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INVESTIGATION OF TORSIONAL DEFLECTION AS AN UNDESIRED MOTION IN ATOMIC FORCE MICROSCOPY WITH SIDEWALL PROBE

Farzad Mokhtarinezhad[a*], Roslan Abd. Rahman[a], Sina Eftekhar[b], Sedigheh Sadegh Hassani[c]

[a]Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Malaysia

[b]Faculty of Mechanical Engineering, University of Tehran, Iran

[c]Research Institute of Petroleum Industry, catalysis and Nano Technology Research Division; SPM team work, Iran Nanotechnology Laboratory Network (INLN)

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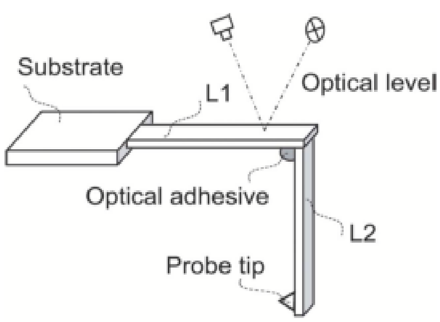
*Corresponding author
Farzad Mokhtarinezhad

Graphical abstract



Abstract

In this paper an analytical model is presented for the Micro-Cantilever (MC) of Atomic Force Microscopy with Side Wall probe (AFM-SW) in the tapping excitation mode. In this model the couple motion of the MC is taken into account while the torsional motion is considered as an undesirable motion which is coupled with the vertical motion. To this end, the effect of several parameters, namely; probe mass, probe dislocation, sidewall extension length, and tip sample interaction force is investigated on the occurrence probability of torsional and vertical motions. It is found that the probe dislocation is the prerequisite factor of the undesired motion happening. For sake of validation, the analytical results are compared against the previously published results, and an excellent agreement is observed.

Keywords: Atomic force microscopy, sidewall probe, micro-cantilever, vibration, coupled motion

Abstrak

Dalam kertas ini, model analitikal dipersembahkan bagi micro- julur Mikroskop Daya Atom dengan prob dinding-sisi dan dalam mod pengujaan menoreh. Dalam model ini, gerakan pasangan bagi mikro-julur diambil kira manakala gerakan kilasan dianggap sebagai gerakan yang tidak diingini yang digandingkan dengan pergerakan menegak. Untuk tujuan ini , kesan daripada beberapa parameter, iaitu; jisim prob, kehelan prob, panjang lanjutan sisi, dan daya interaksi di antara tip dan sampel disiasat ke atas kebarangkalian berlakunya gerakan kilasan dan menegak. Didapati bahawa kehelan prob adalah faktor prasyarat berlakunya gerakan yang tidak diingini. Untuk pengesahan, keputusan analisis ini dibandingkan dengan keputusan yang sebelum ini telah diterbitkan, dan didapati persetujuannya sangat baik.

Kata kunci: Mokroskop daya atom, prob dinding sisi, micro-jalur, getaran, gerakan pasangan

1.0 INTRODUCTION

Atomic force microscope (AFM) is widely used in materials science and has found many applications in surface measurements. The AFM can be utilized to image the topography of materials in nano scales. Furthermore, the AFM is able to probe mechanical properties including obtaining an elastic modulus of a surface, and measuring modulus variations across a sample surface. Whereas scanning tunneling microscope was unusable for nonconductive samples. AFM was developed in 1986 to do away with the need for a conductive sample [1-4]. The AFM can be used for both topographical imaging and force measurements. In the case of topographical imaging, cantilever/tip system scan across the sample surface where cantilever deflections are detected with a position-sensitive photodiode detector. MC deflections are analyzed by the electronic systems to determine topological of the sample. The achievable resolution can approach sub-nanometer for lateral resolution and sub-angstrom for height resolution [1].

Different type of AFM cantilever systems are used in different performance purpose. Quartz tuning fork AFM probe is susceptible to small vibration amplitude and is self actuating and self sensing [5]. Common AFM (C-AFM) is suitable for scanning the flat surface, while the AFM with side wall probe is useful for scanning the edge of materials. Although other types of AFM instruments are useful for scanning the flat surface, but is not suitable to find the properties of the sidewalls and edges of sample like roughness or waviness of microstructures such as micro injection nuzzles, even if the tip become sharp[6]. Therefore, Atomic Force Microscopy with SideWall probe (AFM-SW) allows for determining mechanical properties and measuring of sidewall surfaces [6-10].

