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HIGH PRECISION IMAGING FOR NON-CONTACT MODE ATOMIC FORCE MICROSCOPE USING AN ADAPTIVE NONLINEAR OBSERVER AND OUTPUT STATE FEEDBACK CONTROLLER

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Identification of the probe height above the sample surface is a highly useful method to acquire atomic-resolution AFM images. Most AFM systems in non-contact mode use amplitude or phase measurement to identify the sample-probe distance and thereby the sample topography. However, this process is time consuming. For the purpose of sample height estimation in this paper we propose an adaptive nonlinear observer capable of high-precision probe height estimation within a small fraction of the probe transient motion. In addition, to maintain constant sample height at the set point level determined by the user during scanning and imaging in non-contact mode and achieve high rate data sampling, this paper develops a novel output state feedback controller. In this case, the surface topography image of the sample is created through the feedback signal which adjusts the vertical movements of the sample during scanning. The stability of the proposed observer and control method is proved by the Lyapunov stability analysis. Numerical simulations are employed to evaluate the feasibility and effectiveness of the proposed scheme.

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1. Introduction

Atomic force microscopy (AFM) [1] is a powerful tool in nanotechnology especially in imaging nanoscale structures, nanomanipulation, nanolithography and direct measurement of intermolecular forces with an atomic resolution. As a microscope, the AFM can also be used to obtain quantitative local material properties such as roughness, visco-elasticity, and composition of different materials or force spectroscopy [2].

The main components of AFM are the cantilever-tip system, the piezoelectric scanner, and the photo sensitive detector. AFMs can be operated in one of two principal modes: (i) with feedback control or (ii) without feedback control. Though widely practiced, open-loop operation has the potential for chaotic probe tip response, thus rendering erroneous topographical information. Therefore, in a typical imaging operation the cantilever deflection is maintained at a set point by means of a feedback controller, while scanning the sample surface. The control effort is used as a measure of the sample surface profile. Contact, non-contact and tapping modes are three modes of operation in AFM. In contact mode (C-AFM), the cantilever-probe system is dragged against the sample and moved over it in a raster scan fashion. In this mode, the interaction forces between the tip and sample have repulsive nature and the main duty of feedback system is

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maintaining contact between the sample and the tip during scanning. Furthermore in C-AFM, vertical axis of system motion is controlled, so that deflection of the cantilever is constant.

In tapping mode, the force sensing cantilever is vibrated at or near its resonance frequency near the vicinity of the sample while the sharp tip forms intermittent contacts with the surface. Relatively large vibration amplitudes prevent sticking, and intermittent contacts minimize damage to the sample and the tip.

In non-contact mode operation of AFM, lateral forces exerted by the sample on the tip are negligible. In the typical non-contact imaging, the cantilever deflection is maintained at a set point by means of a feedback controller, while scanning above the sample surface. Since the dynamic response of the tip is sensitive to the tip-sample distance, the feedback signal which regulates the vertical motion of the sample (or the tip) during scanning contains height information. During imaging, the frequency, amplitude, and phase of the tip oscillations are measured and controlled [3]. The topographical image of the sample is then extracted from the time-history of the control effort. The time elapsed before tip oscillations settle down is long since the system is lightly damped and steady-state periodic motion appear after a relatively long transient response [4]. In addition, the interaction force between the tip and sample depends on the distance from the cantilever tip to the sample surface [5]. The tip-sample distance also varies over the sample surface and as a result becomes a time-varying quantity during scanning. These factors combine to make imaging a complicated, and time consuming process [3].

In [6], a transient signal-based detection method which relies on the construction of an observer is presented. The limitations related to the trade-off between resolution and bandwidth is improved and the system becomes independent of the cantilever quality factor. Other techniques are often based on the identification of the active interaction force [7]. The interaction force between cantilever tip and sample is dependent on the distance from the cantilever tip to the sample surface [8]. These approaches are very time consuming and need extra sensors to measure other system parameters needed in force identification, since the cantilever deflection doesn't provide enough data. Therefore, designing a method to calculate the sample-height in order to generate high precision atomic-resolution imaging is desirable. Reference [9] presents a method to estimate sample height and the control of NC-AFM using a combination of PI controller and tip-sample separation identifier technique. The estimator could identify the sample height utilizing the transient response of the probe.

