Dynamic Analysis of AFM in Air and Liquid Environments Considering Linear and Non-linear Interaction Forces by Timoshenko Beam Model

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Received: 26 April 2014, Revised: 13 July 2014, Accepted: 12 October 2014

Abstract: The atomic force microscopy of the cantilever beam frequency response behaviour in the liquid environment is different in comparison with air environment. In this paper, the dynamic analysis of AFM in the air and liquid environments is carried out in consideration of linear and non-linear interaction forces and also the effect of geometrical parameters such as length, width, height; and inclined angle on the vibrating motion of the rectangular cantilever is investigated. A rectangular cantilever based on the Timoshenko theory is simulated in ADAMS software and more accurate results are obtained by considering the probe tip and the angular location of cantilever at simulation. At the end of the cantilever, a silicone probe is considered where the applied forces on it are approximated using two tangential and vertical springs. The vibrational simulation of cantilever at two states is carried out with regard to linear and non-linear interaction forces. The amplitude and resonance frequency of the simulated cantilever based on Timoshenko theory are different from obtained results of Euler-Bernoulli theory due to the effect of shear deformation and rotary moment in Timoshenko theory. Therefore, the Timoshenko theory has better accuracy in comparison with Euler theory. Many chemical and biological processes occur instantly; therefore the use of cantilevers with small length for improving the imaging speed at the tapping mode and in the liquid environment is essential. Eventually short cantilever that is modeled based on the Timoshenko theory may produce more accurate results. This paper is aimed to demonstrate that the amplitude and resonance frequency of vibration in the liquid environment is different from amplitude and frequency of vibration in the air environment due to the damping coeficient and added mass of liquid.

Keywords: AFM, Frequency Response, Interaction force, Liquid Environment, Timoshenko Theory

Reference: Maleki, P., Korayem, M. H., Manafi, B., and Damircheli, M., “Dynamic analysis of AFM in air and liquid environments with considering the linear and non-linear interaction forces by Timoshenko beam model”, Int J of Advanced Design and Manufacturing Technology, Vol. 8/No. 2, 2015, pp. 37-46.

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1 INTRODUCTION

AFM has been known as a powerful tool in the field of imaging and particle manipulation at nanoscale. The AFM founded a way to take image of polymers and biological samples that did not have the ability of conducting current. AFM can take images with atomic resolution by forces between the probe and sample surface and can provide images with high resolution using a very small tip that has been located at the end of cantilever [1].

In the recent advances in the AFM, researchers have used the advantages of the dynamic properties of cantilevers. These developments have allowed AFM to be used as the material descriptor. Theoretical analysis of the dynamic behavior of AFM cantilever is the foundation of many methods in AFM. Linear vibration analysis of rectangular cantilever that has been located parallel to the surface in contact mode was an old problem where its solution has been mentioned in the literature. Hence the dynamic analysis of a linear system has been developed to an acceptable and stable level.

In the past few years, many researchers have attempted to study the dynamic behavior of AFM cantilever [2-6]. Turner and Wiehn [4] have studied the vibration of a rectangular cantilever of AFM and they obtained a closed-form solution. They assumed that the cantilever was parallel to the sample surface and its tip has been exactly located at the end of cantilever. At the real situation of AFM, the tip has not been exactly placed at the end of the cantilever where there is an angle between cantilever and sample surface. Wu et al., [7] examined the effect of tip length, normal and lateral contact stiffness on the vibration response of AFM cantilever, ignoring the effects of the contact position and the angle between the cantilever and sample surface. Song and Bhushan performed the simulation of dynamic behavior of AFM using three-dimensional finite element model [8]. They studied a rectangular cantilever using both linear and non-linear models for interaction between the tip and the sample, by ignoring the effect of contact position. They applied Timoshenko beam theory in their analysis.

Arafat et al., [9] have investigated the interaction effect of AFM in contact mode by considering both linear and non-linear models for the interaction between the tip and the sample. The effects of angle between cantilever and sample surface and the dimensions of the tip have been ignored. The Timoshenko theory has been used for the rectangular cantilever. For non-uniform cantilevers, there is a general solution for special conditions [10-11]. Rankl et al., [12] have studied the frequency response of cantilever near the sample surface in liquid environment. They have considered a squeezed force in a small gap between the tip and sample, but the effect of interaction forces between sample and surface is ignored. Vancur et al., [13] have measured the response frequency of cantilever in both air and liquid environments. Their results have shown that the amplitude and response frequency of cantilever have been decreased in liquid environment. This reduction was due to the squeezed force in liquid environment.

They approximated the hydrodynamic force of fluid by using Sader’s experimental model, and derived the frequency and transient response of the system [14]. Korayem et al., analyzed the frequency response of AFM cantilever in liquid environment by Euler–Bernoulli theory, and used the forward time method for the simulation. In dynamic mode, the frequency response of atomic force micro-scope is a function of the cantilever’s geometrical parameters and the drag force which is applied on the cantilever by the medium. Since drag force is dependent on fluid viscosity and density, these two parameters have significant effects on system response.

