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System Modeling of an AFM System in Z-axis

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***Abstract*—Motivated by increasing the scanning performance of the atomic force microscope (AFM), many efforts have been made to analyze the system behavior of an AFM system, mainly in Z-axis, and then to develop more advanced controllers. However, most of the previously derived models involve complex physical or mathematical analysis, and many parameters need to be identified for actual application. In this paper, an empirical model is obtained for the Z-axis dynamics of an AFM system by utilizing experimental data. Specifically, the model consists of a dynamical component and multiple static gains. As introduced in the paper, the N4SID algorithm is first employed to derive the dynamical part based on input-output data. Then the static gains of the piezo-actuator are calibrated experimentally. It can be seen from the experimental data that the main source of time delay in Z-axis is the finite retraction/protraction velocity of the piezo-actuator.**

***Keywords*：atomic force microscope;system modeling;**

I. INTRODUCTION

Atomic force microscopes (AFM) are utilized to trace the nano-scale topography of a specimen by a sharp tip supported on a micro-mechanical cantilever. The spatially resolved topography is measured by scanning the sample laterally under the probing tip by means of a piezoelectric tube scanner. The cantilever gets deflected due to the sample's topography; the deflection is monitored by an optical lever and a segmented photo-diode. In some AFM designs, the probing tip is scanned instead of the sample. A detailed description of the components and the function of the AFM can be found in [1].

Low scanning speed is the primary bottle-neck of an atomic force microscope for wide applications to real-time imaging of samples [2, 3]. The conventional PI control algorithm is considered as the main cause of the low bandwidth of the system in Z-axis because PI controller is not able to handle the high order dynamics of the piezo-tube [4]. Besides, the tuning of the PI parameters requires lots of experience, which hinders the intelligence of the whole system. First efforts to improve the performance of scanning probe microscopes in the Z-direction have been made by implementing a modern model-based feedback controller [4]. Sitti pointed out that the intelligent and autonomous AFM system should be developed as the next generation of AFM [5]. To achieve this goal, many efforts have been made to model AFM systems and then construct more advanced control strategies to enhance the scanning speed [3]. For example, a robust output feedback controller is proposed in [6] for high rate data sampling to achieve a faster scanning speed. In [4], a modern robust controller is designed to enhance overall performance of the system. The first step of developing new intelligent AFM system is to model the system in Z-axis. However, most of the previously derived models involve complex physical or mathematical analysis, and many parameters need to be identified for actual application [7-10].

This paper analyzes the system behavior of the contact mode for an AFM in Z-axis, and then sets up a model of contact mode by utilizing experimental data of repulsive operating regime. During the experiment, white noise with limited band is applied to the amplifier of the piezo-actuator as excitation signal, and the photo-diode voltage is recorded simultaneously as output. Then the N4SID algorithm is employed to identify the linear dynamical model of the AFM in Z-axis by utilizing the collected input-output data. Besides, the static gains of the photo-diode and piezo-actuator are also determined experimentally. Based on the obtained model, it is expected to develop modern model-based controllers, such as H_∞ robust control, iterative learning control, and so on, to take place of the traditional proportional-integration (PI) control to enhance the scanning speed and measurement performance of AFM system.

The rest of the paper is organized as follows. Section II gives a general description of modeling method of AFM and then the experiment setup is explained in section III. The dynamical model and static gains of the AFM system is obtained in the following two sections. A detailed discussion of the model precision and the model dependence on the experiment setup is given in section VI which is followed by a conclusion.

II. SYSTEM MODEL DESCRIPTION

A discrete state-space system model is utilized to describe the system behavior of the AFM system which characterizes the dynamics of the piezo-tube input and the photodiode output. Based on the primary theory, the discrete state-space model of the AFM system can be described as：

$$X_{k+1} = AX_k + BU_{k+1}, Y_k = CX_k + DU_k$$

where $A \in R_{n\times n}, B \in R_{n\times m}, C \in R_{l\times n}, D \in R_{l\times m}$ are parameter matrices required to be identified. $X_k \in R_{n\times l}$ is the state vector; $U_k \in R_{m\times l}$ is the piezo-tube input voltage in Z-axis; $Y_k \in R_{l\times 1}$ is the photo-diode measurement output; k is the discrete time; n is the order of the system; m and l is the dimension of the input and output signal utilized for identification.