As mentioned above, in order to maintain constant sample height at the setpoint level determined by the user during scanning and imaging in non-contact mode AFM, achieve high rate data sampling and improve AFM region of operation, several feedback control strategies have been developed. Conventional PD, PI, and PID feedback controllers for the AFM probe were presented in [10] and [11]. Two nonlinear control techniques using a learning-based algorithm were presented in [12]. Also Hsu *et al.* [13] utilized feedback linearization and singular perturbation techniques to design an output, high-gain feedback sample surface tracking controller. The AFM model considered in [13] is based on Euler-Bernoulli beam theory and assumes the distributed parameter modeling for AFM. However, this model does not consider complete dynamic behavior of the AFM and needs some modifications. Neither this method is capable of estimating sample height. Reference [10] utilized the Melnikov method to analyze the system dynamics and subsequently developed a proportional/derivative based feedback strategy to inject artificial damping, so that the possibility of chaotic operation is reduced. Control method presented in [11], relies on the frequency modulation of an atomic force microscope which is based on a PI control law that keeps the amplitude equal to a desired value. In this case the image of the sample surface is generated from the time-history of the control effort which needs steady state periodic motion of the system. This is relatively time consuming because transient behavior of the system must pass since control action can take place. Fang *et.al* in [7] and [12] presented nonlinear control techniques, however in [7] no result was provided to show the performance of these approaches and the method in [12] considers the desired cantilever displacement as a reference signal without explaining that how reference signal is calculated.

The control method employed in [14] is PI controller and it uses an estimated sample height as feedback signal to design controller. This scheme inevitably reduces the accuracy of the controller.

In this paper we provide an algorithm which reduces the time needed to acquire height information and design a feedback control system to maintain the sample height at a desired predetermined level. We propose an adaptive nonlinear observer to estimate the tip-sample distance based on adaptive input-output linearization theory and an output state feedback controller to adjust the sample height at the desired setpoint. The proposed observer uses only the cantilever displacement to estimate the sample height in a small fraction of the time elapsed of cantilever's transient motion. Also instead of using estimated sample height as in [9], the proposed controller uses the measured cantilever displacement as feedback signal which increases the accuracy of the controller. The stability of the presented observer and controller are proved by Lyapunov stability analysis.

We present an AFM model in section II. Guidelines for the observer design are presented in section III. The controller design procedure is discussed in section IV. To investigate the performance of the proposed method, section V provides numerical simulations and analysis. Finally, in section VI we provide a conclusion.

2. Modeling of AFM

The AFM model, based on a lumped parameters system approach is shown in Fig.1. The forced dynamic system describing the AFM operation is obtained based on the model proposed by [3, 9]:

$$m_e\ddot{z}(\tau)+c(\dot{z}(\tau)-\dot{d}(\tau))+k(z(\tau)-d(\tau))=f_{vdw}(\tau) \tag{1}$$

In this equation $d(\tau)$ and $z(\tau)$ are the base motion and cantilever-tip displacement relative to the fixed base frame, respectively. The parameters m_e, b, k are the cantilever-tip effective mass, damping coefficient and effective stiffness, respectively. The system oscillates under the influence of the van der Waals interaction force f_{vdw} which can be described by [10]:

$$f_{vdw}=\frac{Dk}{(z_0-z)^2}-\frac{\sigma^6 Dk}{30(z_0-z)^8} \tag{2}$$

where z_0 is the distance from the fixed coordinate frame to the sample, σ is the molecular diameter, and $D=A_H R/6k$ where A_H is Hamaker constant and R is the cantilever-tip radius. The cantilever is driven through a harmonic signal: $d(\tau)=A\sin(\omega\tau)$, where A and ω are the drive signal amplitude and frequency.

We recast the equation of motion of the AFM in first-order nondimensional form as [3, 10]:

$$\begin{aligned}
\dot{x}_1 &= x_2\\
\dot{x}_2 &= -x_1+\frac{4}{27(\alpha-x_1)^2}-\frac{4\hat{\sigma}^6}{810(\alpha-x_1)^8}\\
&+q\sin(\Omega t)+qp\Omega\cos(\Omega t)-px_2
\end{aligned} \tag{3}$$

Where α is the sample height and it is the parameter to be identified.

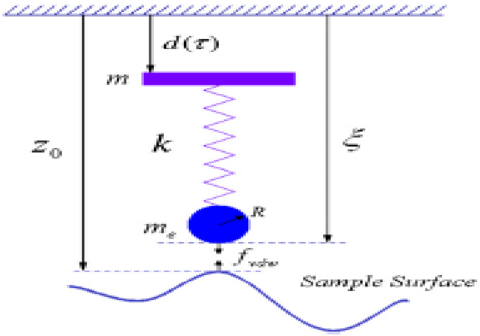


Fig.1. A schematic of the AFM as a 1-DOF harmonic oscillator [9].

