Developing a Control Strategy for AFM Nano-Micro Manipulation

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Abstract: Nowadays, with the growing use of AFM (Atomic Force Microscope) nanorobots in the fabrication of nanostructures, research in this area has been proliferated. The major limiting of manipulation process is the lack of real-time observation. Computer simulations have been widely applied to improve the feasibility of the process. The existing 2D strategies are incapable of presenting the feasibility of the process. Therefore, 3D simulations of effective forces during the manipulation process and the control mechanism of the process have been presented in this research, where the effective parameters are investigated. To evaluate the validity of the presented results, a FEM simulation is proposed. It is observed that the two sets of results (the analytical method and the finite element approach) have adequate correlation, while the discrepancy which is in an acceptable range, is due to the different solving technique of the finite element method. By applying the presented models, it is now possible to accurately predict the effective forces for fabricating the nanostructures.

Keywords: AFM Nano robot, Controlled Manipulation, Finite Element Method, Manipulation Process

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1 INTRODUCTION

AFM (Atomic Force Microscope) based nano manipulation is a cutting edge manufacturing process which is used for micro nano assembly. In the process of nano manipulation, AFM cantilever is used for pushing nano particles and locating them precisely on the surface. Pushing nano particles by means of AFM robots is one of the main manufacturing processes in the nano scale. The process has three major steps, first the location of particle is found using the AFM (Atomic Force Microscope) image, then probe and particle get interaction, after creating the initial contact between the probe tip and particle, the force applied from the cantilever increases until the critical time is reached and the particle dislodges from the surface. Then the applied force becomes constant and the particle is guided towards the desired point.

AFM cantilevers are very delicate, and if they are unable to perform their intended tasks or break during the operation, the displacement of nanoparticles by the AFM robot will become a difficult and costly undertaking. By being able to predict the effective forces and implementing the control strategy, the probability of process failure will be reduced and the feasibility of the manipulation process will be ensured. The ability of pushing particle to manufacture nano structures has been studied in past decade [1]-[3]. The first dynamic model for nano manipulation of spherical particles has been presented by Sitti et al., [4]. The dynamic modes of manipulation and critical time in which the separation happens have been intruded [5], Tafazzoli et al., [6]. The shape of nano particle is a major obstacle; therefore, to have accurate results, modelling techniques are improved by Korayem et al., [7], [8]. Moreover, with the recent developments it is possible to have a force feedback in real time [9], [10]. While the direct measurement for effective forces in the process has been introduced by Mrinalini et al., [11], however, the control process of manipulation is still an undergoing problem addressed in this paper.

Falvo et al., have tried to find a way for real time control, and presented a haptic device that makes a close loop control for manipulation process [12]. Controlled manipulation of CNT has also been introduced by Jiangbo et al., where a special cantilever has been used for this purpose [13]. Also critical situations in which process failure might happen have been investigated by Lianqing et al., [14], [15]. The control of AFM based manipulation process has been studying in the most recent works in manipulation field. Control of AFM cantilever position has been presented by Wang et al., [16], and output feedback is used to improve accuracy of manipulation process by Fang et al., [17]. In the most recent works, manipulation of polyhedron-like nano particle has been widely studied and a mathematical model for surface characterization of multiwall carbon nano tube has been proposed [18], [19]. The control strategy for hysteresis and creep of the AFM piezo actuator has been developed by Xi et al., [20], [21]; a control strategy based on laser beam detection has been proposed by Amari [22]. In the most recent works, Korayem et al., proposed a 3D dynamic model in liquid environment [23]. They also introduce a virtual reality environment for the process [24]. Furthermore, they first and second critical force which are highly important for a precise manipulation process [25]. The control approaches for the manipulation process do not include a comprehensive 3D model for substrate and cantilever; thus, in this paper a 3D model which demonstrates the force deformation relationship and a feedback control strategy has been proposed. In this paper, the model which presents the relation between cantilever deformation and implied force has been introduced. The model has been verified using FEM simulation approach. Furthermore a feedback control strategy for manipulation of nano particle has been proposed. Using the presented models makes the control of precise manipulation process possible.

