Research on the Design Specifications of the Driving Motor in the Magnet-assisted Monolithic Reticle Stage

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Abstract. Photolithography system is a key equipment for semiconductor manufacturers and requires both significant positioning precision and high demand of production rate. Novel reticle stages which utilizes permanent magnetic motors for its acceleration and deceleration have the great advantage in reducing the heat generation and thus can promise the precision. However, the driver noise injected in the driving motor and the force ripples still deteriorate the performance, and it is essential to constrain their effects. In this paper, the relationship between the precision of reticle stage and the force-weight ratio as well as the force ripples is studied, and the design specifications for these two design factors are determined via the method of dynamic error budget. This approach is then used in the design of the driving motor in the magnet-assisted monolithic reticle stage to validate its effectiveness.

Introduction

Photolithography system is a key equipment for semiconductor manufacturers in the integrated circuit (IC) industry. It is extremely required to satisfy both significant positioning precision and high demand of production rate. Classic reticle stage is a layered structure of the coarse stage and the fine stage [1]. The coarse stage is driven by linear motors, whose great acceleration is obtained through a relatively long-distance motion. While, the fine stage is driven by voice coil motors which promises the precision of motion. This structure usually contains a great many components and parts, the interaction between the coarse stage and the fine stage is difficult to study; besides, the enormous heat production rate makes the working temperature difficult to control. The monolithic stage makes the structure lighter and simpler [2]. Still, the driven actuators are required to provide great acceleration, the large amount of heat generated in the actuators and the force ripples existed in the actuators have negative influences on the system precision. In the year 2014, researchers in Tsinghua University established a novel reticle stage which utilizes permanent magnetic motors for its acceleration and deceleration [3]. The driving motors are only used in the period of smooth trajectory and are used to restrain any possible disturbance. This structure can significantly reduce the heat generation, thus promise the desired precision. However, the design specifications on the driving motor are not considered, which makes the design of the driving stage ineffective. In this paper, the relationship between the precision of reticle stage and the force-weight ratio as well as the force ripples is studied, and the design specifications are determined for these two
design factors via the method of dynamic error budget. This method is then used in the design of the driving motor in the magnet-assisted monolithic reticle stage, to validate the effectiveness.

Method

Dynamic Error Budget

Dynamic error budget is used to evaluate the performance caused by the main contributing disturbances acting on different locations in the closed loop system while designing a high performance mechatronic system and facilitates the identification of performance limiting disturbances or the recognition of the limiting component in the plant [4]. The first step of this method is to design and model the conceptual system so as to determine its closed loop transfer functions. The main contributing disturbances acting on the closed loop are then identified and modeled. Then the performance of the system is calculated through the closed loop transfer function and the contribution of each disturbance is evaluated [5].

As illustrated in Fig. 1, the disturbance signals are assumed to be stochastic and can be modelled using PSDs, which are denoted by $S_{wi}$, the variance of the output is then given by

$$\sigma_y^2 = PS_y = \int_0^{\infty} (S_{w1} |SP|^2 + S_{w2} |S|^2 + S_{w3} |SPK|^2) df$$

(1)

From this equation we can figure out the contribution of each disturbance and finally determine the design specifications of the design variable of interest.

Design Specification for Ratio of Force Constant and Driving Mass

In the positioning period of the reticle stage, the main disturbances come from the electrical noise of the driver (denoted by $d_1$) and the vibration in the location of the sensors (denoted by $d_2$). To evaluate the effect of these disturbances, the conceptual system of the stage is modeled as in Fig. 2, the moving stage is assumed to be an ideal rigid body, the driving motor is modeled to be a force constant $A$ and the controller is realized by a PID compensator with classical parameter settings as follows.

$$\sigma_y^2 = PS_y = \int_0^{\infty} (S_{w1} |SP|^2 + S_{w2} |S|^2 + S_{w3} |SPK|^2) df$$

Figure 1. Propagation of Disturbances.