3. Observer Design

The main objective of this section is to obtain the sample height at each operational point in a very short time using only the tip position. To design an adaptive nonlinear observer for NC-AFM we use adaptive input-output linearization technique. The equations for the observer are:

$$\begin{aligned}\dot{\hat{x}}_1 &= \hat{x}_2 \\ \dot{\hat{x}}_2 &= -\hat{x}_1 + \frac{4}{27(\hat{\alpha}-\hat{x}_1)^2} - \frac{4\overline{\sigma}^6}{810(\hat{\alpha}-\hat{x}_1)^8} + \\ & q\sin(\Omega t) + qp\Omega\cos(\Omega t) - p\hat{x}_2 + v\end{aligned} \tag{4}$$

Where v is the observer control input. This input is to be designed by the adaptive input-output linearization method.

Because the only measured parameter is tip position, so the equation (4) is converted to:

$$\begin{aligned}\dot{\hat{x}}_1 &= \hat{x}_2 \\ \dot{\hat{x}}_2 &= -x_1 + \frac{4}{27(\alpha-x_1)^2} - \frac{4\overline{\sigma}^6}{810(\alpha-x_1)^8} + \\ & q\sin(\Omega t) + qp\Omega\cos(\Omega t) - p\hat{x}_2 + v\end{aligned} \tag{5}$$

By considering $\tilde{x}_2 = \hat{x}_2 - x_2, \tilde{\alpha} = \hat{\alpha} - \alpha$, the error dynamics of AFM observer can be written as:

$$\begin{aligned}\dot{\tilde{x}}_1 &= \tilde{x}_2 \\ \dot{\tilde{x}}_2 &= \frac{4}{27(\hat{\alpha}-x_1)^2} - \frac{4\overline{\sigma}^6}{810(\hat{\alpha}-x_1)^8} - \\ & \frac{4}{27(\alpha-x_1)^2} + \frac{4\overline{\sigma}^6}{810(\alpha-x_1)^8} - p\tilde{x}_2 + v\end{aligned} \tag{6}$$

Now we define [9]:

$$\begin{aligned}&\frac{4}{27(\hat{\alpha}-x_1)^2} - \frac{4\overline{\sigma}^6}{81(\hat{\alpha}-x_1)^8} - \frac{4}{27(\alpha-x_1)} + \frac{4\overline{\sigma}^6}{81(\alpha-x_1)^8} \cong \\ &\left(\frac{-2d}{(\hat{\alpha}-x_1)^3} + \frac{32}{810(\hat{\alpha}-x_1)^9}\right) = \phi(\hat{\alpha})(\hat{\alpha}-\alpha)\end{aligned} \tag{7}$$

So, equation (6) is:

$$\begin{aligned}\dot{\tilde{x}}_1 &= \tilde{x}_2 \\ \dot{\tilde{x}}_2 &= \phi(\hat{\alpha})\tilde{\alpha} - p\tilde{x}_2 + v\end{aligned} \tag{8}$$

Now, by defining Lyapanouve candidate as:

$$V = \frac{\tilde{x}_1^2}{2} + \frac{\tilde{x}_2^2}{2} + \frac{\tilde{\alpha}^2}{2\gamma} \tag{9}$$

The time derivative of V is found as:

$$\dot{V} = \tilde{x}_1\dot{\tilde{x}}_1 + \tilde{x}_2\dot{\tilde{x}}_2 + \frac{\tilde{\alpha}\dot{\tilde{\alpha}}}{\gamma} \tag{10}$$

By substituting (8) in (10) we have:

$$\dot{V} = \tilde{x}_1\tilde{x}_2 - p\tilde{x}_2^2 + \phi(\hat{\alpha})\tilde{\alpha}\tilde{x}_2 + v\tilde{x}_2 + \frac{\tilde{\alpha}\dot{\tilde{\alpha}}}{\gamma} \tag{11}$$

By designing control law v as:

$$v = (-\tilde{x}_1 - k\tilde{x}_2) \tag{12}$$

And

$$\dot{\tilde{\alpha}} = -\gamma\phi(\hat{\alpha})\tilde{x}_2 \tag{13}$$

Where $\gamma > 0$.
We have:

$$\dot{V} = -(k + p)\tilde{x}^2 \le 0 \tag{14}$$

It is noted that $\tilde{x}_2$ is calculated from:

$$\tilde{x}_2 = \dot{\tilde{x}}_1 \tag{15}$$

From the above analysis, it is evident that the controller stability is guaranteed.

