Creep in Piezoelectric Scanners of Atomic Force Microscopes

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Abstract

Piezoelectric actuators exhibit creep during open loop operation. Two models for creep, namely, a logarithmic and a LTI model, were presented and discussed. The LTI model was found to be more appropriate in predicting creep. A $3rd$ order LTI filter was used to compensate for creep in an AFM piezoelectric scanner. The performance of the filter was tested by imaging 530 and $1590\,nm$ steps. With compensation, the creep response was reduced to 2.6 %, compared to 9.6 % without compensation, for images taken over 6.67 minutes. Closed loop operation can offer better creep compensation but is a more expensive option. Moreover, it reduces image resolution for small scans/sample features due to limited dynamic range of sensors at high bandwidth.

1 Introduction

Piezoelectric actuators are commonly used in high-precision positioning systems. They can provide sub-nanometer displacement and achieve a high-bandwidth. As a result, high-precision instruments like atomic force microscopes (AFM), and more generally scanning probe microscopes (SPM), use piezoelectric actuators. An AFM has three main components, Fig. 1, a piezoelectric scanner, a cantilever with a sharp probe , and a cantilever deflection sensor comprised of a laser source and a position sensitive diode (PSD). The scanner provides relative motion between a sample and the probe. One of the main operating modes of AFM is contact mode. In this mode, the probe presses against the sample, exerting a vertical force proportional to the cantilever deflection. The probe scans the sample in a raster fashion, while the angle of the cantilever's free-end is measured and fed back. A control system is used to maintain a constant angle (force), by adjusting the vertical displacement of the scanner. Changes in the scanner displacement are therefore, related to changes in the sample topography. However, piezoelectric actuators suffer from several draw backs among them is creep, [1]. Creep can be seen as a slow drift in the actuator displacement after responding to a sudden change in the input voltage. This degrades repeatability of AFM data.

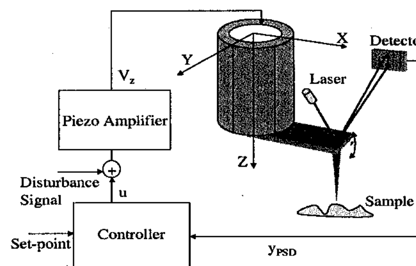

Figure 1: Schematic diagram of AFM main components.

In section 2, models for creep will be presented. Section 3, presents model validation against experimental data. Results on compensation for creep in AFM images is presented and discussed in section 4. A discussion on open loop vs. closed loop operation of AFM is given in section 5. Finally, concluding remarks are presented in section 6.

2 Creep Modeling

The response of a piezoelectric actuator to a rapid change in input voltage, Fig. 2, consists of two main parts. The initial part of the response occurs over a time scale dictated by the mechanical resonance of the actuator. This is followed by a slow creeping response occuring over $10's$ of seconds and amounting to as much as 20 % of the total response. The rate and amount of creep, strongly depend on the piezoelectric material. Two models for creep will be presented, namely, a logarithmic model and a finite-dimension linear time-invariant(LTI), model.

When creep response is plotted verses time on a logarithmic scale, it appears to be linear. Therefore, a common equation, [2, 3], to model creep is,

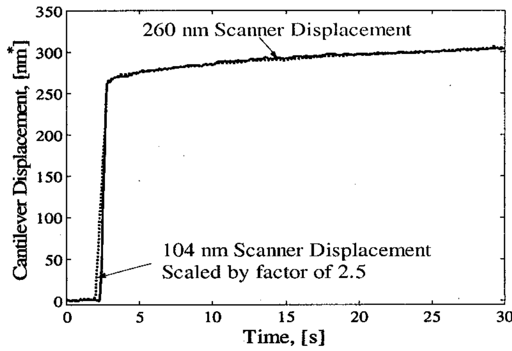

Figure 2: Experimental creep response: Linearity of response.

$$z(t) = z_o[1 + \gamma \, log_{10}(\frac{t}{t_o})] \quad (1)$$

where, $z(t)$ is the actuator displacement, z_o is the nominal fast displacement to the applied voltage, γ is a constant controlling the rate of creep, and t_o is the time after which creep response is considered to occur, i.e. after the fast dynamics response has occured.

Experimental frequency response of piezoelectric actuators displays very little variation in phase at low frequency between input voltage and displacement. On the other hand, a slight decrease in gain is observed with increased frequency. It is possible to simulate creep behavior using a suitable LTI model. The transfer function between the input voltage and actuator displacement should have a relative degree zero at frequencies much lower than the actuator's resonance frequency. The relative degree is defined as the number of poles minus the number of zeros. Both models, however, assume that the ratio between the amount of creep and the fast scanner displacement is independent of input amplitude. The assumption will be experimentally tested.

