An Integrated System of Microcantilever Arrays with Carbon Nanotube Tips for Bio/Nano Analysis: Design and Control

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Abstract - This paper discusses design and control of massively parallel microcantilever arrays with multi-walled carbon nanotube tips. The integrated system can make a powerful tool for imaging, testing and 3D nanomanipulation of nanoparticles and biological samples. The microcantilever has a multi-walled carbon nanotube tip and four additional carbon nanotubes for 3D fine manipulation by electrostatic forces. The reflected light from the deflected microcantilever is collected by a position sensitive photodetector and fast readout is achieved by a time-multiplexing scheme. A distributed parameter system model has been developed to study its dynamic behavior. The open-loop simulation results show that the carbon nanotube tip generates very small nonlinear interaction forces which do not excite significant higher harmonics. It is shown via simulations that the carbon nanotube tip demonstrates an excellent capability for nanomanipulation of samples and tapping mode operation for imaging under a simple PID controller.


I. INTRODUCTION

Since their discovery, carbon nanotubes (CNT) have been recognized as important building blocks for nanoscopic systems owing to their excellent electromechanical properties [1],[2]. Particularly, their potential as probe tip for high resolution atomic force microscopy has been emphasized for reasons, such as high wear resistance, high length-to-diameter ratio, and high bending flexibility that leads to minimal damage to samples [3],[4]. However, the very advantageous characteristic of flexibility presents difficulties inside the feedback system necessary for accurate control of the tip [5]. Especially when the tip is close to sample, nonlinear dynamics between the two make high-speed imaging and manipulation of the sample very difficult [4],[6],[7]. To meet this challenge, its open-loop and closed-loop performances are studied based on a distributed parameter system model to facilitate the use of CNTs as nanomanipulator and probe tip.

However, there is still speed limitation with single microcantilever operation when the tip has to cover a large area or a large number of samples. To solve this problem, we designed microcantilever arrays for simultaneous, multiple, high-speed biological system testing and high-speed imaging. The deflection of cantilevers can be sensed using a position sensitive photodetector. To facilitate high-speed readout of a large number of microcantilevers, a time-multiplexing method is used [8],[9]. There have been researches on massively parallel micro cantilever arrays for chemical sensing and ultrahigh density recording and reading [8]-[11]. None of them, however, has CNT tips for imaging, testing and fine manipulation. Furthermore, our design adds four more CNTs on the bottom surface of the microcantilever to deflect the CNT tip into a desired direction, thus achieving 3D fine manipulation capability.

The proposed system will provide extremely powerful tools for studying a wide variety of phenomena of nanoparticles and biological systems at the micro/nano scale, such as elasticity, surface charge, biomolecular binding, adhesion, wear, friction, spatial orientation, and single molecule conformation [12]. By functionalizing the CNT tips, it can also be used for chemical sensing.

II. DESIGN

The system consists of Si microcantilever arrays, optical system including a position sensitive photodetector to measure cantilever bending, and Z-direction piezoactuators to individually actuate microcantilevers.

The dimensions of the device are 2 mm x 2 mm. At the bottom surface of each cantilever beam, a 7.5 μm multi-walled carbon nanotube (MWNT) tip is attached. Around the MWNT tip, four 4 μm MWNTs are placed 6 μm away from it with 90 degrees apart from each other. Each of the tubes is connected to a find gold wire, which is mounted on Si insulator so that a potential can be applied to it to deflect the long MWNT into a desired direction by electrostatic force [13,14]. When a bias voltage is applied between the short and long nanotubes, the potential difference between the two produces an attractive electrostatic force to deflect the center nanotube into the direction of the short nanotube [13]. Thus, it can function as a fine manipulator or nanotweezer. The electrically charged MWNTs can also apply electrical stimulation to biological samples or make electrical measurements of them. The MWNTs can be attached under the view of an optical microscope or within a SEM or by directly growing them by chemical deposition [15].

The microcantilever is attached to a fine (dither) Z-axis piezoelectric actuator, which is excited at near fundamental
This fine Z-axis piezoactuator is then attached to the piezoactuator that can vertically travel in 0.1 nanometer steps. This system is integrated with a macro X-Y-Z axis linear positioner.

The bending of the cantilevers is optically measured by recording the position of an incident light spot reflected off the surface of a cantilever into a position-sensitive photodetector. Fast readout of a large number of cantilevers is achieved by a time-multiplexing scheme. Each of the light sources can be switched on and off individually [9]. This technique is able to resolve cantilever deflections of fractions of nanometers [8].

III. DYNAMICS

There have been growing interests in the control of AFM tips [16]-[19]. However, none of them deals with CNT tips. To design a controller for carbon nanotube tipped microcantilevers, a suitable model has to be developed first. Dynamics of tapping-mode atomic force microscope (AFM) have been studied using a lumped parameter model and a distributed parameter model [6],[7],[20],[21]. For large tip-sample gaps, the dynamics of the single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems show similar responses [6],[21]. In close proximity to the sample, i.e., at the transition from imaging to nanomanipulation, however, the higher eigenmodes significantly affect the dynamics [6]. In this paper, therefore, a MDOF model has been used to design a controller for nanomanipulation at small tip-sample distance and imaging.