In mean time, some research works have been performed that demonstrate the effect of fluid viscosity on the quality of images taken from biological samples by AFM [15], [16]. The obtained results confirm this important finding that with the increase of kinematic viscosity, image quality drops sharply. More research works have been carried out to determine fluid viscosity and density from the frequency response of the system, where measuring these two properties by other means is impossible [17].

In these studies, the effect of angle between cantilever and sample has been ignored and the cantilever was parallel with sample. The interaction force between sample and cantilever has been considered as linear and the cantilever has been modeled with Euler theory in liquid environment. In this paper the angle of cantilever with the horizon was considered as 30° and the interaction force between sample and cantilever has been investigated with respect to the linear and non-linear effect in both air and liquid environments. The cantilever has been modeled with the Timoshenko theory that the effect of shear deformation and rotational moment has been considered in the model. In this research, initially the frequency response of the rectangular cantilever that has been modeled with Timoshenko theory by considering the linear interaction forces at both air and liquid environments for different separation distances between the tip and sample in both repulsive and attractive regions has been plotted. This has been repeated again by considering the non-linear interaction forces. Further, the effect of changing the geometrical parameters such as length, width, height and angle on the vibrating motion of rectangular cantilever at both air and liquid environments have been investigated.

2 FORMULATION

2.1. Dynamic modeling of rectangular cantilever in different environments

Assuming the Timoshenko beam theory and using Hamilton method, two motion coupled equations which included vertical impact deflection and bending rotational angle of cantilever at tapping mode for liquid environment have been obtained as follows [19]:

$$\frac{\partial}{\partial x}\left[KGA\left(\frac{\partial y(x,t)}{\partial x}-\phi(x,t)\right)\right]-c\,\frac{\partial y(x,t)}{\partial t}-\rho A\frac{\partial^2 y(x,t)}{\partial t^2}+f_h(x,t)=0$$
$$\frac{\partial}{\partial x}\left[EI\,\frac{\partial \phi(x,t)}{\partial x}\right]+KGA\left(\frac{\partial y(x,t)}{\partial x}-\phi(x,t)\right)-\rho I\,\frac{\partial^2 \phi(x,t)}{\partial t^2}=0 \quad (1)$$

Where, K, G, A, y(x,t), Φ(x,t), ρ, I, E, c and $f_h(x,t)$ are, respectively, the shear coefficient, shear modulus, area of cross section, transverse deflection of cantilever, bending angle of cantilever, mass density of cantilever, inertial moment of cross section, Young's modulus, internal damping of cantilever and the hydrodynamic force exerted on the cantilever by the liquid environment. Unlike the Euler theory, in Timoshenko theory, the effect of shear deformation on dynamic response cannot be neglected. This model is usually used when the surface of cantilever is large compared to its length. Contrary to Euler–Bernoulli theory, in Timoshenko theory, the cantilever's shear strain is not zero. The stiffness and mass matrix for each element of Timoshenko beam would be:

$$[K]_e=\frac{12EI}{L(L^2+12\varphi)}\begin{bmatrix}1 & \frac{L}{2} & -1 & \frac{L}{2}\\ \frac{L}{2} & \frac{L^2}{3}+\varphi & -\frac{L}{2} & \frac{L^2}{6}-\varphi\\ -1 & -\frac{L}{2} & 1 & -\frac{L}{2}\\ \frac{L}{2} & \frac{L^2}{6}-\varphi & -\frac{L}{2} & \frac{L^2}{3}+\varphi\end{bmatrix} \quad (2)$$

Where L is the cantilever length.

$$[m]_e=[m_t]_e+[m_r]_e \quad (3)$$

Where $[m_t]_e$ is the mass matrix due to shear inertia.

$$[m_t]_e=\int_0^L \rho A\,[N]^T\,[N]\,dx=\frac{\rho AL}{L^2+12\varphi}\begin{bmatrix}t_{11} & & & sym\\ t_{21} & t_{22} & & \\ t_{31} & t_{32} & t_{33} & \\ t_{41} & t_{42} & t_{43} & t_{44}\end{bmatrix} \quad (4)$$

Matrix elements in Eq. (4) are calculated as in equation (5):

$$t_{42}=(\frac{13}{35}L^4+\frac{42}{5}\varphi L^2+48\varphi^2),\ t_{21}=(\frac{11}{210}L^4+\frac{11}{10}\varphi L^2+6\varphi^2)\,\mathrm{L},$$
$$t_{22}=(\frac{1}{105}L^4+\frac{1}{5}\varphi L^2+\frac{5}{6}\varphi^2)\,\mathrm{L}^2,\ t_{31}=(\frac{9}{70}L^4+\frac{18}{5}\varphi L^2+24\varphi^2),$$
$$t_{32}=(\frac{13}{420}L^4+\frac{9}{10}\varphi L^2+6\varphi^2)\,\mathrm{L},\ t_{33}=t_{11},\ t_{41}=-t_{32},\ t_{43}=-t_{21},\ t_{44}=t_{22} \quad (5)$$

If $[m_r]_e$ is the mass matrix due to rotational inertia:

$$[m_r]_e=\int_0^L \rho I\,[\bar{N}]^T\,[\bar{N}]\,dx=\frac{\rho IL}{(L^2+12\varphi)^2}(\frac{r}{L})^2\begin{bmatrix}r_{11} & & & sym\\ r_{21} & r_{22} & & \\ r_{31} & r_{32} & r_{33} & \\ r_{41} & r_{42} & r_{43} & r_{44}\end{bmatrix} \quad (6)$$