3 Model Validation

A commercial AFM was used to measure the creep response of its piezoelectric scanner. The AFM probe was brought into contact with a hard sample (Glass sample), while in open loop. Commanding the scanner to move up/down in the Z-direction, changes the PSD signal accordingly. This signal shows the scanner response including creep. However, the measured PSD signal could also change due to response of the AFM structure or scanner to variations in the environment temperature, and/or mechanical vibrations. More so, variations in the laser source output, heating of the cantilever by the laser source, cantilever bending due to thermal gradient between the probe and sample, relaxation in probe-sample contact, and/or drift in the drive or sensing electronics can affect the PSD output. All these factors are considered sources of noise in the creep data. To minimized their effect on measurement and obtain a good signal-to-noise ratio, the AFM was placed inside an environmental and vibration isolation chamber. The system was given enough time to reach an equilibrium state, before data collection. A thermocouple measuring the Air temperature inside the chamber was used to recored the extremum temperatures during the experiments. Typical temperature fluctuation was 0.4^oC over the duration of an experiment, $30 - 40$ minutes. The choice of cantilever was dictated by a trade-off between sensitivity and noise. A low stiffness gives a high displacement sensitivity and a small probe-sample force. This results in nonlinear material behavior of the sample is not observed in the measurements. On the other hand, cantilever stiffness should not be too low causing reduced resolution by increasing cantilever displacement response to thermal noise. Another concern is the choice of nominal cantilever deflection (PSD signal). The cantilever deflection vs. scanner displacement curve can exhibit nonlinear behavior hence degrading the linearity of the measurements. The selected nominal deflections and operating range during experiments were chosen to be within the mostly linear part of the curve. In addition, the input voltage V_z, was chosen to be small enough to ensure good linearity in scanner displacement. The excitation signals consisted of steps and ramp signals that are saturated in amplitude. The rate of ramp signal was varied to study the effect of input rate on creep response. The PSD signal was recorded before the scanner is excited to measure total instrument drift (noise). During the experiments, the scanner was commanded to move down a certain displacement. After several minutes it was commanded to move the same displacement up. Both data were combined and averaged to cancel the effect of drift in the PSD signal.

Two Silicon cantilevers were used for these experiments. A cantilever with nominal stiffness of $0.03\,N/m$ that had an equivalent displacement noise of $14\,\mathring{A}\,rms$ and $7\,nm$ peak-to-peak at $100\,Hz$. The second cantilever had a nominal stiffness of $0.2\,N/m$ and an equivalent displacement noise of $5.1\,\mathring{A}\,rms$ and $3.5\,nm$ peak-to-peak at $100\,Hz$. A typical scan requires $2-5$ minutes to complete, depending on scan rate and image resolution. Ideally, this is how long we need to characterize scanner creep for. Instrument drift of $1.4\,\mathring{A}/s$ was typically. Data collection was limited to a maximum of 3 minutes to ensure reliable data.

To test the linearity of creep response, different voltage ramp signals with different saturated amplitudes were used. All signals had the same ramping rate of $1\,V/s$, hence, ramping time was different for each input. The amplitudes were chosen to be small enough such that the nonlinearity in the scanner fast response would not

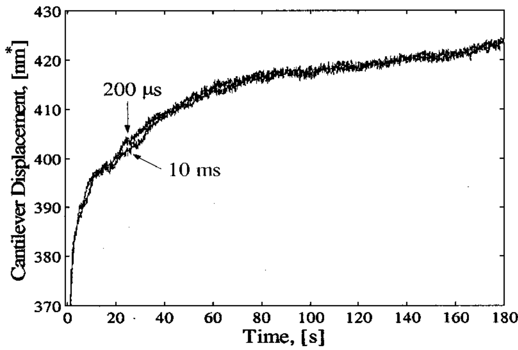

Figure 3: Creep response to inputs with different rates.

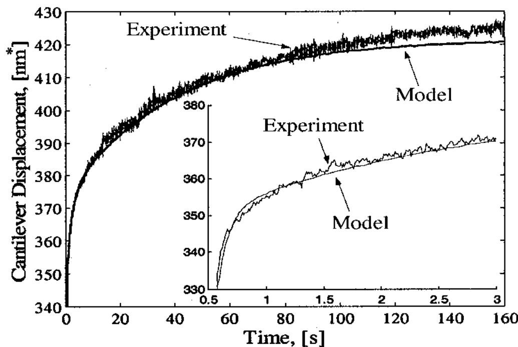

Figure 4: LTI creep model fitted to experimental response: insert shows a zoom on initial part of response.