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In AFM system dynamics identification, the input signal is chosen to be a band-limited noise to excite the working frequency and the output signal is the photodiode voltage. Both of the signals are of one dimension. After acquiring plenty of experimental data, the numerical subspace state- space identification algorithm (N4SID) [11] is employed to the unknown parameter A, B, C, and D.

III. EXPERIMENTAL SETUP

All experiments are performed on an AFM system produced by Benyuan Nano-Instruments. The measurement setup for acquiring input and output data is shown in Fig. 1. A target PC equipped with DAQ card (ADLink) is developed to obtain the photo-diode output data, for which the RTLinux operating system is adopted to ensure real-time data-collecting. The AD/DA resolution is 16 bits, which ensures nano-resolution for a piezo-tube of a range of several tens of micrometers. Besides, a PI algorithm based controller is implemented based on this structure to identify the system static gains in closed loop. The typical sampling time is 50us, which is usually adequate for slow scanning over samples.

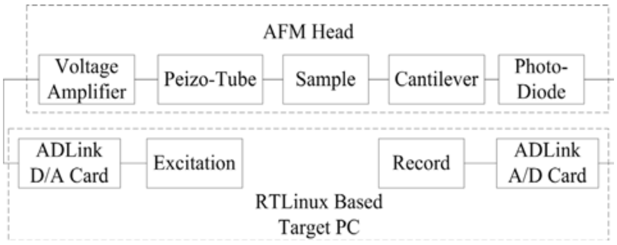

Figure 1. Measurement Experimental Setup.

IV. DYNAMICS MODELING OF AFM SYSTEM

The dynamical model of the AFM system in Z-axis is obtained by the black-box identification scheme. The excitation signal of the piezo-tube and the photo-diode signal are considered as input-output of the system. Turning off the control loop in Z-axis, the dynamics of the system can be obtained from experimental data.

During the experiments, a mica sample is utilized since it has extremely hard surface, and it can be easily cleaned by striping the outer layer. Besides, the evenness of mica surface can decrease the effect of piezo-drift in x-y plane to a large extent. The excitation input and the photo-diode output is recorded simultaneously by the aforementioned RTLinux-based DAC system (Fig.2). Wherein, the excitation signal of band-limited white noise is applied to the piezo-actuator when the cantilever-tip is in contact with the sample. The amplitude of the signal is about 600 mv to guarantee that the system is working in the linear regime.

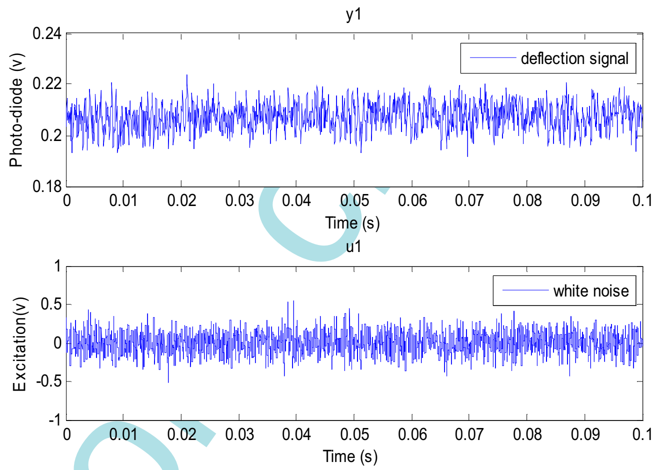

Figure 2. Part of the input and output data used for identification.