4. Output State Feedback Controller Design

For imaging purposes, sample stage or cantilever must be moved vertically to keep sample to the tip distance constant. In this case, a feedback loop adjusts the sample position to maintain constant tip-sample distance at a set point determined by the user. An obtained feedback signal which regulates the vertical movements of the sample (or cantilever tip) during scanning is the representative of sample surface topography. In this section the controller for the AFM is designed based on output state feedback control approach.

In order to model the AFM system, a mathematical model is studied for sensing element and incorporated into system level. From a system perspective, the input signal to AFM is the excitation signal applied to the dither-piezo and the output signal is the displacement of the cantilever-tip.

The equations of motion including the dimensionless form of control force can be written as:

$$\ddot{x} = -x - p\dot{x} + \frac{4}{27(\alpha - x)^2} - \frac{4\hat{\sigma}^6}{810(\alpha - x)^8} + q\sin(\Omega t) + qp\Omega\cos(\Omega t) + u \tag{16}$$

By defining the error signals as:

$$e = x - x_d \tag{17}$$

Where x_d is the reference signal and according to the desired sample height is calculated from:

$$\ddot{x}_d = -x_d - p\dot{x}_d + \frac{4}{27(\alpha_d - x_d)^2} - \frac{4\hat{\sigma}^6}{810(\alpha_d - x_d)^8} + q\sin(\Omega t) + qp\Omega\cos(\Omega t) \tag{18}$$

Taking derivative of the error system gives $\dot{e} = \dot{x} - \dot{x}_d$ and $\ddot{e} = \ddot{x} - \ddot{x}_d$. Therefore we have:

$$\ddot{e}(t) = -x - p\dot{x} + \frac{4}{27(\alpha - x)^2} - \frac{4\hat{\sigma}^6}{810(\alpha - x)^8} + q\sin(\Omega t) + qp\Omega\cos(\Omega t) + u - \ddot{x}_d \tag{19}$$

By designing control input u as:

$$u = x - \frac{4}{27(\alpha - x)^2} + \frac{4\hat{\sigma}^6}{810(\alpha - x)^8} - q\sin(\Omega t) - qp\Omega\cos(\Omega t) + p\dot{x} + \ddot{x}_d - k_1\dot{e} - k_2 e \tag{20}$$

Where k_1 and k_2 are positive constants.
The dynamic error system becomes:

$$\ddot{e} + k_1\dot{e} + k_2 e = 0 \tag{21}$$

And the system is asymptotically stable [15].

It is noted that we use sample height estimated obtained from (13) in (20) instead of nominal value to make the control system robust against the uncertainties and variations in the tip or sample.

As the control signal can not exceed the limited force range of the piezo, we need a bounded control signal when the proposed controller is experimentally implemented.

Depending on the saturation limit of the piezoelectric materials, the control signal is limited to be in the range of [$-\hat{u}, \hat{u}$]. Therefore, Eq. (20), is rewritten as:

$$\begin{cases} u(t) = u & |u(t)| < \hat{u} \\ u(t) = \hat{u}.sign(u) & |u(t)| > \hat{u} \end{cases} \tag{22}$$

The block diagram of the proposed method which includes the designed observer and controller is shown in Fig.2.

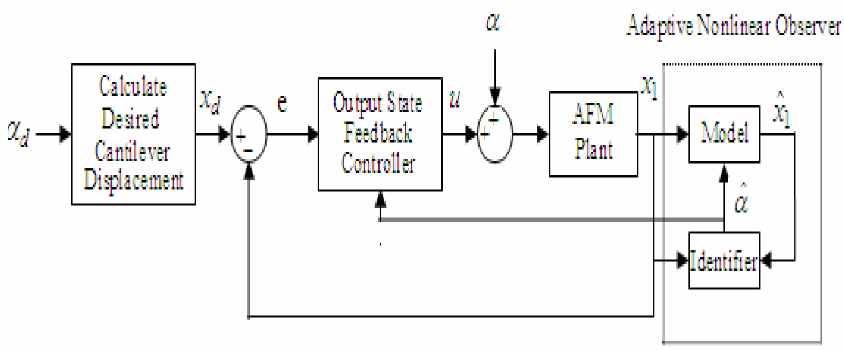


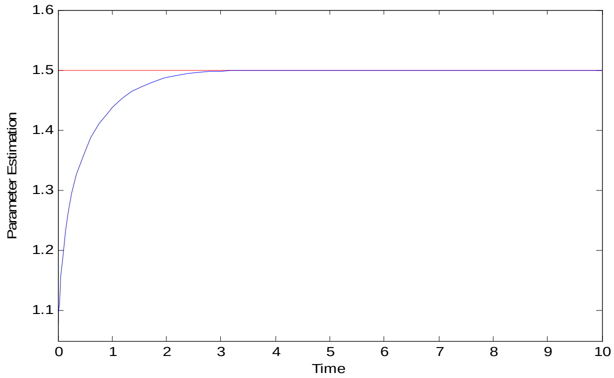
Fig. 2. Block diagram of the proposed method.