The dynamics of the flexible microcantilever is described by one-dimensional Euler-Bernoulli equation based on continuum model. The equation of motion of the vibration microcantilever is

\[ E I \frac{\partial^4 w(x,t)}{\partial x^4} + b_0 \frac{\partial w(x,t)}{\partial t} + b_1 \frac{\partial^2 w(x,t)}{\partial t^2} + m \frac{\partial^2 w(x,t)}{\partial t^2} = f(x,t) \]

where \( m \) is the constant cantilever mass density, \( E \) is Young’s modulus, \( I \) is the moment of inertia, \( f(x,t) \) is the external force applied to the cantilever, and \( w(x,t) \) is the time-dependent transverse displacement. \( b_0 \) is the damping parameter proportional to mass and \( b_1 \) is the damping parameter proportional to stiffness [22]. The overall modal contact damping has two values to simulate the different dissipation phenomena when the CNT is in or out of contact with the sample [23]. The microcantilever is considered a linear time invariant system with \( n \) degrees-of-freedom and can be represented by the following state-space equations of motion:

\[
\begin{align*}
\dot{x} &= Ax + bu \\
y &= Cx + du
\end{align*}
\]

The state vector \( x = (x_1, x_2, \ldots, x_n)^T \), \( u \) is the control input minus the CNT tip-sample interaction force \( F_{int}(y) \), and \( d = 0 \). \( A \) is a \( 2n \times 2n \) matrix with \( \Phi_i \) along the diagonal. \( \Phi_i \) contains the normalized eigenfrequencies \( \hat{\omega}_i, \hat{\omega}_i, \hat{\omega}_i \) and damping \( \gamma_i \) of each mode:

\[
\Phi_i = \begin{bmatrix} 0 & 1 \\ -\hat{\omega}_i & -z_i/\hat{\omega}_i \end{bmatrix}
\]

\( b = [0, \phi(\xi_{\text{tip}}), \ldots, 0, \phi_n(\xi_{\text{tip}})]^T \), where \( \phi(\xi_{\text{tip}}) \) is the normalized modal deflection of the cantilever at the tip. The output vector \( y = (y_1, y_2)^T \), where \( y_1 \) and \( y_2 \) are the actual tip displacement and photodetector signal output, respectively.

\[
C = \begin{bmatrix} \phi_1(\xi_{\text{PSD}}) / n_1 & \cdots & \phi_n(\xi_{\text{PSD}}) / n_1 \\ \phi'_1(\xi_{\text{PSD}}) / n_2 & \cdots & \phi'_n(\xi_{\text{PSD}}) / n_2 \end{bmatrix}
\]

where \( n_1 \) and \( n_2 \) are normalization constants [6].
The CNT tip-sample interaction force $F_{\text{int}}(y)$ is described as follows [4].

$$F_{\text{int}}(y) = \begin{cases} \frac{C_1}{y^3} & (y \geq a_0) \\ C_2 - C_3y + \frac{1}{a_0^3} (C_4 - C_5y) y^2 & (0 \leq y < a_0) \\ C_5 - C_6y^2 & (y < 0) \end{cases} \tag{5}$$

where $C_1$, $C_2$, $C_3$, and $C_4$ are constants and $C_5 = C_4 x y^3$, $C_6 = C_5 x y$, and $C_7 = C_5 x$. $a_0$ denotes the intermolecular distance when the CNT tip contacts the sample surface.

IV. SIMULATIONS

In the MATLAB simulations, three eigenmodes are included. The parameters for the microcantilever are: cantilever length = 225 µm, cantilever width = 15 µm, cantilever thickness = 2.6 µm, fundamental resonance frequency = 72.5 kHz, stiffness of the cantilever = 1 N/m, $E = 130$ GPa, $\rho = 2300$ kg/m$^3$. The modal noncontact damping $\gamma_i$ is set to 0.0028 for all modes from the microcantilever Q factor of 180. The Hamaker constant $H$ (C-C) = $3.19 \times 10^{-19}$ J. The intermolecular distance $a_0$ is 0.246 nm. $C_1 = -9.109 \times 10^{-25}$ N/m, $C_2 = 2.462 \times 10^{-7}$ N/m$^2$, and $C_3 = 1.180 \times 10^{-2}$ N/m. The driving frequency $\omega = 1.0$.

First, open-loop performances of the CNT-tipped cantilever are observed. Position is set to zero at the undeformed sample surface. Positive force indicates repulsive force or elastic restoring force, whereas negative force indicates attractive force.