2 INTRODUCING SPRING CONSTANTS

In this section a model for force deformation in AFM cantilever (the most sensitive part of AFM) is introduced. It contains two sections 1) a cantilever in which force applies and 2) a sensor which measures the deformation. In order to model cantilever's behaviour, forces in three dimensions also cantilever's response to each of these forces are considered (as shown in Fig. 1).

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix} = \begin{bmatrix} K_X & 0 & 0 & 0 & \frac{K_{\theta_Y}}{H} \\ 0 & K_Y & 0 & \frac{K_{\theta_X}}{H} & 0 \\ 0 & 0 & K_Z & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \varepsilon_X \\ \varepsilon_Y \\ \varepsilon_Z \\ \theta_X \\ \theta_Y \end{bmatrix} \quad (1)$$

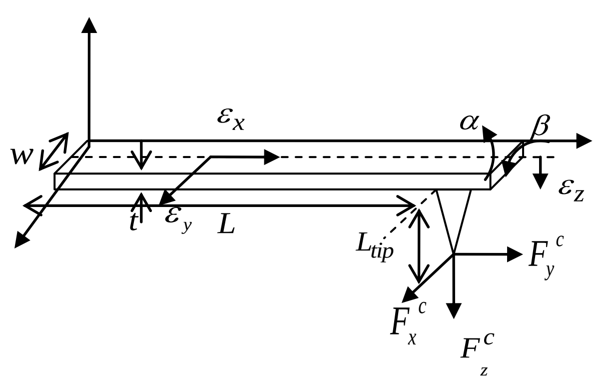

Fig. 1 Atomic force Microscope and effective forces

The generalized model in 3D manipulation is used in this work based on equation 1, where the spring constants have been introduced in earlier works [7], [8].

3 FINITE ELEMENT SIMULATIONS FOR ATOMIC FORCE MICROSCOPE

In the first step according to the technical information from handbooks, a model of cantilever is designed. Solid 95 is applied which is a type of 3 dimensional FEM elements in this simulation. This element is highly accurate and suitable for complicated geometry and it is also recommended for different analysis including large deformation and plasticity. With respect to the geometry and dimension of the cantilever, it is suitable for the simulation, where the mechanical properties of the cantilever is introduced using Table 1.

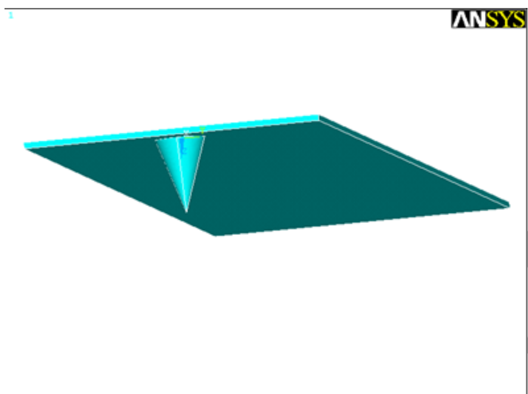

Fig. 2 Finite element model for AFM cantilever

Table 1 Mechanical Properties of Cantilever

ν	$E(Gpa)$	$p\,(kg/m^3)$
0.28	169	2330

In this step the cantilever is meshed, and in this simulation due to the fact that a high precision is essential, hence a fine mesh is applied. This fine mesh is focused in the corners of cantilever which are critical regions. In next step one side of the probe is fixed by closing all DOF in all nodes. Then, a constant force is applied and the model is solved.

Response will be compared with the present model's simulation as shown in Fig. 4. The same process is repeated by different forces and results for each step are compared by analytical results. Considering the current simulation (Fig. 4), it is concluded that both FEM and analytical simulation contain the same results, hence the present model is valid and the results are satisfactory. As it is demonstrated in Fig. 4, both results have adequate correlation.