Several motions of MC during scanning of surface can occur which are: vertical, torsion, extension, and lateral bending motions. By oscillating the MC, its motion can be the combination of coupled motions. In most studies, the motion of cantilever was decoupled and considered as pure motion. For instance in torsional resonance(TR) and lateral excitation(LE) mode, the tip-mass moves close to surface and the lateral oscillation of cantilever is quite small. The normal force is considered almost constant as the motion of cantilever was considered as a pure motion. However this is not true for all cases. H. N. Pishkenari *et al*. [11] used finite-element method (FEM) to investigate the influence of tip mass on tip-sample interaction forces. Eslami and Jalili [12] presented a comprehensive analytical model or the AFM system using a distributed-parameters model of micro-cantilever beams utilized in AFM systems. Song and Bhushan [13] studied coupling of lateral bending and torsion for AFM with common tip. Dynamic analysis was used for both torsional and lateral excitation modes with the coupling of cantilever torsion and lateral bending taken into account. It was shown that if tip-sample interaction force is relatively huge compared to micro cantilever stiffness, the pure torsional motion approximation cannot provide accurate MC response and the coupled motion should be considered. Lee and Chang [14] studied the influence of the contact stiffness and tip lengths on the resonance frequencies and sensitivities of lateral cantilever modes due to coupled lateral and torsional motions. It was shown that resonance frequency changed to variations in contact stiffness. Each frequency increased until it eventually reached a constant value at very high contact stiffness. Furthermore, the frequency response is sensitive to tip length.

Influence of tip-mass and its dislocation including considering the coupled motion on the sensitivity of all three vibration modes, lateral excitation (LE), torsional resonance (TR) and vertical excitation (VE), was studied by Mokhtari-Nezhad *et al* [15]. The results indicated that performing coupled motion in the analysis of AFM micro-cantilever is almost necessary. Probe mass and location effects on amplitude of the AFM micro-cantilever were found. These effects caused by the interaction between flexural and torsional motion due to the moment of inertia of the tip mass and tip-sample interaction.

In this study, the analytical method is performed by considering these effective parameters: (1) the tip mass (2) damping coefficient of MC and (3) visco-elastic forces between probe and sample in all directions of normal, lateral and tangential. Considering and analyzing all these effective parameters, which have been neglected in previous studies, leads to obtaining more accurate response functions of MC oscillation. Thus studying the coupled motion and parameters which causes undesired deflections seems essential. In this study, dynamics of AFM with extended sidewall beam is investigated with regard to coupled motion of MC. Torsional displacement is studied as undesired motion which AFM-SW works in its vertical mode.

2.0 ANALYSIS

2.1 Tip-sample Interaction Modelling

When the AFM micro-cantilever is brought close to the sample, the probe is greatly affected by the sample surface. In the absence of external fields, the interaction forces, molecular and electromagnetic origin are the predominant forces between head of probe and sample surface. Van der Walls forces, capillary forces, short-range repulsive interaction, and adhesion are main effective interaction forces [16]. Indeed, quantum mechanics and molecular dynamics rule on the tip-sample interaction. So, modeling the realistic tip-sample interaction is critical for accurate simulation [17].

Hertz, Johnson-Kendall-Roberts (JKR), Maugis-Dugdale (MD), and Derjaguin-Muller-Toporov (DMT) models have been used to define the continuum mechanics approaches of the AFM tip and sample interaction [15]. Samples with hard stiffness material and small diameter of tip head, the DMT model is applicable. While the JKR modeling is used for the inversely condition [18-20].

The normal interaction force between probe and sample surface is a nonlinear function of tip-sample separation. Based on the contact theory of Hertz, the forces of tip-sample interaction in the lateral or tangential directions are some functions of normal contact force and tip-sample distance. However, it has linear relationship with the lateral deformation of the specimen [15, 18]. In the normal direction, if the cantilever oscillates around the equilibrium position with very small amplitude, the tip-sample interaction can be linearized by a linear visco-elastic model [18]. In this case, the interaction forces are:

$$f_i = -k_i(\delta_i - a_i) - \eta_i(\dot{\delta}_i - \dot{a}_i) \quad (1)$$

where f_i is the interaction force between probe head and sample, k_i and η_i are the stiffness and damping coefficients of the linear visco-elastic model respectively and i presents normal, lateral, and tangential directions as illustrated in Figure 1. Displacements of sample surface and displacements at tip head in the normal, lateral, and tangential directions are presented by a_i and δ_I respectively.

