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Nanopositioning and Nonlinearity Compensation for Step Imprint Lithography Tool

Abstract In this paper, the motion mode and nanopositioning accuracy in the step imprinting lithography process are presented, and the positioning errors different from the traditional errors, such as the gap error existing in the hinges of the stage structure and the random error produced during the process of the stage position adjustment, are analyzed. To avoid and eliminate these nonlinearity errors, radial basis function–proportional integral derivative and position control algorithms are introduced into the macro- and microdriving processes, respectively. The innovation of this driving method is that the motion locus is monotone, nonoscillatory, and a multistep approaching target, which eliminates the root of the random error by single direction driving mode and avoids the backlash error through preloading function. Driving experiments of different motion ranges prove that this nonlinearity compensation is very effective and the positioning accuracy during the step imprinting process can be improved up to 10 nm.

Keywords step imprint lithography, tool, nanopositioning

1 Introduction

When the feature size of a lithography pattern is down to sub-100 nm, the traditional technology, such as photolithography, being developed is distinct because of the diffracting limitation [1,2]. Nontraditional patterning technologies, such as imprint lithography, soft lithography, capillary force lithography, and others, with a wide area of applicability than lithographies do based on x-ray, ion beam, maskless, electron beam, and scanning proximal probes, have been explored in the recent years [3–6]. Especially in imprint lithography, experimental result has shown that a feature size down to 6 nm can be patterned [7–9]. One of the key techniques in the imprint lithography process is the nanoscale driving and positioning—it is the precondition of the step imprint and the overlay alignment lithography. In the recent reports of the nanopositioning research, Sakuta et al. [10] developed a dual-servo mechanism composed of a friction drive and a piezoelectric (PZT) actuator. The PZT actuator was mounted on the friction drive slide, and the positioning system was controlled using a special inchworm movement method. Lee and Kim [11] developed a dual-servo stage mechanism composed of a three-degree of freedom (DOF) linear motor-driven coarse adjustment stage and a three-DOF, PZT-actuated fine motion stage, where the mechanism was controlled by a proportional-integral-derivative (PID) scheme. Thus, due to different purposes, the structure of the position system is different, the driving and positioning method is different, and the kinds of errors coming from the structure and controlling method are also different. In this paper, a novel step imprint lithography (SIL) prototype machine is developed, and for the purpose of the large traveling range and nanometer positioning accuracy, an ultra precision positioning system, including a coarse stage and a fine stage, has been designed and used in this system. In addition, several simple flexure hinges were used to support the fine stage and became the connector between the coarse stage and the fine stage at the same time. The system was controlled with a dual-servo control loop algorithm, and nanometer movement over a large range was implemented. Based on this special design of the SIL tool structure, the nonlinearity positioning errors caused during the imprinting process have their own distinctiveness. Thus, considering how to eliminate and avoid these errors, the system structure, the system motion mode, the root of the positioning errors, and the controlling method must be analyzed and reestablished. The purpose of this research is to successfully apply the developed method to the practical positioning system and prove this method to be capable of compensating the nonlinearity errors properly.
2 Motion errors of SIL stage

When the feature size of the transferring pattern is below 0.1 μm, the positioning accuracy should be 20 nm or better to match the need of the overlay imprinting lithography. To satisfy the requirement, the system must have the ability to travel a large range and position with nanoscale accuracy at the same time, but this is a conflict. Thus, designing an adaptable tool is very necessary. Figure 1 is an image of an SIL-prototype machine developed by the Institute of Advanced Manufacturing Technology (IAMT) of Xi’an Jiaotong University, which includes a pressing system, stage, flexure hinge support, macro- and microdriving system, and laser interferometer alignment system. A single macrodriving system can achieve 150 mm traveling range with 1 μm positioning accuracy, and a single microdriving system can reach 1 nm positioning accuracy with a 30-μm motion range. It seems that this driving combination has prevented the abovementioned conflict, but in the actual driving experiments, the positioning error has always reached the micron scale and even more, but not in one direction. Is the SIL positioning structure or the driving method invalid and not adaptable to the needs of nanoscale positioning? Of course, there is no evidence to that. To solve this problem, finding the root of the errors is the first step. Through analyzing the SIL tool, three factors may be the main causes and ought to be considered: (1) the gap between the flexure hinge and the stage, (2) the backlash of the macroactuator, and (3) the control algorithm. Comprehensively analyzing these three factors, the motion process of the SIL stage is the direct cause of the positioning errors. Thus, deeply analyzing the motion process and confirming the correct motion mode are the preconditions of finding the cause of the nonlinearity errors.

Stage motion controlling mode includes the confirmation of the control algorithm and the controlled object model. As shown in Fig. 1, the connectors between the coarse and fine stages are three flexure hinges; it is an efficient method and has no any friction and gap in the hinge while it is bent [12]. Although during the stage motion process there is a gap in the joint place between the stage and hinges, considering its nondeterminacy, the hinges and the stage briefly look the same at first. This method can simplify the problem and can get the controlling model of all the stages. Of course, the nonlinearity errors of the gap and the friction in the joint of the hinges will influence the positioning accuracy, but they can be avoided and compensated through the next optimizing method. Figure 2 is the structure of the flexure hinge, where is the radius of the half circle of the semicircular notched hinge and is the thickness. Its dynamics analysis is as follows:

The bending stiffness of the hinge is formulated as Eq. (1), where is the Young’s modulus of flexure material [12,13]:

\[ k_B = \frac{E t^3/2}{20R^{1/2}} \]  

(1)

The multiple hinges as shown in Fig. 1 are designed to give a symmetrical structure and little parasitic motion. The direction motion is driven by one PZT, while the -direction and yaw motions are driven by two PZTs. Based on the design of the hinges’ structures, can be converted into two PZT displacements. Then, the motion of three DOFs can be converted into the displacement of three PZTs. The total elastic energy of the fine stage becomes the sum of the elastic energy of the hinges. In different orientations, the total elastic energy of the stage is expressed as in Eq. (2), where is the effective length between the macro- and microstage and is the number of the hinges:

\[ U = \sum_{i=1}^{n} \frac{1}{2} k_B \left( \frac{d_i}{L} \right)^2 \]  

(2)

The total kinetic energy of the stage along the , , or direction is expressed as Eq. (3), where and are the velocity and acceleration, respectively, of the stage along the direction, and is the moment of inertia of the body of the flexure hinge with respect to the center of the flexure body. is expressed as Eq. (4), where is the mass of the stage, is the mass of the flexure hinge, and is the length of the flexure hinge:

\[ T = \frac{1}{2} m_d d^2 + \frac{n}{2} I_0 \left( \frac{d''}{L} \right)^2 \]  

(3)

\[ I_0 = \frac{m_h l^2}{12} + m_h \left( \frac{l}{2} \right)^2 = \frac{m_b l^2}{3} \]  

(4)

Fig. 1 SIL tool. 1 Pressing actuator and curing light fiber, 2 pressing head, 3 micro-actuator PZT1-3, 4 microstage, 5 flexure hinge, 6 macrostate, 7 laser interferometer

Fig. 2 Structure of the flexure hinge