Figures 2 (a) and (b) show the open-loop responses when the gap between the tip and the sample surface is within the intermolecular distance. The driving force is $1.24 \times 10^{-12}$ N. There is approximately 90 degree phase lag between the driving force and the actual position. It was the same phenomenon as observed in [24]. This phase lag of approximately 90 degree is observed in all the following open-loop simulation results even though it is not shown explicitly in the figures. Figures 2 (c) and (d) show the results when the CNT tip passes through the intermolecular distance with a driving force of $2.2 \times 10^{-12}$ N. It is shown that the tip experiences repulsive forces when it pushes against the sample surface. Figures 2 (e) and (f) show open-loop responses at 0.2 nm gap. The driving force is $3 \times 10^{-12}$ N. The attractive force outside the intermolecular distance is not shown since it is many orders smaller than that within the region. All the open-loop responses demonstrate the long settling time to reach the steady state. As shown in Fig. 2, our MDOF model does not display the distorted open-loop responses when the tip
approaches near the sample surface as reported in [6] because the tip-sample interaction force is too small to excite the higher harmonics noticeably.

Figure 3 shows the open-loop responses when the tip experiences positive and negative steps on the sample surface. Position is set to zero at the undeformed sample surface. The driving force is $3 \times 10^{-11}$ N. Figure 3 (a) and (b) show the system responses when the tip encounters a negative step of -30 nm at 800 secs while it taps the sample surface with the gap of 20 nm. Note that the amplitude increases after the step since the gap increases. On the other hand, Fig. 3 (c-f) display the open-loop responses when there is a positive step. It is noteworthy that the amplitude decreases as the gap size decreases. This change of amplitude with gap size was also observed in [16].

Figure 4 demonstrates the open-loop and closed-loop responses when the tip pushes against the surface 6 µm deep with the gap of 20 nm between the sample surface and the tip. Figure 4 (a) exhibits that the open-loop settling time is relatively short. The driving force is $4.2 \times 10^{-8}$ N. As shown in Fig. 4 (b,c), the tip follows the desired trajectory within 10 secs under the PID controller, whereas it takes 300 secs to reach the steady state without feed back. Under the PID controller, there is not a phase lag any longer. The interaction force is a few orders larger when the tip pushes down to 6 µm deep.

Figure 5 shows the open-loop and feed back responses when the tip encounters a positive step of 15 nm at 400 secs while it pushes against the surface by 28 nm with the gap of 20 nm. The driving force is $2 \times 10^{-10}$ N. Again, the amplitude

Fig. 3. Open-loop response : (a,b) with gap of 20 nm and step of -30 nm at 800 secs., (c,d) with gap of 20 nm and step of 10 nm at 750 secs, and (e,f) with gap of 20 nm and step of 30 nm at 750 secs.

Fig. 4. (a) Open-loop and (b,c) PID responses with gap of 20 nm and depth of 6 µm.
decreases as the gap decreases as shown in Fig. 5 (a). Figure 5 (b) shows that the PID controller settles the system within 50 secs each time. When the tip encounters the step, the PID controller sends a command to reset the set point and achieves a good trajectory following.

Figure 6 demonstrates the PID response when the gap between the tip and the sample surface is 2 nm. The driving force is $3 \times 10^{-12}$ N. The settling time is 20 secs.

Figure 7 represents the effectiveness of PID controllers when the tip encounters the steps of Fig.3. The driving force is $3 \times 10^{-12}$ N. The system settles into steady states within 30 secs in all cases.

The CNT tip shows excellent closed loop performance under a simple PID controller, facilitating its use for imaging and nanomanipulation.

**V. CONCLUSIONS**

This paper discusses design and control of microcantilever arrays with multi-walled carbon nanotube tips. The proposed system will provide extremely powerful tools for bio/nano analysis and nanomanipulation since it is capable of imaging, nanomanipulation, and electrical and chemical testing simultaneously.

A multi-degree-of-freedom model has been developed to study dynamic behaviour of the carbon nanotube tipped microcantilever and to design a controller for imaging and nanomanipulation at small tip-sample distance.

The open-loop simulation results indicate that the CNT tip generates very small nonlinear interaction forces, and thus does not excite higher harmonics significantly.
PID controllers are applied for nanomanipulation and tapping mode operation. It is shown via simulations that the simple PID controller can quickly settle the system and achieve a good trajectory following even when there exist large steps on the sample surface, thus demonstrating an excellent tapping mode operation for imaging. Under the PID control, the CNT tip can push against the sample surface in a repetitive manner showing a good manipulation capability. To investigate manipulation capability further, more simulations should be done with the model which includes environment stiffness and damping.

The simulation study shows that the integrated system of microcantilever arrays with multi-walled carbon nanotubes are excellent for imaging and nanomanipulation since their nonlinearity force is very small and allows the use of a simple PID controller. Combined with electrical and chemical testing capability, the system will make a power tool for bio/nano analysis and manipulation.

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REFERENCES