After collecting sufficient data, a sixth-order linear model (after changing the discrete state space model to a 'Z' transfer function) for the AFM is obtained by employing N4SID algorithm based on the input-output data analysis, whose bode-diagram is shown in Fig.3. To test the performance of the model, another white noise signal is applied to the actuator, and the photo-diode voltage is recorded and then compared with the model predication output. As shown in Fig.4, the comparison exhibits excellent consistence except marginal mismatch. The maximum error is about 0.05v and the average match ratio is about 89%.

$$G(z)=\frac{-0.00011z^4+0.001512z^3+0.01062z^2+0.01057z-0.0008574}{z^5-0.9979z^4-0.6761z^3+0.6541z^2+0.5269z-0.3975}$$

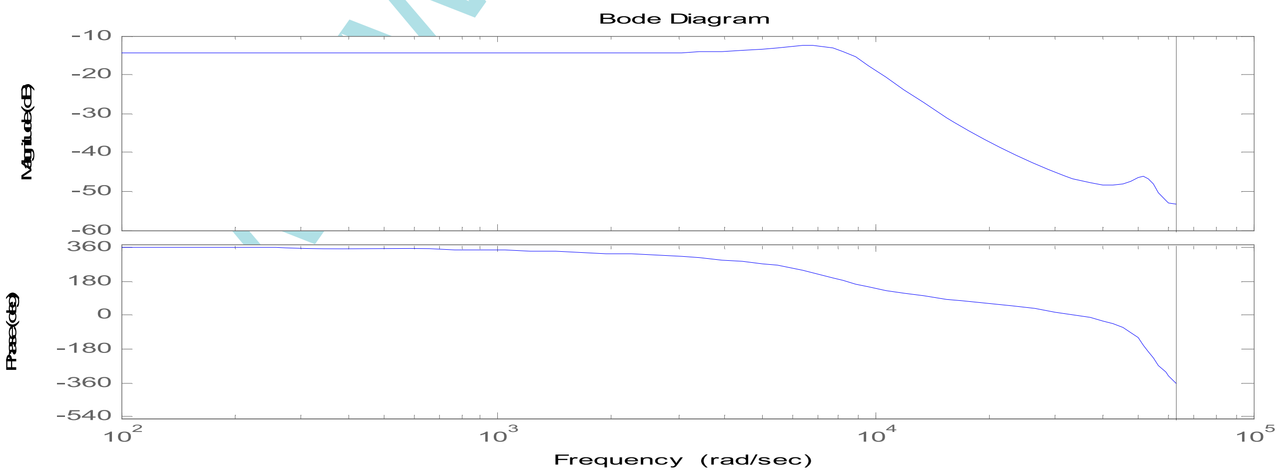

Figure 3. The bode diagram of the dynamical model

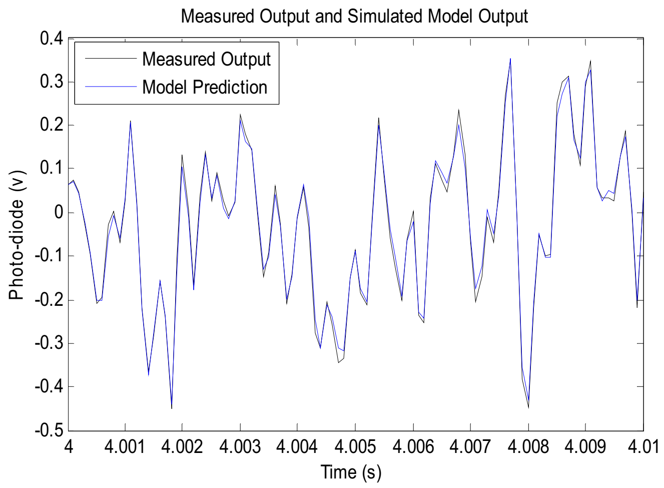

Figure 4. Dynamical model validation. The sampling time is 50us.

V. CALIBRATION OF STATIC GAINS OF AFM SYSTEM

The static gain of the photo-diode is defined as the ratio between the photo-diode output voltage and the cantilever deflection. To obtain this gain, Z-axis calibration gratings (MicroMasch Inc., USA) are scanned slowly with the Z-axis control signal completely turned off, in this case, the tip is supposed to trace the up-downs of the gratings and the cantilever deflection can be regarded as the calibrated height of the gratings since the piezo drift can be ignored. The corresponding photo-diode output is recorded. The variation of the photo-diode voltage is 0.45v for a grating with nominal value of 100nm (Fig.5), and 1.35v versus a 278nm grating. After integration of a large mount of experimental data, the static gain is finally determined as 214nm/v.