Matrix elements in Eq. (6) are calculated as in Eq. (7):

$$r_{11}=\frac{5}{6}L^4,\ r_{21}=(\frac{1}{10}L^2-6\varphi^2)\,\mathrm{L}^3,\ \mathrm{r}_{33}=\mathrm{r}_{11},\ \mathrm{r}_{41}=\mathrm{r}_{21},$$
$$r_{22}=(\frac{2}{15}L^4+2\varphi L^2+48\varphi^2)\,\mathrm{L}^2,\ \mathrm{r}_{31}=-\mathrm{r}_{11},\ \mathrm{r}_{32}=-\mathrm{r}_{21}$$
$$r_{42}=-(\frac{1}{140}L^4+\frac{1}{5}\varphi L^2+\frac{6}{5}\varphi^2)\,\mathrm{L}^2,\ r_{43}=-r_{21},\ r_{44}=r_{22} \quad (7)$$

And to calculate the structural damping matrix, first, the diagonal damping matrix should be derived as:

$$\left[M_{Diagonal}\right]\{\ddot{P}\}+\left[C_{Diagonal}\right]\{\dot{P}\}+\left[K_{Diagonal}\right]\{P\}=0 \quad (8)$$

$$\left[C_{Diagonal}\right]=\begin{bmatrix}\frac{\sqrt{m_{diag,1}k_{diag,1}}}{Q_1} & 0 & \cdots\\ 0 & \ddots & 0\\ \vdots & 0 & \frac{\sqrt{m_{diag,2n}k_{diag,2n}}}{Q_{2n}}\end{bmatrix}$$

And then, the non-diagonal damping matrix will be obtained as:

$$C=\Phi^{-T}C_{\Lambda}\Phi^{T} \quad (9)$$
$$C_{\Lambda}=diag[2\xi_1\omega_1,2\xi_2\omega_2,...,2\xi_n\omega_n]$$

Where, φ is the matrix of eigenvectors, ξ_n is the n[th] damping coefficient and ω_n is the n[th] natural frequency of the cantilever.

2.2. Interaction forces

The vertical interaction forces in the air environment have been approximated with Vander Waals force and DMT force model in the attractive and repulsive region respectively.

$$F_{air-n}(d)=\begin{cases}F_{vdW}(d)=-\dfrac{AR_t}{6d^2} & d\ge a_0\\ F_{DMT}(d)=\dfrac{4E_{eff}\sqrt{R_t}}{3}(a_0-d)^{\frac{3}{2}}-\dfrac{AR_t}{6{a_0}^2} & d<a_0\end{cases} \quad (10)$$

Where A is the hamaker constant, R_t is the tip radius, d is the transient distance between sample and cantilever, a_0 is the intermolecular distance and E_{eff} is the effective elastic modulus between the sample and cantilever tip and can be achieved by the following equation:

$$E_{eff} = \left[\frac{(1-\nu_t)}{E_t} + \frac{(1-\nu_s)}{E_s} \right]^{-1} \quad (11)$$

Where E_t, E_s, ν_t and ν_s are elastic moduli and Poisson's ratios of cantilever tip and sample respectively. The tangential force between cantilever tip and sample can be expressed using Hertz theory as follows:

$$F_{air-t}(d) = \begin{cases} 0 & d \geq a_0 \\ -8G_{eff}\left(\frac{3R_t f_c}{4E_{eff}}\right)^{\frac{1}{3}}\Delta_t & d < a_0 \end{cases} \quad (12)$$

At above equation, G_{eff} is the effective shear modulus between the sample and cantilever tip and can be obtained as follows:

$$G_{eff} = \left[\frac{(2-\nu_t)}{G_t} + \frac{(2-\nu_s)}{G_s} \right]^{-1} \quad (13)$$

The G_t and G_s are the shear modulus of cantilever tip and sample respectively and f_c is the vertical contact force and can be achieved through the following equation:

$$f_c = \frac{4E_{eff}\sqrt{R_t}}{3}(a_0 - d)^{\frac{3}{2}} \quad (14)$$

2.3. Approximation of interaction forces with linear spring

For a cantilever that was vibrated around its equilibrium point, it was possible to linearize a vertical force with a vertical linear spring:

$$F_{int} = -K_n \Delta_n$$

$$K_{air-n} = -\left.\frac{\partial F_{air-n}}{\partial d}\right|_{d=D_0} = \begin{cases} -\frac{AR_t}{3D_0^3} & d \geq a_0 \\ 2E_{eff}\sqrt{R_t}(a_0 - D_0)^{\frac{1}{2}} & d < a_0 \end{cases} \quad (15)$$

D_0 is the equilibrium distance between the cantilever tip and sample surface and tangential force between the tip and sample when vibrated around its equilibrium point, can be linearized with a tangential spring; and Hertz theory was used for tangential force.

$$F_{tan} = -K_{tan}\Delta_t \quad (16)$$

$$K_{tan} = -\left.\frac{\partial F_{tan}}{\partial d}\right|_{d=D_0} = \begin{cases} 0 & d \geq a_0 \\ 8G_{eff}\left(\frac{3R_t f_c}{4E_{eff}}\right)^{\frac{1}{3}} & d < a_0 \end{cases}$$

2.4. Approximation of interaction forces with non-linear springs

At this state, the simulation of rectangular cantilever in the air environment with consideration of non-linear interaction forces is carried out. Vertical forces between sample and cantilever versus the transient distance between them are depicted in Figure 1, based on the DMT model in the ADAMS software.