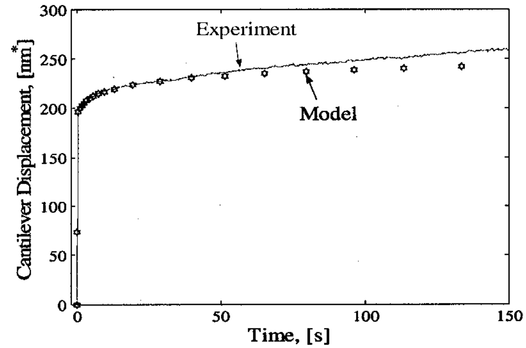

Figure 5: Logarithmic creep model fitted to experimental response.

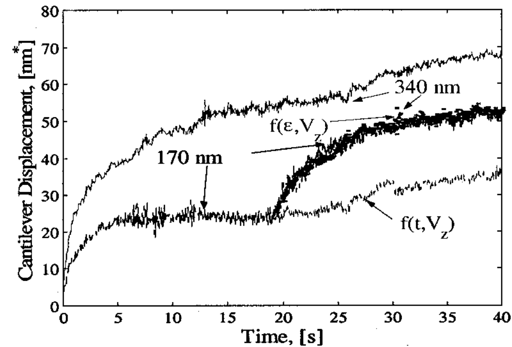

Figure 6: Creep response comparison between a single $340\,nm$ step and two $170\,nm$ steps.

be a concern. The results are shown in Fig. 2, where the cantilever response to a $260\,nm$ scanner displacement is compared with the response to a $104\,nm$ which has been scaled by a factor of $\frac{260}{104} = 2.5$. The Figure shows the good linearity of the response. This tends to suggest that the creep part of the response tends to scale linearly with the fast response. Therefore, a linear model of creep may be justified. The nonlinearity in the fast scanner displacement could be accounted for separately. Figure 3, display the creep response for two ramp inputs of the same saturated amplitude but ramped over $200\,\mu s$ and $10\,ms$. The response does not show any dependence of creep rate on input rate.

Figures 4 and 5 show the response of the LTI and logarithmic models, respectively. The parameter values for the logarithmic model are, $\gamma = 0.12$, and $t_o = 0.18\,s$. A $3rd$ order LTI model was used with poles at $3.98\,mHz$, $79.57\,mHz$, and $1.59\,Hz$ and zeros at $4.48\,mHz$, $84.79\,mHz$, and $1.71\,Hz$. Both models reproduced the creep response reasonably well. The fit for both models degraded at larger times. The fit can be improved by increasing the order for the LTI model or adding more terms of different rates in the logarithmic model.

A model used to predict and compensate for creep in AFM has to be able to reproduce creep behavior under excitations typical during operation. The input signals for lateral motion (scanning), are a triangular wave, not necessarily with a linear slope, and a ramp for the fast and slow scan directions, respectively. The model fitting can be optimized specifically for these signals, yielding good agreement with actual response. The Z input voltage depends on sample topography and is not known a priori. Hence, a creep model for the Z-direction scanner displacement has to be capable of reproducing scanner creep not only for a prescribed input signal.

Both models presented displayed ability to closely predict creep response for a step-like input. However, the structure of the models is quite different. In the logarithmic model, the strain rate of the scanner (or velocity) is assumed to be an explicit function of time $\frac{d\epsilon}{dt} = f(t, V)$, suggesting that the scanner is a non-autonomous system. In contrast to the LTI model, $\frac{d\epsilon}{dt} = f(\epsilon, V)$, which is time-invariant (autonomous). Physically the scanner response depends on the input voltage history and the state of strain of the scanner. To portray this graphically, two experiments were performed. In the first experiment, the scanner was stepped by $340\,nm$, and the PSD signal was recorded. In the second experiment, the scanner was stepped by half the displacement of the first experiment $170\,nm$ at

time zero. After 19 s, it was stepped by an additional 170 nm. The creep part of the response is shown in Fig. 6, for both experiments. The logarithmic model would predict, for the second 170 nm step, the curve labeled $f(t, V)$ which is the portion of the 340 nm curve after $t = 19\,s$. This prediction does not match the actual response. The LTI model prediction labeled as $f(\epsilon, V)$ matches the actual response well. It was obtained using the portion of the 340 nm curve starting at 24 nm. Hence, demonstrating that the creep response depends on the input and state of strain of the scanner and not explicitly on time.

Note that creep is also a function of temperature as the sensitivity of the scanner is. It is assumed however, that AFM would be operated in an environment where temperature fluctuations are not large. Otherwise, obtaining reliable measurements will be difficult.