5. Simulation Results & Discussion

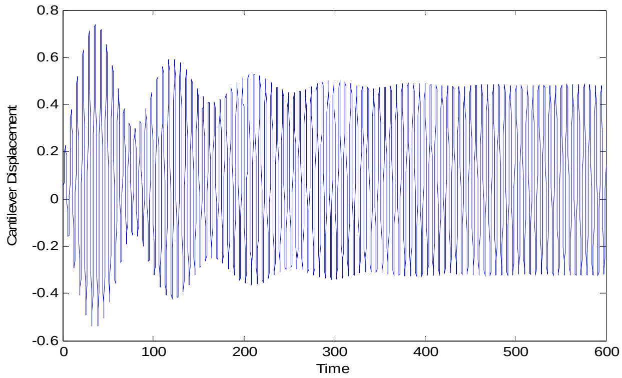
In this section, simulation results are presented to investigate the feasibility and performance of the proposed method. In this numerical test, the AFM parameters are set to: $p = 0.02, q = 0.05, \Omega = 1, \hat{\sigma} = 0.3$ and a scan of $10nm \times 10nm$ area is recorded.

Observer Tests:

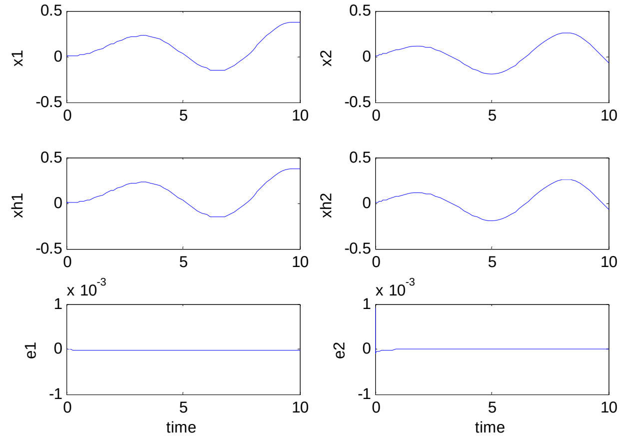
Fig.3 shows the results obtained for the sample height identification with the present method. In this figure x_1 and x_2 are the tip displacement and velocity respectively, x_{h1} and x_{h2} are the tip displacement and velocity estimated by the observer, and e_1 and e_2 are the errors between actual and estimated parameters. It is concluded from this figure that the designed observer can reduce the time needed to identify the sample height from ~ 300 to less than 4 normalized time ($t = \tau\omega_0$) units.



(a)



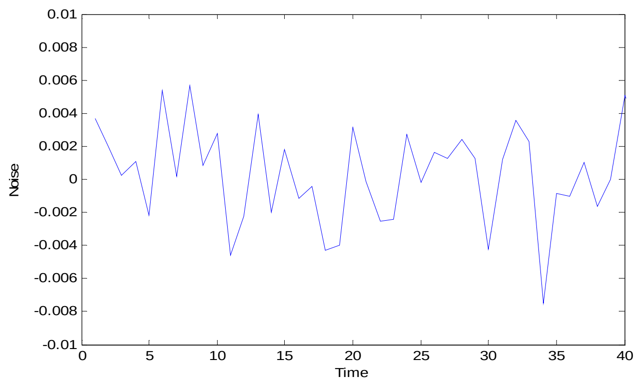
(b)



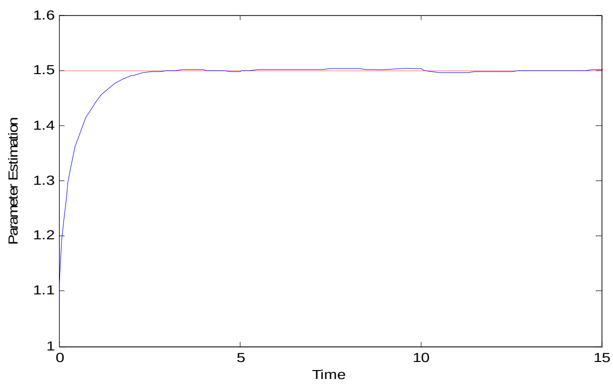
(c)

Fig.3: a) The actual (red) and estimated (blue) sample height, b) The tip displacement, c) The system and observer responses and the errors between them.