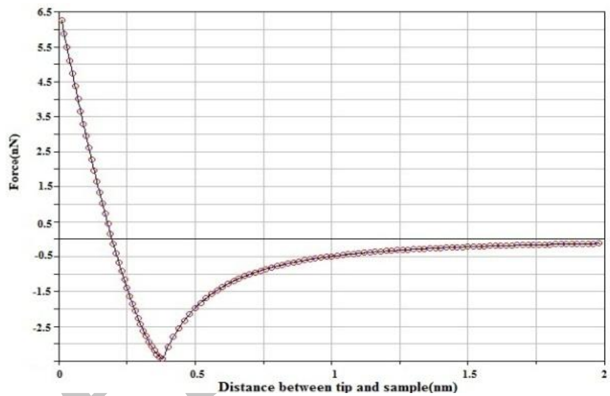

Fig. 1 The graph of non-linear vertical force versus distance between cantilever and sample in the air environment

The 3Dimensional graph of non-linear tangential force between the cantilever tip and sample based on the Hertz model versus vertical and tangential displacement of cantilever tip in the ADAMS software is plotted in the Figure 2.

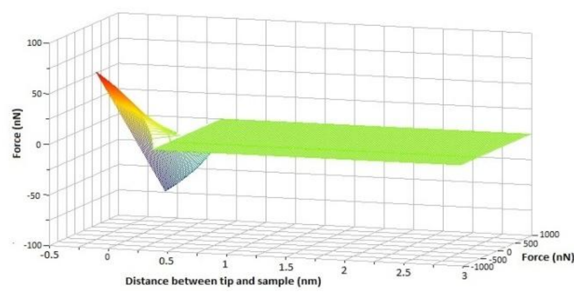

Fig. 2 The graph of non-linear tangential force versus distance between cantilever and sample in the air environment

3 SIMULATION AND DISCUSSION

3.1. Vibrational simulation of cantilever considering the linear and non-linear interaction forces in the air environment

The rectangular cantilever with uniform cross section and the tilting angle of 30 degrees that has been affected by vertical and tangential interaction forces is shown in Figure 3.

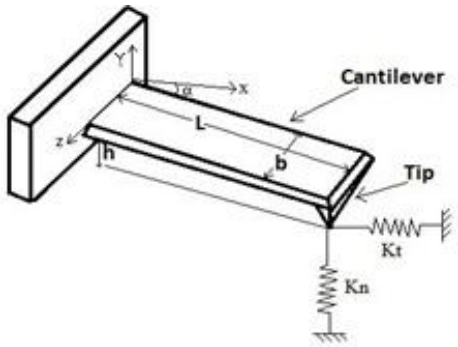

Fig. 3 The Schematic view of a rectangular cantilever with uniform cross section and the tilting angle of 30 degrees

The rectangular cantilever has been modeled using the conditions as mentioned in table 1 [19].

Table 1 Modeling parameters of the rectangular cantilever

Cantilever and tip parameters	Magnitude
Cantilever length(L)	$252\mu m$
Cantilever width(b)	$35\mu m$
Cantilever thickness(h)	$2.3\mu m$
Tip Radius (R_{tip})	$10nm$
Tip length(l_{tip})	$10\mu m$
Angle between cantilever and sample	30^0
Effective elasticity modulus(E_{eff})	$10.2GPa$
Effective shear modulus(G_{eff})	$4.2GPa$
Intermolecular distance(a_0)	$0.38nm$
Hamaker constant in air (H_{air})	2.96×10^{-19} J
Hamaker constant in water (H_{water})	2.96×10^{-20} J
Cantilever mass density(ρ)	$2330\,kg/m^3$

Initially, the frequency response has been plotted for simulated cantilever by Timoshenko theory, considering the linear interaction forces in air environment at different separation distances between the sample and the tip in repulsive zone. With respect to the separation distances at repulsive state, the stiffness of vertical and tangential springs are considered in Table 2.

As shown in Figure 4, the resonance frequency is increased at repulsive region due to the increase of stiffness. In smaller molecular distances, the resonance frequency is increased due to the reduction of equilibrium distance where the variations of first domain are remarkable. The vibration amplitude of vertical displacement in air environment in the repulsive region is shown in Figure 4. The specification of the modeled cantilever is the same as in reference [18]. The results of simulation in ADAMS software are in full agreement to the results of the reference.