4 Creep Compensation

It has been shown that the LTI model is more suitable for predicting creep response. To compensate for creep, the model was inverted and a pole at 10 kHz was augmented to the inverse filter to limit exciting high-frequency system modes. The filter was placed in series with the controller. To test the performance of the filter, two silicon Steps were imaged using different cantilevers than the ones used for collecting the creep data.

4.1 530 nm Steps

A Silicon Nitride cantilever with nominal stiffness of 0.37 N/m, a triangular cross section, and resonance frequency of 20kHz was used for results in Fig.'s 7-9. It shows image of 530 nm ± 1.5 nm Silicon steps scanned at 2.8 $\mu m/s$ with and without creep compensation. The side walls of the steps appear to have different angles due to convolution errors. The probe was tilted with respect to the sample, hence, one side of the steps is imaged by the probe's side wall instead of its tip. As a result, one side of the sample appears to the feedback system as a ramp disturbance, while the other could closely approximate a step disturbance. This allows us to examine the effect of the rate of disturbance on the image and compensation effectiveness. The image is created from the closed loop scanner input voltage responding to changes in sample topography (disturbance). The linear model of the system has zeros making the response dependant on the disturbance rate in addition to amplitude. This explains why the amount of creep at the top of the steps are different than at the bottom.

Without compensation, there is creep of 30 nm (5.7 % of step height), at the bottom of the step over 0.26 s.

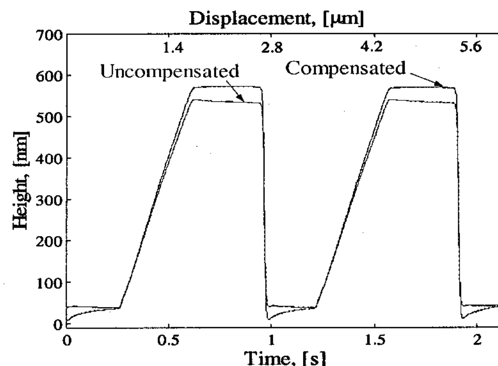

Figure 7: AFM image of 530 nm Silicon steps, with and without creep compensation, 2.8 $\mu m/s$.

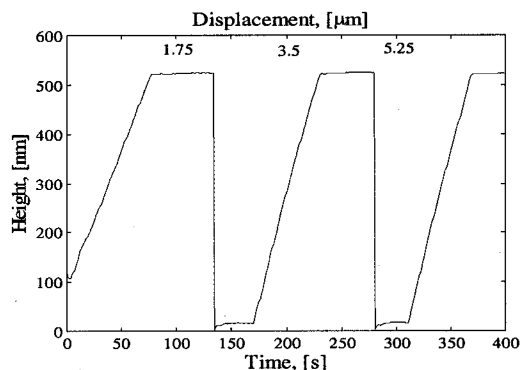

Figure 8: AFM image of 530 nm Silicon steps, with creep compensation, 17.5 nm/s.

With compensation this reduces to 4.5 nm (0.85 % of step height). At the top, creep is 2.2 nm(0.4 %) and 9.5 nm(1.8 %) over 0.22 s with and without compensation, respectively. Figures 8 and 9, show the image at a very slow scan speed of 17.5 nm/s with and without creep compensation. Without compensation, creep of 14.1 nm (3.1 %) over 35 s and 48.5 nm (10.1 %) over 35 s at top and bottom, respectively. With compensation, this reduces to 2.9 nm (0.57 %) over 50 s and 13.7 nm (2.6 %) over 35 s. The compensation, has dramatically reduced the effect of creep. However, as seen in Fig. 4, there is as much as 5 nm error between the model and experiment during the first second of the creep response. As a result, Fig. 8, there are peaks just after the steeper-looking side wall of the sample that was not well compensated for.

4.2 1590 nm Steps

In Fig. 10, an image of 1590 nm±1.5 nm steps is shown for a scan speed of 10 $\mu m/s$. The measured height is 1495 nm due to nonlinearity of scanner displacement (6 % nonlinearity). Creep at top and bottom of steps, with compensation, is 6 (0.4 %) and 8.3 nm (0.56 %) over 0.5 s. At a much slower scan speed of 41.67 nm/s, Fig.'s 11 and 12, images are shown with and without

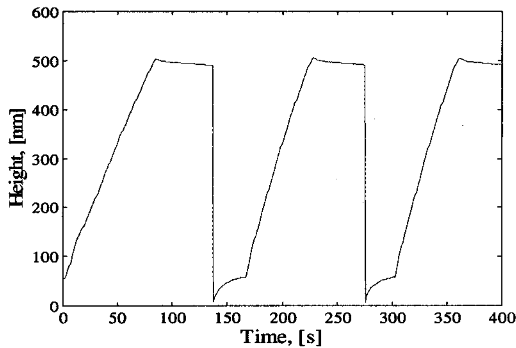

Figure 9: AFM image of 530 nm Silicon steps, without creep compensation, 17.5 nm/s.