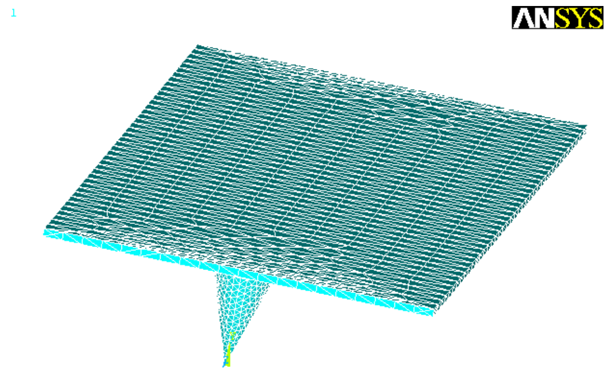

Fig. 3 Mesh generation for AFM cantilever

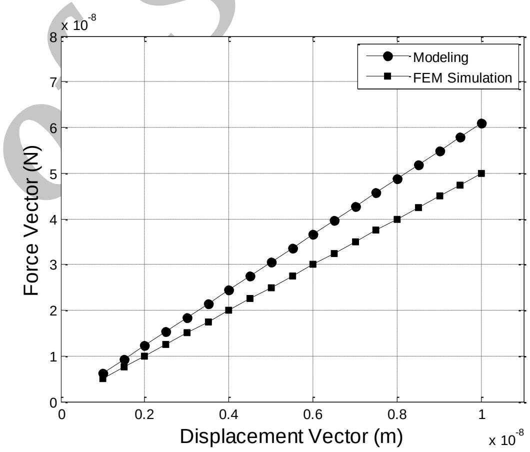

Fig. 4 FEM results compared with analytical results

5 3D CONTROL SYSTEM FOR AFM BASED NANO ROBOTS

In this section an analysis for control strategy is provided. It is important to have a suitable strategy in Nano fabrication process because achieving our goals in Nano manufacturing is highly depended on this strategy. Commercial AFM microscopes have an open loop control strategy which is not suitable for Nano fabrication process. A closed loop strategy is essential for this purpose while force detection is a necessary part of the control strategy. The force deformation model which is described in pervious sections is used for this purpose. In Nano manufacture process, a linear control is demanded during manipulation process, where two strategies are applied for this purpose.

Two main strategies which are used in Nano manipulation process are constant height strategy and constant force strategy. First strategy is built upon the fact that during the manipulation process, height of cantilever should be unchanged. Therefore, cantilever and particle would be ceaselessly attached so process would be possible. However, there would be some difficulties for this strategy including surface preparation before the process. Surface roughness is a crucial point in this process because having an uneven surface makes z level control impossible. The second approach which involves less preparation process is used in this research as well.

In constant force approach, instead of constant z height, force in the z direction is constant. In every step of the process cantilever deformation is monitored therefore Fz is found. With using a defined Fz and comparing these forces it is possible to see quickly any changes on force and response. A compensator is used to find the difference between monitored force and constant force which is defined by the operator. The designed controller compensates the produced error. In the x and y direction, piezoelectric stage is compelled to move, and the particle's position is monitored. This strategy would be applied until particles accomplish the desired position. In order to model the process a dynamic model for piezo stage has been introduced (Eq. 2 to 4).

$$M\ddot{x} + 2Mb_x\omega_x\dot{x} + M\omega_x^2 = Mu_x(t) - f_{ps}^{x}(t) \quad (2)$$

$$M\ddot{y} + 2Mb_x\omega_x\dot{y} + M\omega_x^2 y = Mu_y(t) - f_{ps}^{y}(t) \quad (3)$$

$$M\ddot{z} + 2Mb_x\omega_x\dot{z} + M\omega_x^2 z = Mu_y(t) - F_{ps} \quad (4)$$

Where b is the damping coefficient and ω is natural frequency, M is the mass of piezoelectric, f is the friction force, Mu is the piezoelectric force and F is the contact force between particle and substrate which is a nonlinear force. However, F is inconsiderable; consequently, it is neglected in the present model. Therefore, the system will be achieved as follows:

$$G_x(s) = \frac{1}{\frac{1}{\omega_x^2}s^2 + \frac{2b_x}{\omega_x}s + 1} \quad (5)$$

$$G_y(s) = \frac{1}{\frac{1}{\omega_y^2}s^2 + \frac{2b_y}{\omega_y}s + 1} \quad (6)$$

$$G_z(s) = \frac{1}{\frac{1}{\omega_z^2}s^2 + \frac{2b_z}{\omega_z}s + 1} \quad (7)$$

Table 2 Mechanical Properties of Cantilever

Simulation parameters	Damping Ratio	Natural Frequency
X Direction	669.07	.0366
Y Direction	407.07	.0293
Z Direction	686.13	.0410

Some experimental results are used for natural frequencies and damping coefficients as presented in Table 2. Step responses are represented in Fig. 5.