It is considered that the MC holder oscillates in harmonic motion. Thus the relative displacement at the tip head (δ) is also assumed to be harmonic with the frequency of Ω where:

$$\delta_i = \Delta_i . e^{i\Omega t} \quad (2)$$

The symbol Δ_i is tip head displacement amplitude with frequency of Ω. Also, the applied forces on the tip head are:

$$\bar{f}_i = k_i \delta_i + \eta_i . \dot{\delta}_i + m_{tip} \ddot{\delta}_i \quad (3)$$

Substituting Eq. (2) into (3) gives:

$$\bar{f}_i = (k_i + i.\eta_i.\Omega + m_{tip}\Omega^2).\Delta_i.e^{i\Omega t} \quad (4)$$

Hence, the consequent applied force is also harmonic with frequency of Ω where,

$$\bar{f}_i = \bar{F}_i.e^{i\Omega t} \quad (5)$$

And

$$\bar{F}_i = (k_i + i.\eta_i.\Omega + m_{tip}\Omega^2).\Delta_i \quad (6)$$

2.2 Torsional and flexural vibration

The second and fourth order partial differential equations respectively, drive the torsional and flexural oscillations of the MC with uniform and homogeneous beam and constant cross section. Schematic model of AFM-SW is illustrated in Figure 1 and the equations of motion regarding damping coefficients of torsional or vertical bending of the MC are [13, 21]:

$$GJ\frac{\partial^2\theta(x,t)}{\partial x^2} = \rho I_p \frac{\partial^2\theta(x,t)}{\partial t^2} + C_t\frac{\partial\theta(x,t)}{\partial t} \quad (7)$$

$$EI\frac{\partial^4 y(x,t)}{\partial x^4} + \rho A\frac{\partial^2 y(x,t)}{\partial t^2} + C_b\frac{\partial y(x,t)}{\partial t} = 0 \quad (8)$$

where A is cantilever cross section area, ρ is cantilever density, c_t and c_b are the damping coefficients for the torsional and vertical bending of the MC, G and E are the shear modulus and Yong's modulus, I_z and I_p are the area and polar area moment of inertia of MC cross-section. The parameter x is the coordinate along the longitudinal direction of the micro cantilever, t is time, $\theta(x,t)$ and $y(x,t)$ are rotation angles around the x axis and vertical bending of MC respectively.

The MC holder is assumed to move in harmonic motion defined as $h_y(t) = Y_0.e^{i\Omega t}$ which oscillates the MC with amplitude of Y_0 and frequency of Ω. The motion of MC is assumed harmonic due to linear dynamic system. Therefore, The solution of Eq. 2 and 3 can be expressed by:

$$\theta(x,t) = \Theta(x).e^{i\Omega t} \quad (9)$$

$$y(x,t) = Y(x).e^{i\Omega t} \quad (10)$$

Where the solution of differential equations are obtained as follows:

$$\Theta(x) = a_1.e^{a_t x} + a_2.e^{-a_t x} \quad (11)$$

$$Y(x) = a_1.e^{a_b x} + a_2.e^{-a_b x} + a_3.e^{i a_b x} + a_4.e^{-i a_b x} \quad (12)$$

The corresponding governing boundary conditions are:

Displacement of MC;

$$y(0,t) = h_y(t) \quad (13a)$$

Slip;

$$\frac{dy(x,t)}{dx}\Big|_{x=0} = 0 \quad (13b)$$

Momentum at end of MC;

$$EI\frac{d^2 y(x,t)}{dx^2}\Big|_{x=L} = \bar{f}_t.c.l_{tip} - \bar{f}_n.H \quad (13c)$$

Shear force at end of MC;

$$EI\frac{d^3 y(x,t)}{dx^3}\Big|_{x=L} = \bar{f}_t \quad (13d)$$

Angular displacement of MC;

$$\theta(0.t) = 0 \quad (14a)$$

Applied torque at end of MC;

$$J\frac{d\theta(x,t)}{dx}\Big|_{x=L} = -\bar{f}_{lat}.H - \bar{f}_t.d_{tip} - J_{tip}\ddot{\theta}(x,t) \quad (14b)$$

In the above equations, J_{tip} is rotary inertia of probe where $J_{tip} \cong m_{tip}.H^2$. The parameter m_{tip} is probe mass, H is the sidewall length, l_{tip} is the tip length, d_{tip} is tip dislocation (Figure1). The conical probe is considered as a concentrated mass where the center of gravity is one-quarter of the probe length (l_{tip}). In Eq. 6c, the ratio coefficient (C) is equal to 1 for applied lateral force of tip-sample interaction and is 0.4 for the tip mass inertia force in lateral direction.

The parameters $\bar{f}_n$, $\bar{f}_{lat}$ and $\bar{f}_t$ are summation of the visco-elastic interaction forces and the tip mass inertia force in directions of normal, lateral, and tangential coordinates, respectively.

