euspen's 24th International Conference &
Exhibition, Dublin, IE, June 2024
www.euspen.eu

Iterative learning control for nano-positioning stage of defect imaging equipment

Hyunchang Kim[1], Kyung-Rok Kim[1], Dongwoo Kang[1], Jaeyoung Kim[1]

[1]*Department of Flexible and Printed Electronics, Korea Institute of Machinery and Materials(KIMM), Daejeon, 34103, Republic of Korea*

hckim0128@kimm.re.kr

Abstract

In recent years, the semiconductor industry has witnessed a significant transformation in the semiconductor exposure process, with the adoption of EUV (Extreme Ultraviolet) light sources. This paradigm shift necessitates the use of EUV light sources in mask inspection equipment for exposure, demanding impeccable performance in defect imaging. To achieve these requirements, the stage components within such equipment must exhibit the capability to align the optical system and mask in parallel while precisely operating within nanometer-level tracking errors. Furthermore, these stages must function effectively in a vacuum environment. Among the various technologies available, ultra-precision stages employing piezoelectric elements is most suitable.

This research is focused on enhancing the dynamic tracking performance of the developed XY scanning stage for defect imaging. To achieve this objective, we designed a parallel compliant mechanism that effectively decouples motion along the x- and y-axes and minimizes the coupling crosstalk between these two axes. This design incorporates mechanical symmetry, resulting in nearly identical dynamics for both axes. Piezoelectric stack actuators are strategically integrated into both axes, facilitating a maximum displacement of 14.9 µm.

To realize superior tracking performance, we implemented Proportional-Integral (PI) control and iterative learning control techniques. By adapting these control strategies, we achieved an impressive tracking performance of ±5 nm (3σ) at a scan speed of 400 µm/s

Nano-positioning stage, Iterative learning control, Ultra precision, Tracking performance

1. Introduction

A nano-positioning stage represents a pivotal technological advancement widely employed across diverse fields including inspection equipment, optical systems, and atomic force microscopy (AFM) [1-3]. In a previous study [4], we proposed an ultra-precision XY stage for use in defect review imaging system. Utilizing a decoupled parallel compliant mechanism, the stage achieves similar dynamics in both x- and y-axes while minimizing coupling crosstalk. The implementation of a proportional double integral (PII) feedback control algorithm enables a tracking error performance of ±3 nm in the 20 µm/s constant velocity region, though significant error peaks persist during acceleration and deceleration. However, in order to fulfill the requirements for integration with the equipment, ±5 nm tracking performance at 400 µm/s was necessary. To address this issue, iterative learning control (ILC) is applied in this study to enhance dynamic tracking performance across the entire motion profile.

2. Design and fabrication of stage

Figure 1 illustrates the ultra-precision XY nano-positioning system utilized in this study [4]. A parallel compliant mechanism is designed to decouple motion along the x- and y-axes and minimize coupling crosstalk. The system employs piezoelectric stack actuators in both axes, providing a maximum displacement of 14.9 µm, with resulting displacements measured using capacitive sensors. Constructed from AL6065, the XY stage supports a 1.8kg payload, exhibiting a first resonant frequency of 297 Hz in the yaw direction and a translational mode frequency of 1012 Hz. The frequency response of the X-axis is experimentally measured and illustrated in Figure 2 (a). The XY stage measures 200×200×20 mm and is mounted atop a ZTilt stage, although the details of the latter are not elaborated upon as it remains fixed during XY plane scan motions.

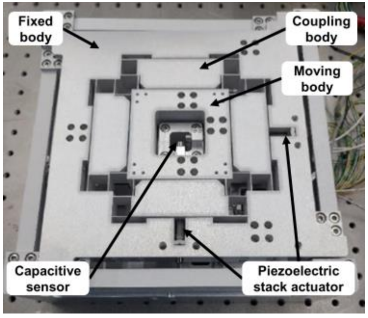

Figure 1. Fabricated nano positioning stage

3. Feedback controller design

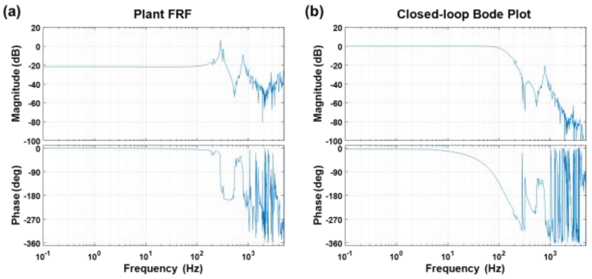

Figure 2. Frequency response measurement in X-axis(a) and Closed-loop bode plot with PI controller(b)

As shown in Figure 2(a) utilizing experimentally obtained Frequency Response Function (FRF) data, a Proportional-Integral (PI) controller is formulated through loop-shaping techniques. Preceding the PID controller design, a notch filter at 297 Hz is implemented to counteract yaw-direction resonance, followed by the application of a 200 Hz low-pass filter to diminish sensor noise interference. The PI controller is meticulously tailored to meet specific design criteria, ensuring a phase margin of ≥ 60˚, gain margin of ≥ 5 dB, and bandwidth of ≥ 50 Hz. Through loop-shaping, the PI controller gains are determined as Kp=6.242 and Ki=3804. The attained performance metrics encompass a phase margin of 60˚ at 50 Hz, a gain margin of 5.89 dB at 135 Hz, and noise attenuation of -42.5 dB at 1 kHz. The closed-loop bode plot of the implemented PI controller is depicted in Figure 2(b).