Table 2 The stiffness of vertical and tangential interaction forces for different seperation distances at repulsive region

Separation distances	K normal	K tangential
D=0.08	K_n=35.3338e3	K_t=58.1969e3
D=0.1	K_n=34.135e3	K_t=56.223e3
D=0.2	K_n=27.369e3	K_t=45.079e3
D=0.3	K_n=18.246e3	K_t=30.0527e3
Free	K_n=0	K_t=0

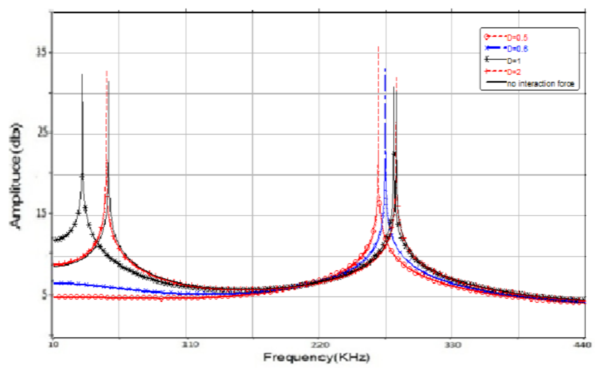

Fig. 4 Vibration amplitude of vertical displacement in air environment in repulsive region

Table 3 Stiffness coefficients of the vertical and tangential springs of intercation forces for different seperation distances in the attractive region

Separation distances	K normal	K tangential
D=0.5	K_n=-7.8933e3	K_t=0
D=0.6	K_n=-4.5679e3	K_t=0
D=1	K_n=-986.666	K_t=0
D=2	K_n=-123.33	K_t=0
Free	K_n=0	K_t=0

Then the frequency response of the modeled cantilever by Timoshenko theory with respect to the linear interaction forces in air environment for different separation distances between the tip and sample in the attractive region has been plotted in Figure 5. Obviously, the resonance frequency is decreased due to the decrease of vertical stiffness and the reduction of resonance frequency is more obvious because of the decrease of equilibrium distance. The first frequency was zero at very low equilibrium distances but the variation range of second amplitude was very small. The vibration amplitude of vertical displacement in air environment in the attractive region is shown in Figure 6. The specification of the modeled cantilever is the same as in reference [18]. The results of simulation in

ADAMS software are in full agreement to the results of the reference. With respect to the separation distances at attractive state, the stiffness of vertical and tangential springs are considered as in Table 3.

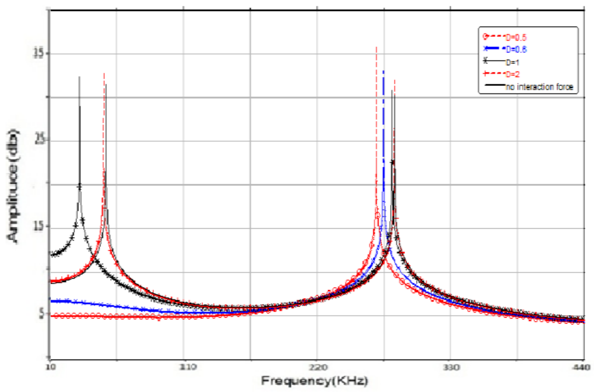

Fig. 5 Vibration amplitude of vertical displacement in air environment in the attractive region

3.2. Vibration Simulation of cantilever considering both linear and non-linear interaction forces in liquid environment

A rectangular cantilever under vertical and tangential linear and non-linear interaction forces in liquid environment is simulated by ADAMS software. The frequency response of modeled cantilever by Timoshenko beam theory with respect to the linear interaction forces in liquid environment for different separation distances between the sample and the tip in repulsive region is plotted in Figure 6. The first and second resonance frequency and vibration amplitude of cantilever in repulsive region is reduced.

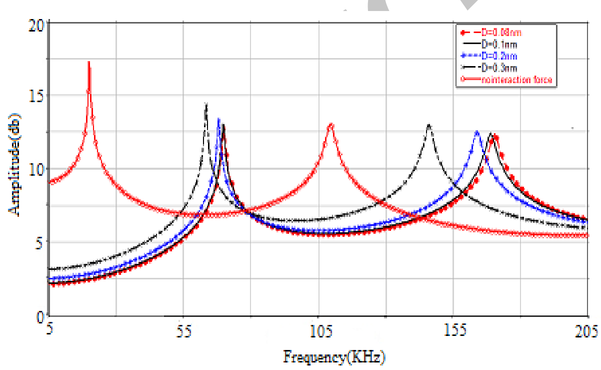

Fig. 6 Vibration amplitude of the vertical displacement in liquid environment in the repulsive region

The frequency response of the modelled cantilever by Timoshenko beam theory considering the linear interaction forces in liquid environment for different separation distances between the sample and the tip in the attractive region is plotted in Figure 7. Obviously, the resonance frequency has been decreased due to the reduction of vertical stiffness in the attractive region where the reduction of resonance frequency is more obvious as the equilibrium distance is decreased. The first frequency was zero at very low equilibrium distances but the changes of second amplitude were negligible. The first and second resonance frequencies in liquid environment were less than resonance frequency in air environment.