The governing boundary condition on the MC is used to obtain the equation of torsional and vertical motion of the MC. By substituting Eq. (11) and (12) into boundary conditions (Eq.s (13) and Eq.s (14)), the response function for each motion can be obtained.

3.0 RESULTS AND DISCUSSION

In this paper, the effective parameters on dynamic behavior of AFM-SW were inspected with reference to coupling motion of MC. Table 1 shows parameters of MC and its probe which are considered to be same as studies by Sang *et al* [13] and Mokhtari-Nezhad *el al* [15] in order to evaluate and verify the results. The sidewall micro-beam (H) was set 0.5 of MC length. In previous studies, it was demonstrated that mass of probe in analytical or numerical studies is needed to obtain more accurate dynamic responses of MC [15, 22]. Here probe mass is considered in the analytical analysis of AFM-SW dynamics. The AFM micro-cantilever mostly oscillated in its first resonance frequency. However, in some cases it is exciting at higher RFs. The first and higher (fourth RF) resonance frequencies are acquired as presented in Table 2.

Table 1 Parameters of simulated AFM cantilever with sidewall probe [10, 12]

Cantilever and probe parameters	Magnitude
Cantilever length	$234(\mu m)$
Cantilever Width	$40(\mu m)$
Cantilever thickness	$3(\mu m)$
Cantilever density	$2330(kg/m^3)$
Cantilever Young's modulus (E)	$1.5\times10^{11}(Pa)$
Cantilever Young's modulus (G)	$6.4\times10^{10}(Pa)$
Cantilever Vertical damping coefficient (C_b)	$8.3\times10^{-3}(Ns/m^2)$
Cantilever torsional damping coefficient (C_t)	$1.1\times10^{-13}(Ns)$
Tip Length	$15(\mu m)$
Tip mass	$6.54264\times10^{-12}(kg)$

Table 2 Obtained resonance frequencies in low and higher interaction forces due to considering tip mass and all three interaction forces of tip-sample

Frequency (Rad/S)	First mode	Fourth mode
Low Int. Force $k_i = \sim 10^{-6}(N/m)$, $\eta_i = \sim 10^{-11}(Ns/m)$	$\omega_{1,l} = 4.3339\times10^5$	$\omega_{4,l} = 1.0252\times10^7$
High Int. Force $k_i = \sim 10^{0}(N/m)$, $\eta_i = \sim 10^{-5}(Ns/m)$	$\omega_{1,h} = 2.4655\times10^6$	$\omega_{4,h} = 1.7452\times10^7$

The MC amplitude should not be higher than the critical value during oscillation. Small value of amplitude of MC or probe oscillation is the condition of assuming no slip between sample and probe and linear dynamics systems of AFM [13, 15, 23, 24]. Indeed, tip-sample interaction is one of factors that have effect on MC deflection. In this study it was found that the effects of interaction forces and inertia force/momentum of probe mass on MC motion is much more than Common AFMs. The mentioned enormity of effects is because of sidewall beam which caused increasing of applied forces and momentums on MC system. Indeed, the shear forces and the torsional/bending momentum applied at the end of MC is greatly larger compared to the C-AFM which are detected in Eq. 6(c), 6(d), and 7(b).

As mentioned, MC deflection and displacements are used to analyze the sample surface [16, 17]. Therefore, the study of MC deflections is also required. The undesired deflections would occur during the MC vibration modes which can cause the mistake in surface scanning. The coupled deflection of MC is considered in this study whereas the torsional displacement is assumed as an undesired motion. The reciprocal effects of various sets of parameters on MC, due to the torsional/flexural stiffness of MC, inertia force, moment of inertia of probe mass, and the tip-sample interaction, cause complicated recognizing of the reduction or increase in the amount of MC deflections. Lateral shear forces and torsional momentum, which are applied on the MC, cause torsional deflection in AFM-SW micro-cantilever. Based on the circumstances illustrated in Figure 1 and boundary condition equations (Eqs. 6 and 7), applied lateral shear forces include the lateral interaction forces (f_{lat}) and the tip mass moment of inertia in lateral direction ($m_{tip}.H\ddot{\theta}$). Also tortional momentum is the result of tip mass inertia forces and tip-sample interaction forces in lateral and tangential directions ($\bar{f}_{lat}$ and $\bar{f}_t$). Considering the above mentioned, the asymmetric position of tip mass from the neutral axis of sidewall micro-beam (d_{tip}) can cause torsional deflection.