4. Stage motion profile

The proposed XY stage outlined in this study is intended for integration into a defect review imaging system, facilitating defect detection across a comprehensive area by traversing a maximum 10x10 μm square region through raster scanning. Given the symmetrical design of the X and Y axes, scanning along either axis is viable. In this investigation, scanning primarily occurs along the X-axis, with step-wise movement along the Y-axis. Figure 3(a) illustrates the plane motion, while Figure 3(b) depicts the motion profiles for both axes over one scanning cycle. The motion profile along the X-axis is characterized by an acceleration-limited S-curve. During constant velocity motion of the X-axis, the Y-axis remains stationary. Subsequently, during acceleration or deceleration phases of the X-axis, Y-axis step motion is initiated, synchronized with the acceleration phase of the acceleration-limited S-curve. The duration of the acceleration and deceleration phases for X-axis scan motion are set at 5ms.

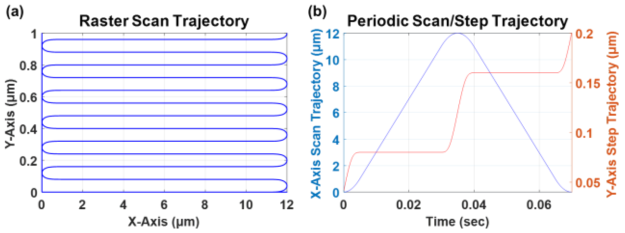

Figure 3. X, Y raster scan and motion profile for single scan period

5. Iterative learning controller design

In this paper, we introduce iterative learning control (ILC) as a method to enhance dynamic tracking performance across the entire motion profile, aiming to achieve tracking precision of ±5 nm or less throughout the scanning process and consequently reduce tac time. Derived from the concept that performance in subsequent tasks can be improved by leveraging outcomes from previous tasks, ILC focuses on attaining better transient tracking performance. The ILC control utilizes the preceding round-trip scan as the foundation for a single cycle, retaining the tracking errors encountered in both the X and Y axes from the previous scan in memory. These errors are then iteratively updated to construct a control diagram, as illustrated in Figure 4 [5,6]. The ILC input for each iteration is computed based on the error from the previous iteration stored in memory and is adjusted by modifying the loop gain L and Q filter. This resulting ILC input is then added before the PI controller, following an 'input injection method'[6]. Additionally, alongside the designed PI controller, ILC logic is implemented in parallel.

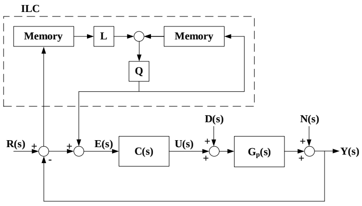

Figure 4. Control block diagram (PI + ILC)

6. Experimental Verification

An experiment is conducted to evaluate the tracking performance of the designed PI controller. A motion profile is generated with an 400 μm/s constant maximum speed and a 10 μm constant velocity region in the X-axis, along with an 80 nm grid for the Y-axis. The tracking error for this scenario is depicted in Figure 5. With an acceleration time set to 5 ms, the experimental results reveal notable findings. Along the step axis (Y), the controller demonstrates some degree of tracking during the constant speed segment but exhibits an offset error, alongside significant tracking errors in the acceleration and deceleration phases. Conversely, on the scan axis (X), the controller showcases substantial tracking errors throughout, including during the constant speed segment, rendering the attainment of a target tracking error unfeasible solely with the PI controller.

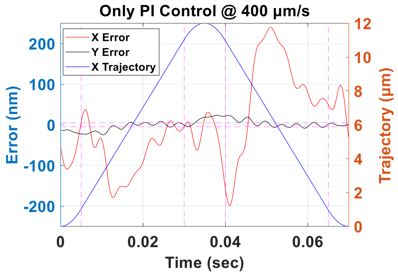

Figure 5. Tracking error with only PI controller

Subsequent tracking experiments are conducted using the same motion profile as in the case of the PI controller alone, with results shown in Figure 6. Through the application of ILC, tracking errors of ±5 nm or less are achieved across the entire scanning area, significantly reducing 3-sigma errors to 4 nm for the X-axis and 3 nm for the Y-axis.

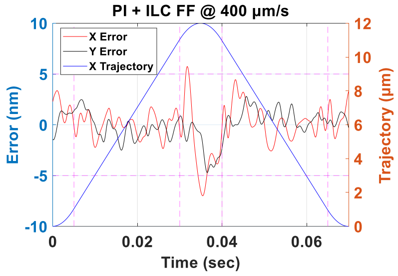

Figure 6. Tracking error with ILC + PI controller

7. Conclusion

It was confirmed that as the iterations progress through iterative learning control (ILC) when the same motion is repeated, the motion tracking performance can be improved.

It was observed that solely applying PI control resulted in a tracking error of ±250 nm during the constant speed section. However, when PI control was combined with ILC, the tracking error reduced significantly to ±5 nm under identical conditions. In the future, it is intended to theoretically and experimentally validate the performance based on various applied ILC methods.

References

[1] Gu L, Li X, Bao H, Liu B, Wang Y, Liu M, Yang Z, Cheng B 2006 *J. Micromech. Microeng* **16** 1349

[2] Schitter G, Astrom KJ, DeMartini BE, Thurner PJ, Turner KL, Hansma PK 2007 *IEEE Trans. Control Syst. Technol.* **15** 906-915

[3] Ru C, Liu X, Sun Y 2016 2016 *J. J. Springer Cham* 295-324

[4] Kim J, Kang D, Kim KR, Kim H 2021 *IEEE Access* **9** 88931-88941

[5] Bristow DA, Tharayil M, Alleyne AG 2006 *IEEE Control Systems Magazine* **26** 96-114

[6] Fine BT, Mishra S, Tomizuka M, 2009 *American Control Conference* 931-936