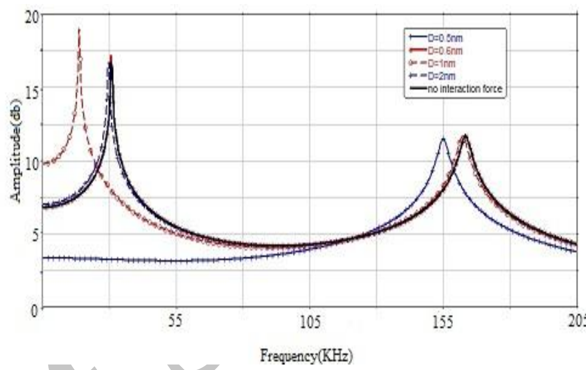

Fig. 7 The vibration amplitude of vertical displacement in liquid environment in the attractive region

3.3. Effect of geometrical parameters on vibrating motion of rectangular cantilever in air environment

The effect of geometrical parameters such as the length, height, width and angle on the vibrating motion rectangular cantilever in air environment considering the non-linear interaction forces has been investigated.

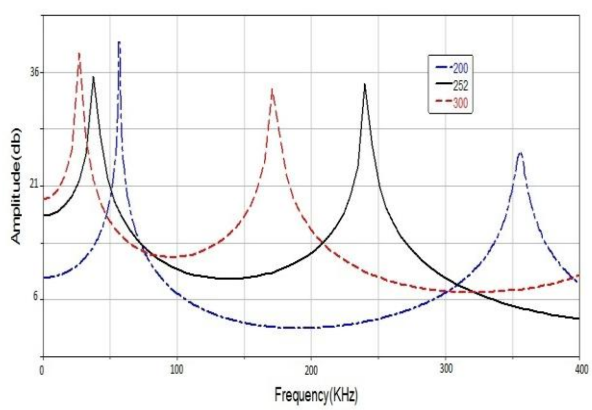

Fig. 8 The effect of cantilever length on the vertical displacement in air environment

3.3.1. The effect of length parameter

In Figure 8, the width, height and the angle of cantilever is assumed to be constant and the length of cantilever has been investigated at 3 states of 200 µm, 252 µm and 300 µm. As was observed, the length parameter has a large impact on the frequency response. The first and second frequencies have been increased with increasing the length of cantilever. While the lengths of cantilever were 200 µm, 252 µm and 300 µm, the first resonance frequency was reported as 62 kHz, 43.7 kHz and 28 kHz respectively.

3.3.2. The effect of height parameter

The cantilever parameters such as length, width and angle were considered as constant and the effect of changing the height parameter at three states of 0.5h (1.15µm), h(2.3µm), 2h(4.6µm) has been investigated in Figure 9. At the height of 0.5h, the first resonance frequency was about 25 kHz and by increasing the height, the frequency reached to 80 kHz at the height of 2H. As was obtained, the height parameter of the cantilever has a large impact on the frequency response. With increasing the height of cantilever, the resonance frequency and vibration amplitude is increased and also the distance between the first and second resonance frequency has increased due to the large impact of altering the height parameter on the response frequency.

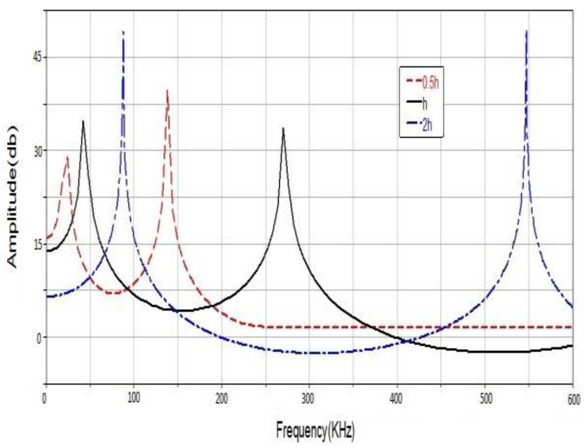

Fig. 9 The effect of cantilever height on the amplitude of vertical displacement in air environment

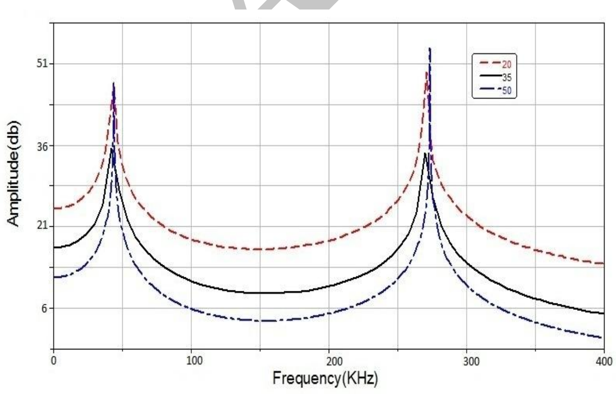

Fig. 10 The amplitude of vertical displacement versus the frequency in air environment at different cantilever widths

3.3.3. The effect of the width parameter

The influence of width parameter on the frequency response is shown in Figure 10. Cantilevers with the widths of 20, 35 and 50 µm have been studied. As was obtained, the width parameter has a very little impact on the frequency response. Variation of the cantilever width has little impact on the first frequency but it was more effective on the second frequency. At different widths, the first and second resonance frequencies were about 44 kHz and 270 kHz respectively, thus the variation of resonance frequency was very low at different widths.