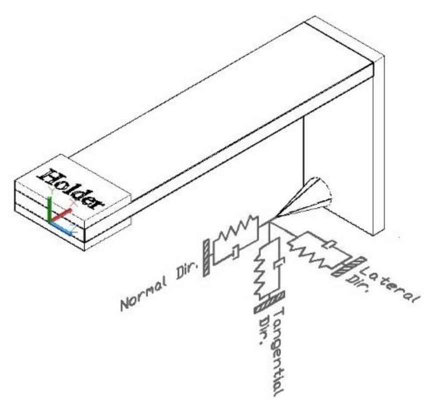
It was found out that by increasing the tip mass dislocation (d_{tip}), the torsional deflection will greatly increase. The obtained response function of torsional deflection shows that torsional deflection is directly proportional to the amount of probe dislocation. Figure 2 shows the torsional deflection response at $\theta(x=L)$ to unit excitation amplitude of Y_0 at first resonance frequency ($\omega_{1,l}$ and $\omega_{1,h}$) considering the tip mass dislocation between 0 to ½ width of micro-beam cross-section area and the tip mass ($0-6.54264\times10^{-6}$) in two cases of LIF ($k_i \cong 10^{-6}, \eta_i \cong 10^{-11}$) and higher tip-sample interaction ($k_i \cong 10^{-4}, \eta_i \cong 10^{-9}$). Besides, it is obtained that torsional deflection is highly depended to tip-sample interaction force. In a sense that in lower interaction force the torsional deflection is higher specially when tip mass displacement (d_{tip}) get larger. Indeed, weaker lateral interaction force (f_{lat}) can lead to higher torsional deflection.

Figure 3 illustrates vertical and torsional amplitude at the end of MC ($\theta, Y(x=L)$) considering the tip mass ($0-6.54264\times10^{-6}$ kg) and the sidewall micro-beam length ($0-117\times10^{-6}$) in two different conditions of LIF ($k_i \cong 10^{-6}, \eta_i \cong 10^{-11}$) and HIF ($k_i \cong 10^{0}, \eta_i \cong 10^{-6}$) in their 1st and 4th RFs ($\omega_{1,l}$, $\omega_{1,h}$, $\omega_{4,l}$ and $\omega_{4,h}$) where probe dislocation is 10^{-5} m. Noticing 3D figures, tolerance as a peak in deflection of MC is prominent in higher resonance frequencies which is clear for 4th RF in Figure 3. Mokhtari-Nezhad *et al.* [15] also detected the peak tolerance of MC amplitudes that can happen in the specific range of tip mass. However, it is noticeable that in general, the increased of tip mass ultimately caused the decline of the vertical MC amplitude which are clarified in Figure 3 and 4.

Figure 4 and 5 respectively illustrate vertical and torsional deflection amount considering probe mass in varieties of tip-sample interaction forces. The sidewall length is neglected in Figure 5a and is equal to half of MC length in Figure 4 and 5b. In first RF, unlike the decrease of vertical amplitude, the torsional deflection increases when tip mass is heavier, especially in weaker interaction forces between tip and sample as illustrated in Figure 3(a), 4, and 5. It is shown that longer sidewall micro-beam caused the increase of torsional deflection in the case of lower interaction forces as well as vertical amplitude in the condition of strong tip-sample interaction. However, in lower interaction force the impact of sidewall micro-beam length on vertical amplitude is not sensible. Vice versa, with the increase of tip-sample interaction force, the sidewall length and tip mass effects on torsional deflection becomes less and less.

In sum up, probe dislocation can cause torsional deflection of AFM-SW micro-cantilever which in the case of weaker interaction force with heavier tip mass, the amplitude of torsional movement is more while the vertical amplitude may decreases. Therefore, regarding the instrument performance, it is recommended that in the mentioned case the torsional deflection as an undesired motion need to be considered.

a.



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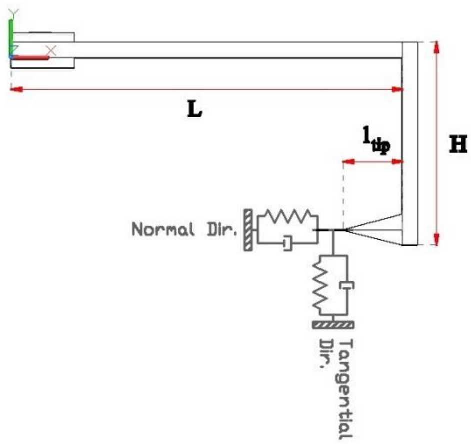