Figure 2.
\[ C = k_p \left(1 + \frac{f_i + s}{s f_d} \right), \quad f_i = f_b / 10, \quad f_d = f_b / 3 \]  

where \( f_b \) is the designed closed loop control bandwidth, which is determined by the requirement and constraints of the system. According to the definition, the closed loop control bandwidth is commonly defined as the frequency where the magnitude of the closed-loop frequency response does not drop more than 3dB [6], e.g.

\[ 20 \log \left| \frac{C k_m P}{1 + C k_m P} \right|_{\omega = -j2\pi f_b} = 20 \log \left| \frac{k_p k_m}{m} \left(1 + \frac{f_i + s}{s f_d} \right) \right|_{\omega = -j2\pi f_b} = -3dB \]  

Thus \( k_p \) can be determined by the control bandwidth with the force constant \( A \) and the mass of the moving stage \( m \) provided. The positioning error can be calculated through the transfer function between the disturbance and the positioning error. From this equation we can find out that as long as the control bandwidth is determined, the open loop gain of the system is determined, which makes the error caused by the vibration where sensors are located \( (d_2) \) is determined. However, the error caused by the electronic noise of the driver has a linear relationship with the ratio of the force constant and the mass of the stage. As the ratio increases, the error caused by the electronic noise of the driver increases linearly. An upper limit of the ratio has to be set in order to guarantee the positioning precision. And this upper limit can be determined using the equation above.

**Design Specification for Force Ripples**

During the moving of the reticle stage, the accuracy is degraded by the main disturbances come from the electrical noise of the driver (denoted by \( d_1 \)), the vibration in the location of the sensors (denoted by \( d_2 \)) and by minor variations in the generated force as function of position, known as force ripples [7] (denoted by \( d_3 \)). The conceptual system of the stage is as illustrated in Fig. 2.

The force ripples can be expressed as the sum of multiple sine harmonics as below.

\[ d_3 = F_0 \sum_{i=1}^{N} \frac{A_i}{A_0} \sin w_i y \]  

\( F_0 \) is the main force of the motor, \( A_0 \) is the main amplitude in the force and \( A_i \) is the amplitude of each harmonic. The error caused by the force ripples is calculated as
\[
\text{error} - d_3 = \frac{d_3}{ms^2(1 + PC)} = \frac{F_0 \sum_{i=1}^{N} A_i \sin w_i}{s^2 \left( s^2 + k \left( 1 + f_i / s + s / f_d \right) \right)}
\]  

(6)

The error caused by the force ripples is proportional to the product of the main force and force ripple ratio, either the main force or the ratio has to be constrained to guarantee the moving precision. The allowable ranges can be determined through the relationship above.

**Application**

According to the performance and constraints of the reticle stage to be designed, the control bandwidth $f_b$ is set to be 150 Hz. And the positioning precision is designed to be 10 nm. The moving precision of the reticle stage is represented in the form of MA and MSD [8], which is designed to be 3 nm and 8 nm respectively.

The PSD of the electrical noise of the drive is experimentally identified as in Fig. 3.

![Figure 3. PSD of the Electrical Noise of the Drive.](image)

The reticle stage adopts the laser interferometer as the measuring system, and an active vibration isolation system is used to keep the measuring system isolated from the ground and the moving stage. The PSD of the acceleration where the laser interferometer is located is derived through vibration tests and illustrated in Fig. 4.

![Figure 4. PSD of the Acceleration Where the Laser Interferometer Is Located.](image)

Use the methods above to calculate the positioning error caused by these two disturbances, the results show that the positioning error caused by the vibration of the laser interferometers is 0.27 nm which is negligible. This is attributed to the excellent performance of the active vibration isolation system. The upper limit of the ratio of the force constant and the mass of the
stage is calculated to be 2.4 N/(A*Kg). The force ripple ratio during the moving of the stage is experimentally identified as in Fig. 5.

![Force Ripple Ratio](image)

**Figure 5. The Force Ripple Ratio during the Moving of the Stage.**

The calculation gives the conclusion that the force provided by the motor should be within ±100 N to satisfy the demand for moving precision. The force ripples in this case will yield a maximum MA of 2 nm and a Maximum MSD of 6 nm as illustrated in Fig.6.

![MA and MSD](image)

**Figure 6. MA and MSD of the Moving Error of the Stage.**

**Summary**

The magnet-assisted reticle stage adopts the magnetic motors for its acceleration and deceleration which prevents the driving motor to generate heat and thus promise the desired precision. However, the river noise injected in the driving motor and the force ripples can both deteriorate the performance. In this paper, analysis to reveal the relationship between the precision of reticle stage and the force-weight ratio as well as the force ripples is conducted and the method of dynamic error budget is applied to determine the design specifications for these
two design factors. This method is then used in the design of the driving motor in the magnet-assisted monolithic reticle stage, the results showed that this method is effective.

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