The static gain of the piezo-tube in Z-axis is defined as the corresponding photo-diode output voltage induced by the cantilever deflection. Two methods are utilized to determine this parameter: 1) A step excitation is applied to the piezo-scanner in Z-axis with control signal turned off. In our experiment, the photo-diode is about 0.36v corresponding to 1v excitation signal. Therefore, based on the static gain of the photo-diode, the static gain of the piezo-scanner can be calculated as

$$214nm/v*0.36v=77nm.$$

2) Gratings with nominal value of 100nm is scanned slowly with the feedback on. In this case, the photo-diode error signal is extremely small; hence, the static gain can be directly calculated from the control voltage. After plenty of data analysis, the control signal is taken as 1.28v corresponding with a 100nm grating (Fig.6). Therefore, the static gain can be determined as:

$$100/1.28v=78nm/v.$$

It is obvious that the results obtained from the two methods are almost identical. Finally, the dynamics and the static gains are combined to obtain a complete model of the AFM system.

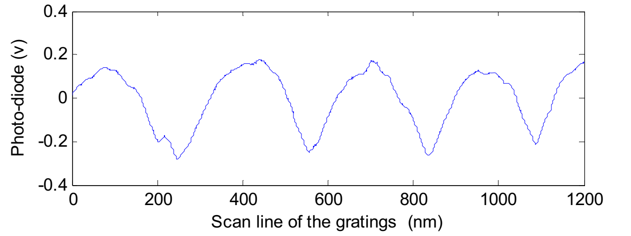

Figure 5. Photo-diode output of scanning 100nm gratings in open loop

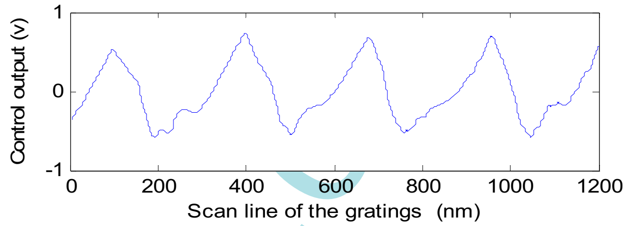

Figure 6. Control output of scanning 100nm gratings in closed loop

VI. RESULTS AND DISCUSION

A. The precision of the complete model

The complete model is composed of two parts: the dynamic part and the static gains of the AFM system. After combining both of the parts, a complete model is obtained. The step response of the AFM system is measured to validate the complete model. A step excitation is applied to the amplification of the piezo-tube and the corresponding photo-diode voltage is recorded. The comparison of the experimental data with the simulation results is shown in Fig.7. It can be seen from the figure that the predication matches the measurement except that the measured step response exhibits some higher order dynamics.

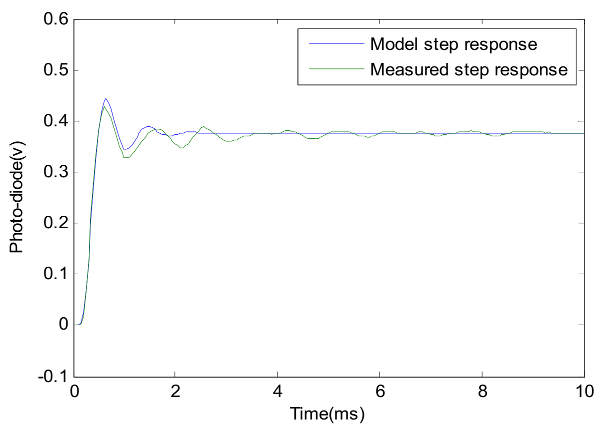

Figure 7. Comparison of the measured step response and model prediction

B. *Model Dependence on the Experimental Setup*

The cantilever of the AFM system has to be changed very frequently due to the regular damage. Therefore, the initial state of the system often varies slightly. In this study, the dependence of the model on the experimental setup is also examined. The model obtained is utilized to predict the system dynamical behavior after changing the cantilever. The comparison is shown in Fig.8 which demonstrates that the model still captures the main dynamics of the system.