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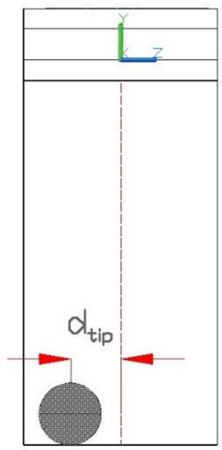
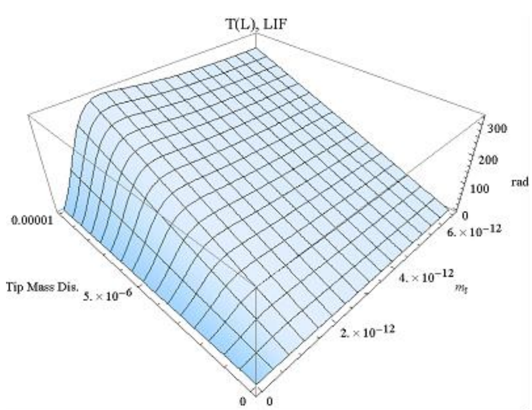


Figure 1 (a) Schematic figure of AFM micro-cantilever with SideWall probe and the tip-sample interaction (b) front view (c) left view

a.



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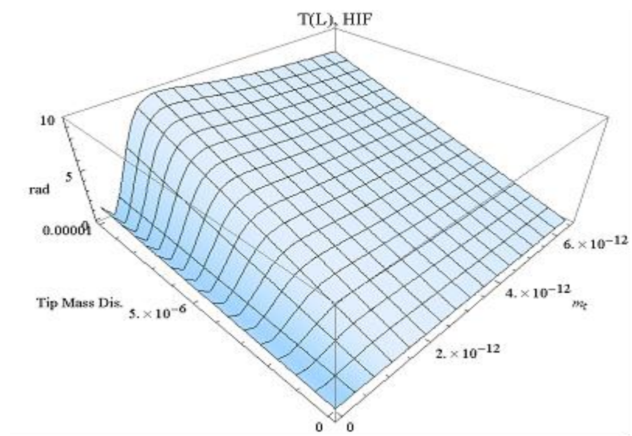
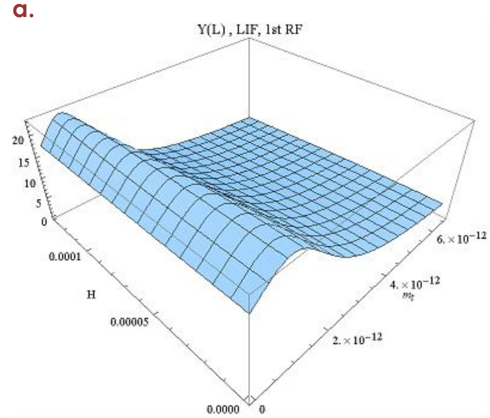
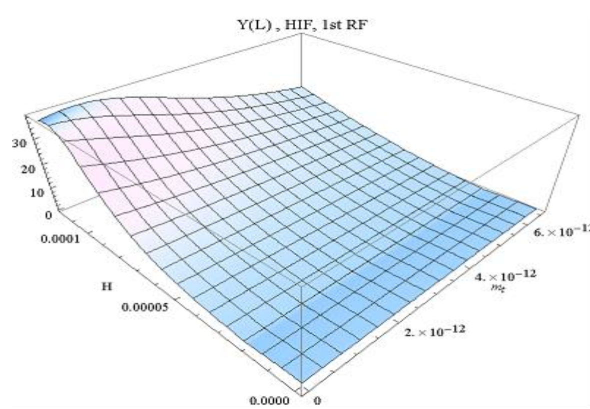
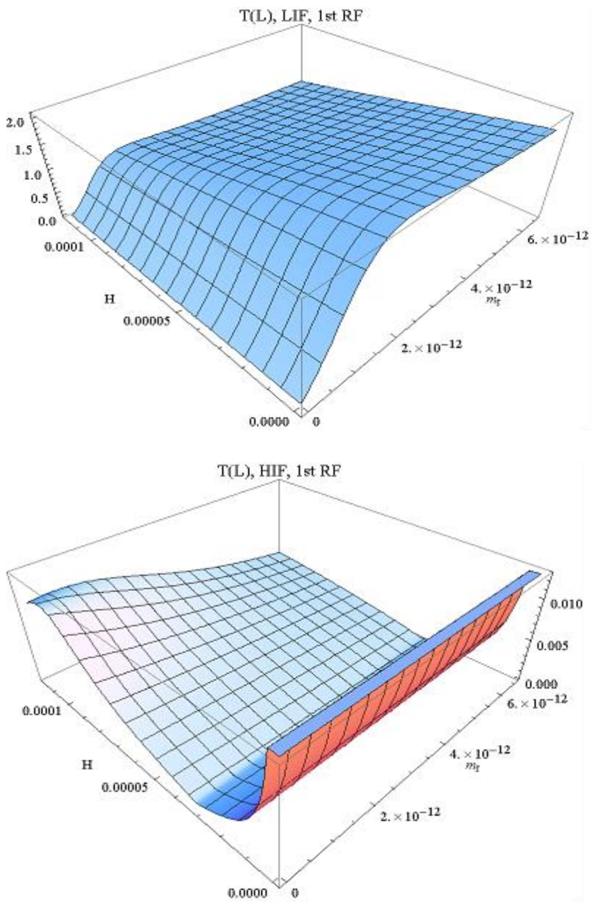