To investigate the behavior of the observer in the presence of the noise, the Gaussian noise in the interval of [-.008 .008] as depicted in Fig.4a is added to the system.



(a)



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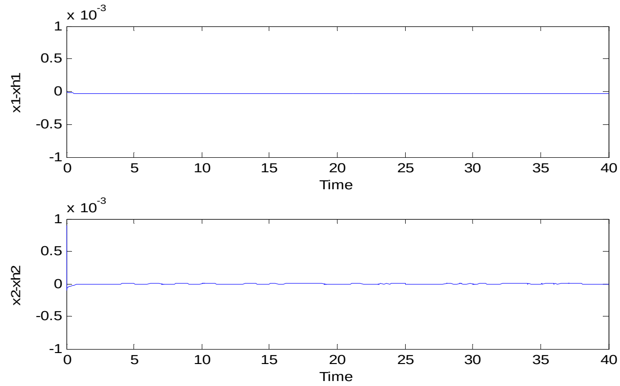
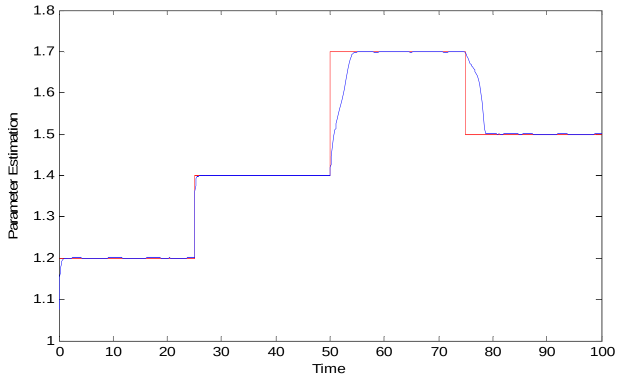


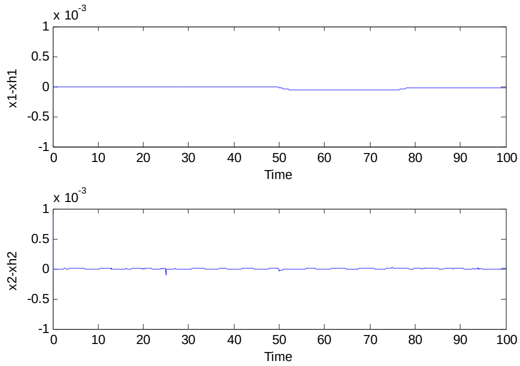
(c)

Fig.4: a) The noise, b) The actual & estimated sample height in the presence of the noise, c) The errors between system and observer states.

A second numerical test is carried out to investigate the performance of observer, when the sample height is varied. The results of this test are shown in Figs.5 and 6. As the sample height varies with time, the observer maintains its performance and continues to identify variations in the surface height in less than 4 normalized time units.



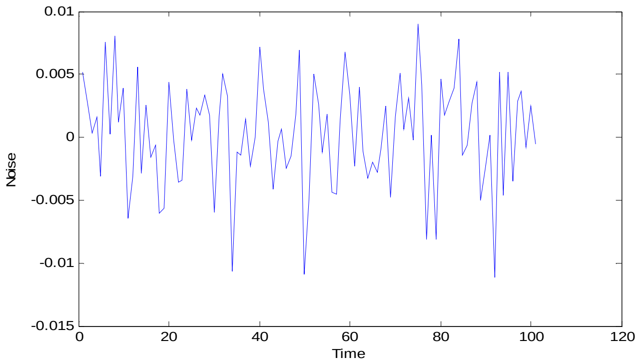
(a)



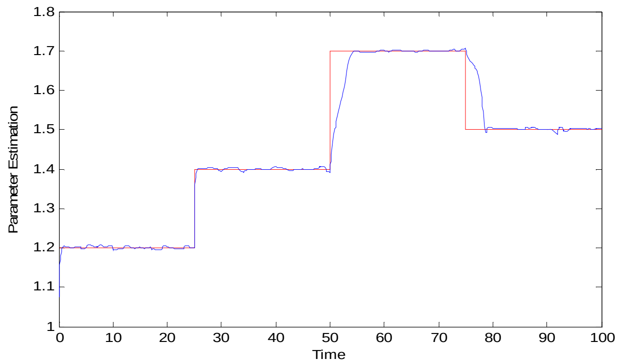
(b)

Fig.5: a) The actual (red) and estimated (blue) sample height. b) The errors between system and observer states.