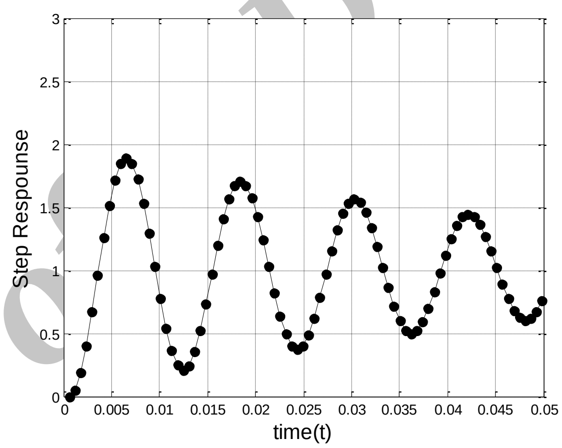

Fig. 5 Step response for transfer function (Eqs. 5 to 7)

Due to the fact that the poles are imaginary and are on the left side of imaginary axis, an under damped and oscillating response is expected. Settling time which has a key role in the Nano fabrication process is not suitable in this system; hence a feedback control system is used for a better control.

$$\dot{X} = AX + BU$$
$$Y = CX + DU \quad (8)$$

Finding suitable feedback control for the system, the system's poles could be pushed to the desired position. Position of the ideal poles is a function of settling time and damping ratio. Therefore, considering settling time as .01s and damping ratio as .6, position of ideal poles could be found. Finally, a controller has been proposed to achieve the designed goals (Fig. 6).

As it is observed step response has a remaining error which could be omitted by modifying the proposed controller. In the proposed feedback control system settling time would be $ts = .01$ which is acceptable for micro manipulation process.

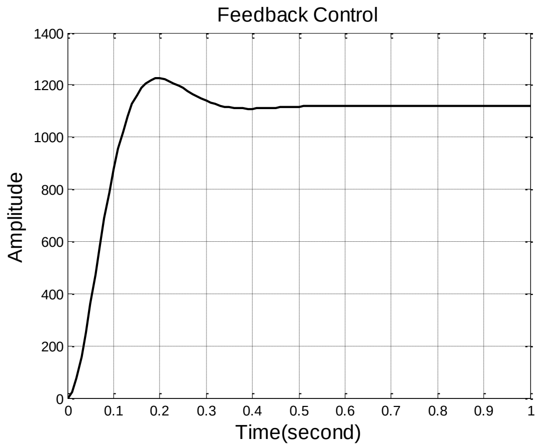

Fig. 6 Step response with feedback control

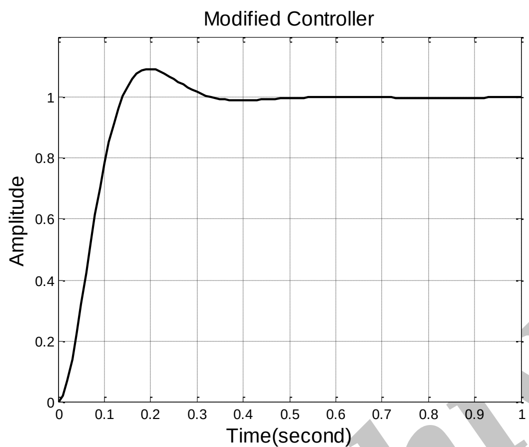

Fig. 7 Step response in X direction with feedback control

5 CONCLUSION

In this paper, a model is introduced which determines three dimensionally the relation between force and deformation. The same strategy could be used for cantilever with different geometries. A FEM simulation is proposed as verification approach which confirmed that the model works precisely in 3D form.

A constant Fz is found from experiment and compared by Fz which monitored during process then a signal would shows differences. For precise manipulation, it is vital to have a control strategy; therefore, a feedback control system has been proposed. The modelling and simulation of control feedback is introduced three dimensionally to present a comprehensive approach, where this method could be applied in any desired cantilever geometry.

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