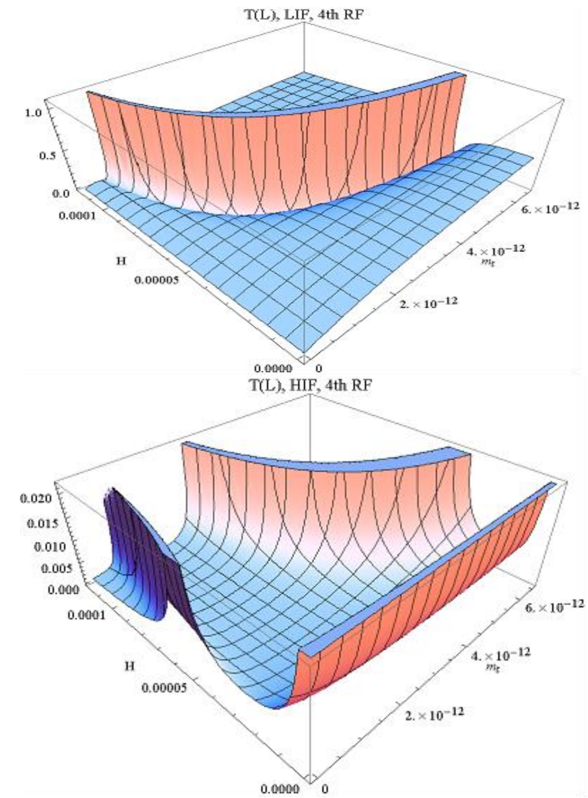
Figure 2 The torsional deflection at the end of micro-cantilever (T(L)) in 1st RF in cases of (a) LIF and (b) HIF, regarding to the tip mass and its dislocation

a.









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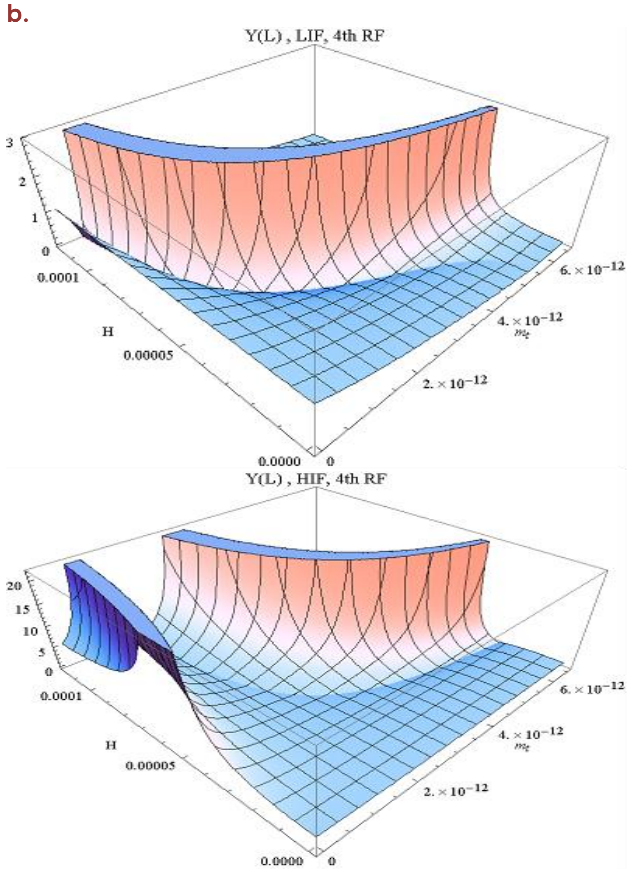


Figure 3 Micro-cantilever amplitude responses at Y(L) to unit excitation amplitude Y_0 (a) in First RF and (b) in higher RF in cases of LIF and HIF , regarding to the tip mass and the height of sidewall micro-beam. Probe dislocation is considered as 10^{-5} m