3.3.4. The effect of the angle parameter

The influence of the variation of angle parameter on the response frequency is shown in Figure 11. Rectangular cantilever has been simulated at angles of 10, 30 and 50 degree by considering a constant value for length, width and height parameters. As can be seen in Figure 11, the first and second frequencies and vibration amplitude have been increased with increasing the cantilever angle.

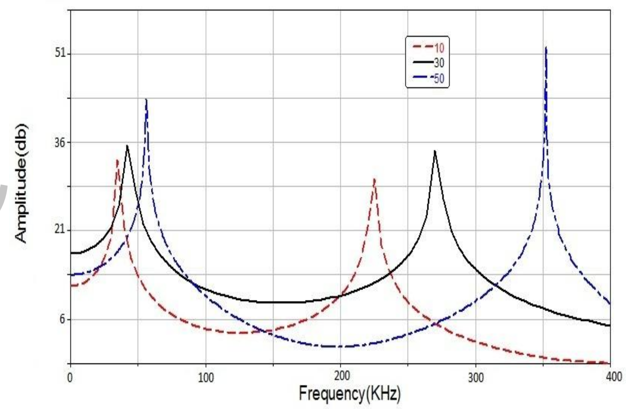

Fig. 11 The amplitude of vertical displacement versus frequency in air environment at different cantilever angles

3.4. The effect of geometrical parameters on the vibrating motion rectangular cantilever in liquid environment

The Effect of geometrical parameters such as length, height, width and angle on the vibrating motion rectangular cantilever in liquid environment has been investigated by considering the non-linear interaction forces based on both Euler and Timoshenko theory. Also the influence of geometrical parameters on the cantilever has been studied by both Euler and Timoshenko theory. The angle and width parameters of the cantilever have not been affected by the beam model based on both Euler and Timoshenko theory. The influence of modeling the cantilever based on both Euler and Timoshenko theory has been examined on the length and height parameters.

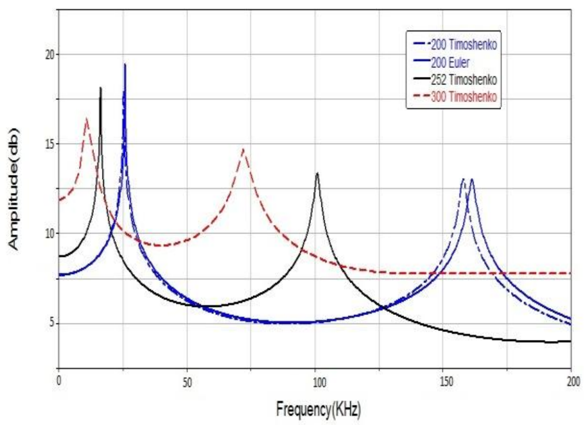

Fig. 12 The amplitude of vertical displacement versus the frequency in liquid environment at different cantilever lengths

3.4.1. The effect of the length parameter

As shown in Figure 12, a rectangular shape cantilever has been simulated in liquid environment by considering the non-linear forces in which a cantilever with 200 µm length has been simulated by Euler Bernoulli theory at three states of 200, 252 and 300 µm. As a result, the length parameter has a large impact on the frequency response. The first and second resonance frequencies are decreased due to the increase of the length of cantilever. The first resonance frequency in liquid environment is lower than the first resonance frequency in air environment. The amplitude of the second resonance frequency in air environment is higher than the amplitude of second resonance frequency in liquid environment due to the damping coefficients of liquid. At the length of 200 µm by comparison between modeled cantilever with both Euler Bernoulli and Timoshenko theory, it has been obtained that the second resonance frequency of modeled cantilever by Timoshenko theory is less than the second resonance frequency of modeled cantilever by Euler Bernoulli theory. Modeling the cantilever by Timoshenko theory has better effect on the higher modes. As is observed in Figure 12, at second mode the modeled cantilever by Timoshenko beam model with the length of 200 µm is better than modeled cantilever by Euler Bernoulli beam model but it is ineffective on the first mode.

3.4.2. The effect of the height parameter

The length, width and angle of cantilever have been considered as constant in Figure 13. The effect of the height parameter on the vibrating motion rectangular cantilever in liquid environment has been investigated by considering the non-linear forces. The height of the cantilever at different amounts of 0.5h, h and 2h have been simulated by Timoshenko beam model and also at the height of 0.5h has been simulated with Euler theory. The first resonance frequency in liquid environment is lower than the first resonance frequency in air environment. For example at the height of 0.5h, the first resonance frequency in air and liquid environment were 25 kHz and 10 kHz respectively. As it can be seen, the amplitude of frequency response is changed by altering the height. The height of cantilever has a large impact on the frequency response. The added mass and damping coefficients have been decreased with increasing of the cantilever height. When the added mass is decreased, the resonance frequency and vibration amplitude are increased and also the damping coefficient is decreased. The difference between the vibration amplitude and resonance frequency at both air and liquid environment is due to the added mass and damping coefficient of liquid environment.

At the height of 0.5h, with comparison between Euler Bernoulli and Timoshenko theory, it is obtained that the second resonance frequency of Timoshenko theory is less than the second resonance frequency of Euler Bernoulli theory. At higher modes, Timoshenko theory has better effects. As shown in Figure 13, the Timoshenko theory at second mode is better than Euler theory at the height of 0.5h.