To investigate the behavior of the observer in the presence of the noise, the Gaussian noise is added to the system in the interval of [-.01 .01] as depicted in Fig.6a.



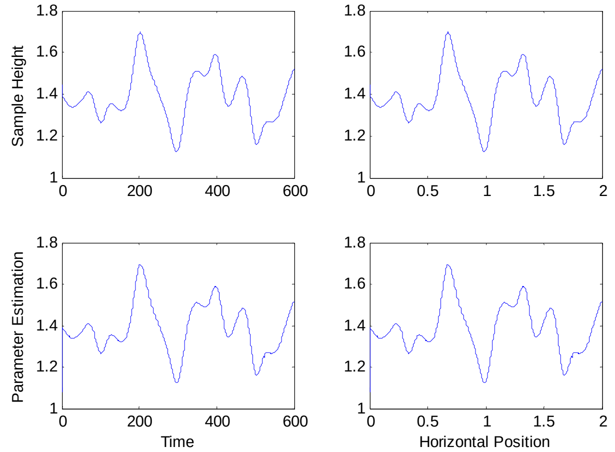
(a)



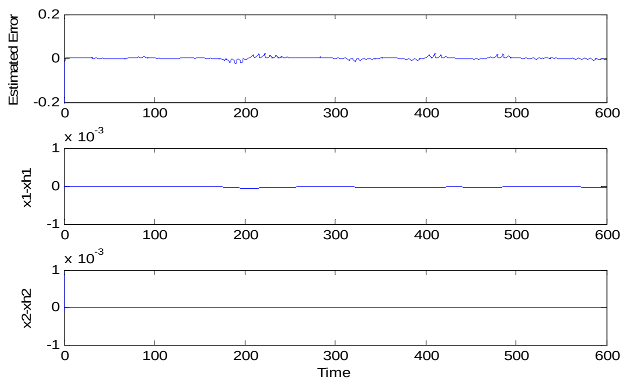
(b)

Fig.6: a) The noise, b) The actual & estimated sample height in the presence of the noise.

A third test is carried out to identify the sample height in a nearly flat surface by moving the sample with very small speed. Fig. 7 shows the effectiveness of the proposed method to identify sample height with high accuracy.



(a)

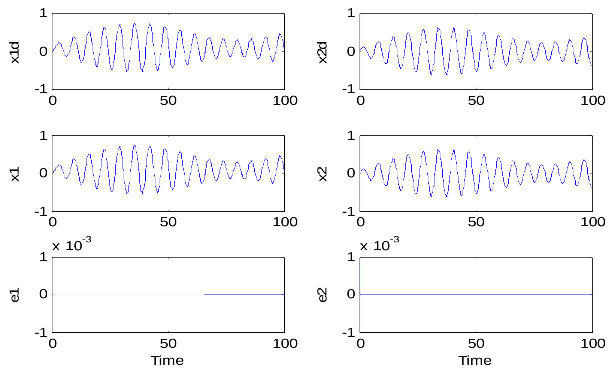


(b)

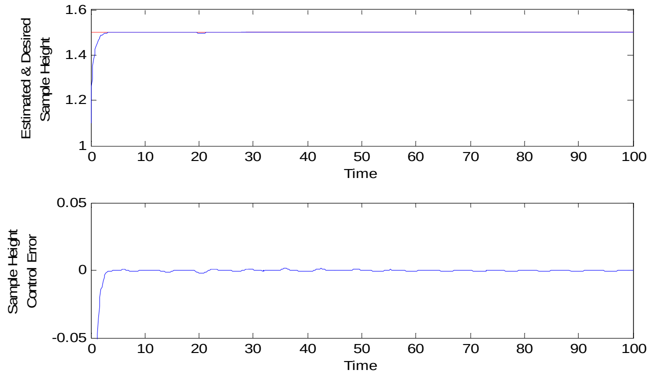
Fig.7: a) The actual and estimated sample height based on horizontal position & normalized time. b) The estimated & observer errors.

Controller Tests:

In order to evaluate the controller performance, another simulation tests are done. Fig. 8 illustrates the response of controller in tracking the desired sample height, in spite of the high sample roughness. In this simulation the desired sample height is 1.5 and actual sample surface height is shown in Fig.5a.