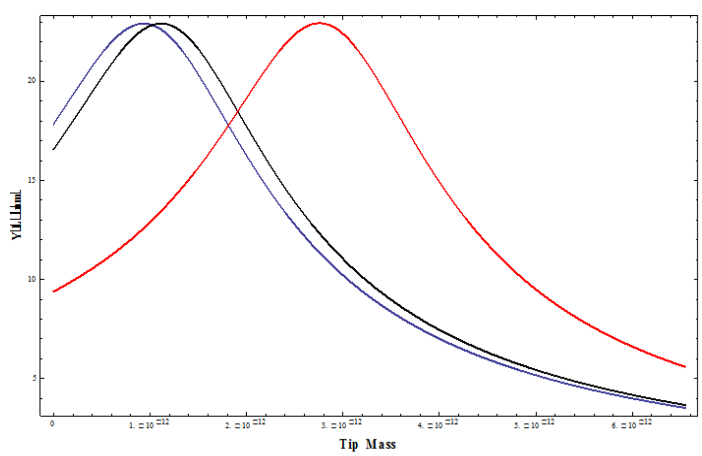
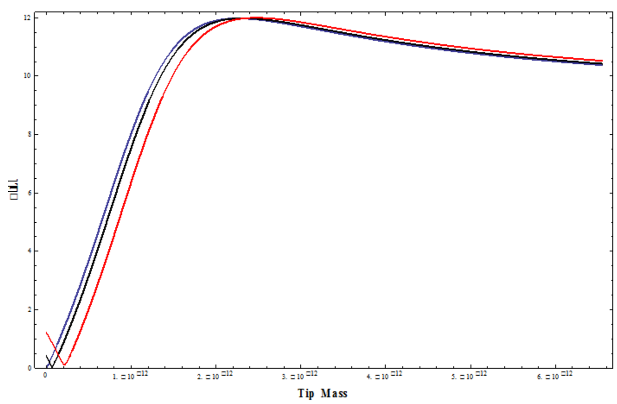


Figure 4 Micro-cantilever amplitude responses at $Y(L)$ to unit excitation amplitude Y0 in first RF when $\omega = 4.34 \times 10^5 (rad/s)$ regarding to the tip mass. Probe dislocation is considered as $d_{tip} = 10^{-5} (m)$

a.



b

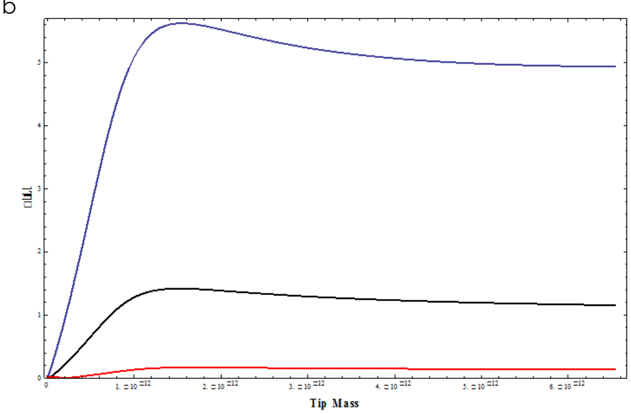


Figure 5 Micro-cantilever amplitude responses at $\Theta(L)$ to unit excitation amplitude Y0 in first RF when $\omega = 4.34\times10^{5}(rad/s)$ regarding to the tip mass. Probe dislocation is considered as $d_{tip} = 10^{-5}(m)$. (a) Neglecting sidewall beam ($H = 0$) (b) considering sidewall beam as $H = 117\times10^{-6}(m)$

4.0 CONCLUSION

An analytical study has been developed for the coupled motion of MC system in the AFM with Side Wall probe (AFM-SW), meanwhile the occurrence probability of undesired motions has been assessed. The torsion deflection of MC, which is coupled with the vertical excitation, has been treated as an undesired motion. While investigating the effect of probe mass, probe dislocation, and sidewall micro-beam length on the coupled motion, it has been observed that dislocation of tip from sidewall beam neutral axes causes' undesired torsional motion. In addition, the heavier probe mass, shorter sidewall beam, and lower tip-sample interaction force led to more torsional deflection. However, the high the interaction force between tip and sample is, the more insignificant the effect of probe mass, probe dislocation, and sidewall beam length becomes. To verify the obtained results the previously published results have been used and a good agreement is observed. Finally, according to our findings the torsional deflection of MC as an interfered motion cannot be neglected in the weak tip-sample interactions and heavier probe mass.

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