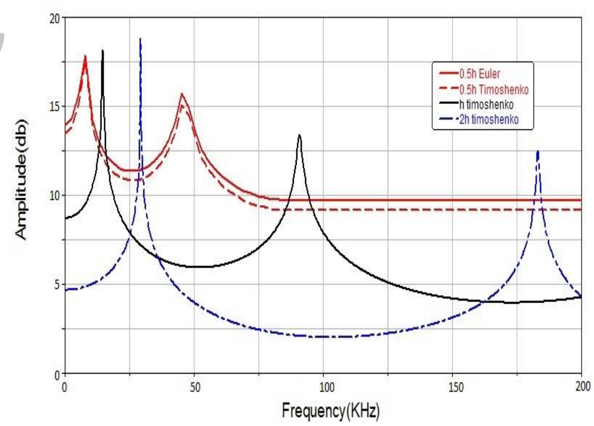

Fig. 13 The amplitude of vertical displacement versus the frequency in liquid environment at different cantilever heights

3.4.3. The effect of width parameter

The effect of width parameter on the frequency response has been studied in Figure 14. The length, height and angle of cantilever were set as constant and the effect of different cantilever widths on the frequency response is investigated. The width of cantilever at different amounts of 20, 35 and 50 µm in liquid environment has been investigated by Timoshenko theory. The variation of cantilever width has a little influence on the first frequency but it has a large impact on the second frequency where the amplitude of frequency response is increased due to the decrease of cantilever width.

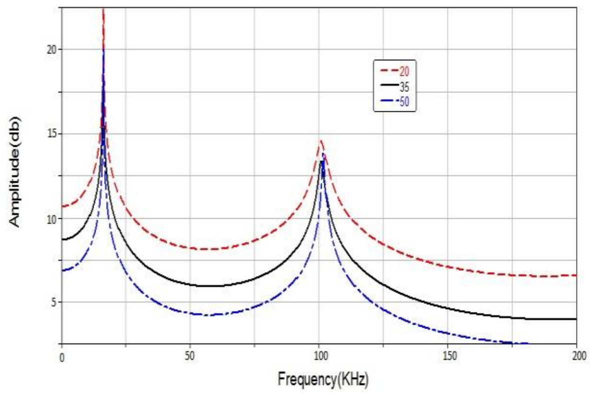

Fig. 14 The amplitude of vertical displacement versus the frequency in liquid environment at different cantilever widths

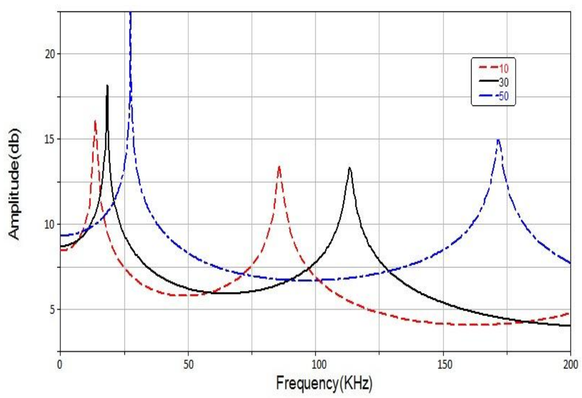

Fig. 15 The amplitude of vertical displacement versus the frequency in liquid environment at different cantilever angles

The first resonance of simulated models with mentioned widths were 14 kHz and 44 kHz in liquid and air environments respectively. By observing the influence of cantilever width parameter at both air and liquid environments, it may be concluded that the width parameter has very little influence on the frequency response. The difference between vibration amplitude and resonance frequency in air and liquid environment is due to the existence of added mass and damping coefficient in liquid environment.

3.4.4. The effect of the angle parameter

The effect of the angle parameter variation on the frequency response is shown in Figure 15. The width, length and height of the cantilever is supposed to be constant and the cantilevers with angles of 10, 30 and 50 degree have been simulated with Timoshenko theory. As shown in Figure 15, the first and second resonance frequencies are increased due to the increase of the angle of cantilever. The first and second resonance frequencies are increased due to the increase of the angle of cantilever.

4 CONCLUSION

A rectangular cantilever of the AFM has been simulated by Timoshenko theory in the ADAMS software environment. In this paper, the frequency response in air and liquid environments by considering the linear and non-linear effect of tangential and vertical interaction forces between the tip of cantilever and the sample has been investigated. The frequency response was one of the most important diagrams for describing the dynamic behavior of the atomic force microscope.

The vibration in liquid environment in terms of vibration amplitude and resonance frequency was different in comparison with air environment due to the added mass and damping coefficient. That actually was affected by the mechanical parameters such as liquid density, viscosity and etc. The influence of cantilever geometrical parameters such as length, width, height and angle on the frequency response has been investigated. Better results are observed by decreasing the width, height and angle parameters. The length, height and angle of the cantilever have a large impact on the frequency response where the width parameter has a little effect on the frequency response. Resonance frequency is better observed in liquid environment in comparison with air environment. Modeled cantilever with Timoshenko theory has better effect on the higher modes and as obtained, it has little effect on the first mode but it has better effect on the second mode versus the cantilever model by Euler theory.

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