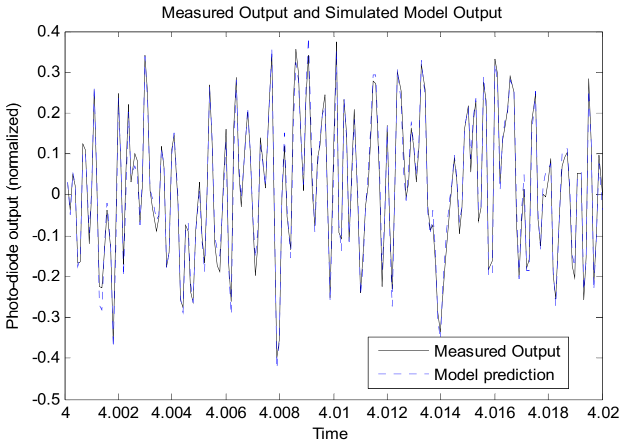

Figure 8. Comparison of the measured response after changing the cantilever and model prediction

Besides, the piezo-tube usually has to be changed on the demand of different scan scope and precision. In our experiments, two different kinds of piezo-tube are utilized. It is obvious that due to their different static gains, the models of the system with different kinds of piezo-tube vary. It is also found out that the main system response time is caused by finite retraction/protraction velocity of the piezo-actuator.

VII. Conclusion

Developing intelligent and autonomous AFM requires modeling of the AFM system in Z-axis. However, most of the previously derived models involve complex physical or mathematical analysis, and many parameters need to be identified, thus hindering its actual application for controller development. This paper proposes an experimental method for modeling AFM system in Z-axis. The model is composed of dynamical part and static gains. The step response of the AFM open loop demonstrates that the model determined from experiment is comparatively precise. Besides, the model variation is neglectable if another kind of cantilever is replaced with the former one only if the piezo-tube is the same. Those characteristics make the model extremely suitable for sophisticated controller design. Future work will focus on intelligent and robust control of the system based on the obtained model.

References

[1] Franz J. Giessibl, “Advances in atomic force microscopy,” Reviews of Modern Physics, vol. 75, pp. 949-983, July 2003.

[2] Q. Zou, K. K. Leang, E. Sadoun, M. J. Reed, and S. Devasia, Control issues in high-speed AFM for biological applications: collagen imaging example [J], *Asian J. Control*, vol. 6, no. 2, pp. 164–178, Jun. 2004.

[3] D.Croft, G. Shedd, and S.Devasia, Creep, hysteresis, and vibration compensation for piezoactuators: Atomic force microscopy application [J]. ASME Journal of Dynamic Systems, Measurement and Control, 2001, vol.123 (35):35–43.

[4] G Schitter, Karl J. Astrom, Barry DeMartine, and G.E. Fantner, “Design and modeling of a hign-speed scanner for atomic force microscopy,” *Proceedings of the 2006 American Control Conference*, pp.502-507.

[5] M.Sitti, “Micro- and nano-scale robotics”, Proceedings of American Control Conference, 2004,pp.1-8.

[6] Su-Hau Hsu, and Li-Chen Fu, “Robust output high-gain feedback controllers for the atomic force microscope under high data smpling rate,” *Proceedings of the 1999 IEEE International Conference on Control Applications*, 1999, pp. 1626-1631

[7] S. I. Lee, W. Howell, A. Raman, and R. Reifenberger, “Nonlinear dynamics of microcantilevers in tapping mode atomic force microscopy: comparison between theory and experiment ,” PHYSICAL REVIEW B 66, 115409 ,2002.

[8] Osamah M.EI Rifai, and Kamal Youcef-Toumi,Design and control of atomic force microscopes, American Control Conference, 2003, pp.3714-3719.

[9] Szuchi Tien, Qingze Zou, and S.Devasia, “Control of Dynamics-Coupling Effects in Piezo-Actuator for High-Speed AFM Operation”, Proceedings of American Control Conference, 2004,pp.3116-3121.

[10] A.Sebastian, M.V.Slapaka, and J.P.Cleverland, “Robust Control Approach to Atomic Force Microscopy”, Proceedings of Conference on Decision and Control , 2003, pp.3116-3121.

[11] Peter Van O, Bart DeM, N4SID: Subspace Algorithms for the Identification of Combined Deterministic-Stochastic System [J]. Automatica, 1994, 30 (1) : 75- 93.