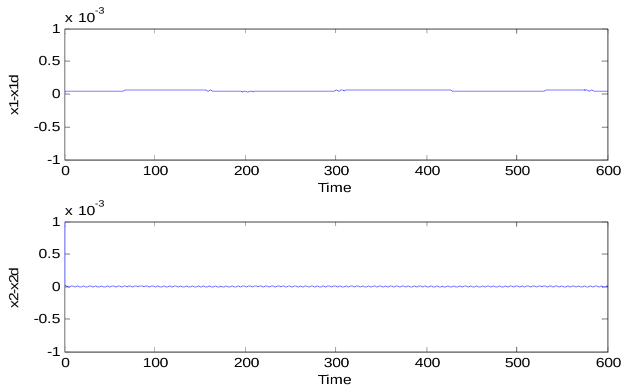
(a)



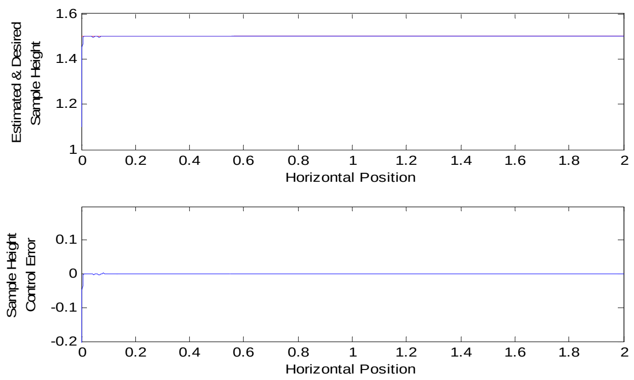
(b)

Fig.8: a) The actual and desired cantilever displacement & velocity. b) The estimated & desired sample height & error between them.

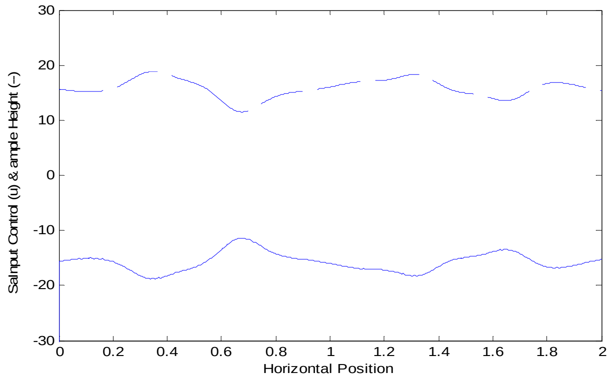
Fig.9 shows the another set of simulation results. In this test, the desired sample height is 1.5 and real sample surface is assumed to be as shown in Fig.9c. As depicted in Fig.9, the controller can track the desired signal perfectly and the control input can be a representative of the real sample surface height.



(a)



(b)



(c)

Fig.9: a) Errors between the cantilever actual and desired cantilever displacement and velocity. b) The estimated and desired sample height and error between them. c) The control input and sample height.

Finally, for the purpose of comparison between open loop operation with only observer and closed loop operation with feedback controller and observer, we consider a sample in the case of high data rate sampling and high frequency. As concluded from Fig. 10, in this situation, the observer doesn't capable of estimation of sample height due to the open loop nature of imaging system, while in the closed loop system, the controller can detect the surface height.

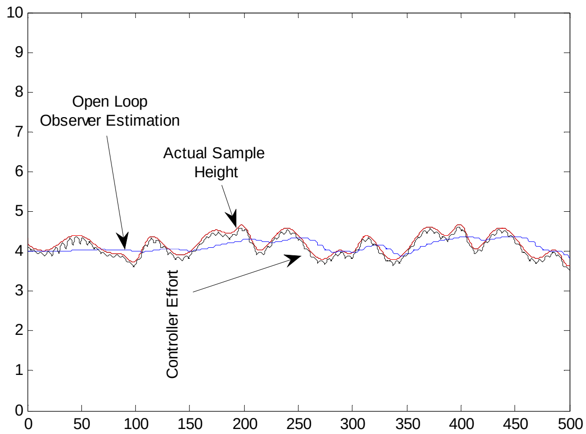


Fig. 10: Comparison between open loop & closed loop system with observer in the presence of noise.

6. Conclusions

In this paper an adaptive nonlinear observer was deigned to identify the distance between the tip and the sample surface in a small fraction of the time during the transient motion of the cantilever-tip take place. The only measured parameter in this identification method is the tip displacement. Also to keep the sample height in a preset value, an output state feedback controller is designed using the measured cantilever displacement as the only feedback signal. Simulations were carried out to investigate the validity of the proposed technique. The results are compared with other techniques recently published in the literature and show the effectiveness of the proposed method identification of the topography of the sample. In addition the designed observer is robust against the noise and external disturbances.

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