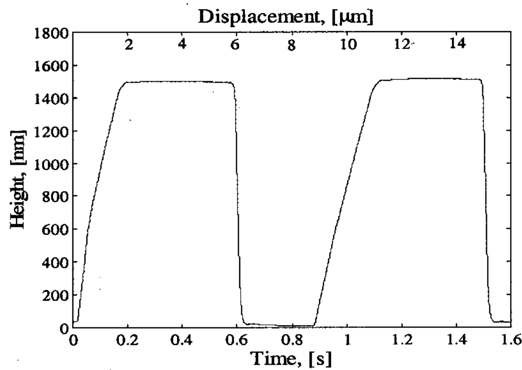

Figure 10: AFM image of 1590 nm Silicon steps, with creep compensation, 10 $\mu m/s$.

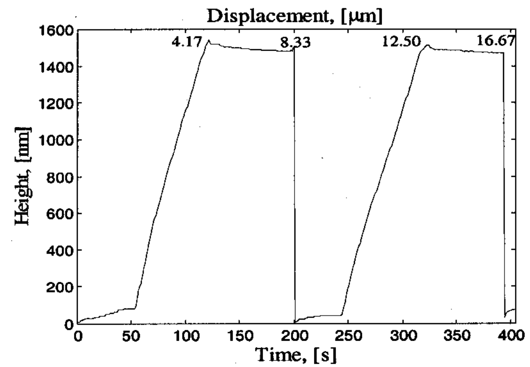

Figure 11: AFM image of 1590 nm Silicon steps, with creep compensation, 41.67 nm/s.

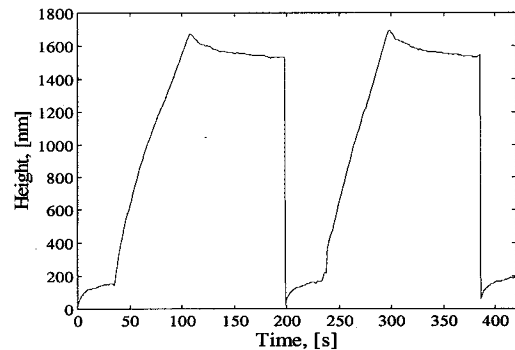

Figure 12: AFM image of 1590 nm Silicon steps, without creep compensation, 41.67 nm/s.

compensation. Un-compensated images show creep of 135 nm (9 %) and 143 nm (9.6 %) at top and bottom of steps. Compensated images show 35 nm (2.4%) and 41.6 nm (2.8%) of creep. Note that the compensation did not degrade because of the larger sample height. This again suggests that the assumption of linearity in creep response is reasonable.

5 Open Loop vs. Closed Loop

We have shown one method to compensate for scanner creep when operated, as it is commonly, without measuring scanner displacement. An inverse filter can provide inexpensive method of compensation. However, its performance will strongly depend on the quality of creep data, the order of the filter, and fitting algorithm. Obtaining reliable creep data for long time proved to be a difficult task especially for the common AFM user. In addition, the order of the model would grow if good short and long time compensation is desired. Another compensation alternative, is to sense the scanner displacement in the Z-direction and use that signal to create the sample image. This would virtually remove the effect of creep on the image. Many displacement sensing technologies, e.g. capacitive, inductive, optical, can provide short term stability of 100 $ppm/^oC$. For a 4 μm scanner like the one used in this study and a temperature change of 1^oC during experiments, sensor drift of 4 $\AA$ is expected. This is superior and more reliable than the results of the filter. However, it is far more expensive. In addition, most sensors do not have large dynamic range at high bandwidth. As a result noise performance is worse than open loop operation especially for small scans or when scanning samples with small features (few nanometers).

6 Conclusion

Piezoelectric actuators exhibit creep during open loop operation. Two models for creep, namely, a logarithmic and a LTI model, were presented and discussed. The LTI model was found to be more appropriate in predicting creep. A $3rd$ order LTI filter was used to compensate for creep in an AFM piezoelectric scanner. The performance of the filter was tested by imaging 530 and 1590 nm steps. With compensation, the creep response was reduced to 2.6 %, compared to 9.6 % without compensation, for images taken over 6.67 minutes. Closed loop operation can offer better creep compen-

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