occurs with a slight decrease in the excitation frequency. This jump will lead to a considerable decrease of the amplitude. As seen in Figure (8), this amplitude jump occurs in higher modes of vibration and at different radii of the nanoparticle. Since the probe tip-nanoparticle Van der Waals force is nonlinear, as the probe approaches the nanoparticle, not only does the amplitude decrease, but also the resonance frequency reduces as well. Figure (8) shows the reduction of MC resonance frequency in its first three vibration modes. As seen in the Figure, with the increase of the size of the nanoparticle and consequently the increase of the Van der Waals force, there will be a higher reduction in the resonance frequency. This phenomenon can be seen in higher vibration modes.

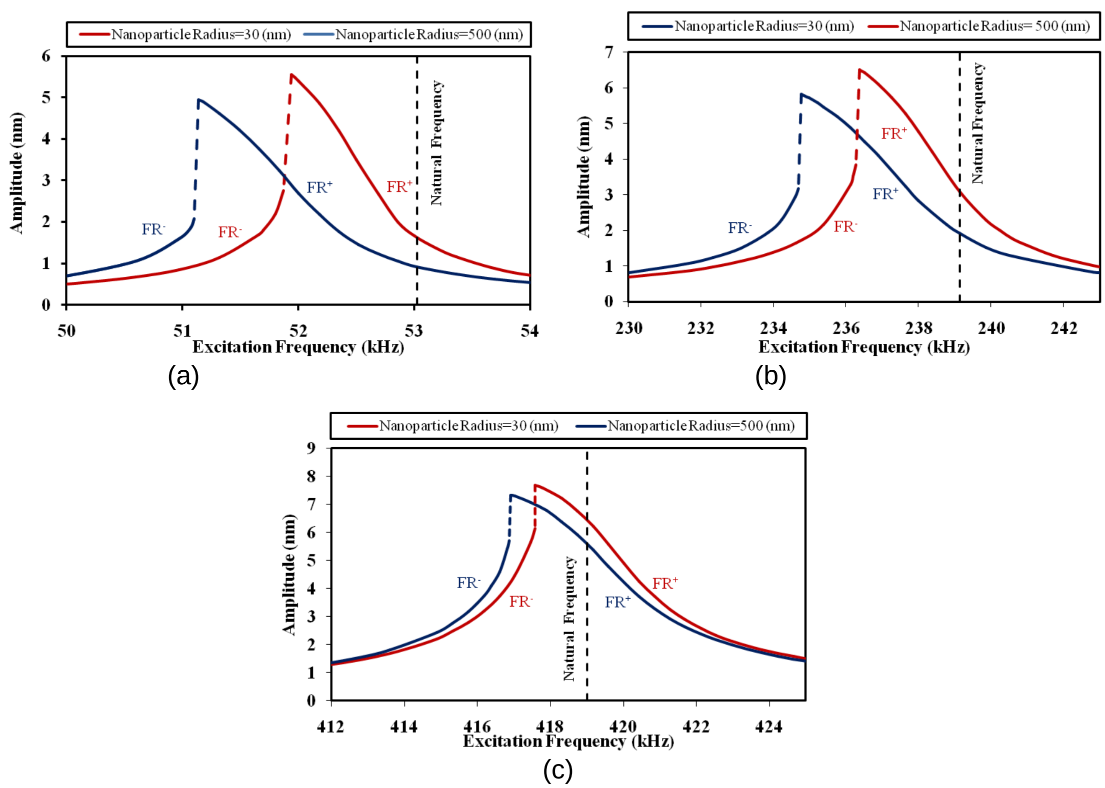

Figure 8. Frequency response of piezoelectric MC nearby the nanoparticle, (a) first mode, (b) second mode, (c) third mode

Figure (9) shows the frequency shift of the MC in its first ten vibration modes. The results obtained from this figure indicate that the maximum frequency shift occurs in the first vibration mode and the amount of frequency shift decreases in higher modes. Hence, it can be concluded that the sensitivity of the vibrating motion to the nonlinearity of the tip-nanoparticle force decreases in higher modes of vibration.

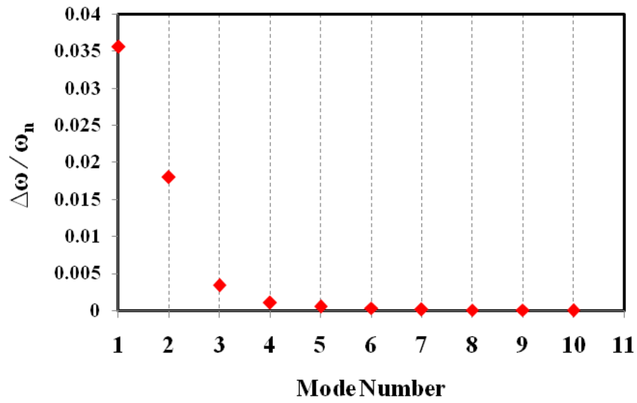

Figure 9. Variations of resonance frequency of the MC in its first ten vibration modes near by the nanoparticle

CONCLUSION

The study of piezoelectric MC vibrating motion close to nanoparticles shows that as the probe tip approaches the nanoparticle, the amplitude and resonance frequency decrease owing to the increase of Van der Waals nonlinear force. Studying the results indicates that as the probe tip approaches nanoparticles with more radii, the decrease of amplitude and resonance frequency of the MC intensifies. Studying the vibration response of the piezoelectric MC in higher vibration modes indicates that the first vibration mode has the most sensitivity to the nanoparticle interaction. In addition, if a MC is excited in higher modes, the effect of nanoparticle interaction on the MC decreases. It can be concluded that the first vibration mode is the best operating mode for this type of MC in the non-contact state and in interaction with nanoparticle.

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