Study on Repetitive PID Control of Linear Motor in Wafer Stage of Lithography

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Abstract

A ‘Repetitive + PID + feedforward’ control mode is proposed to improve the trajectory-tracking performance of linear motors in wafer stage of lithography. The positioning error of linear motor is decreased greatly compared to PID control and ‘PID + feedforward’ control. The contradiction of high speed and high positioning accuracy has been solved. The results of MATLAB simulation and experiments demonstrated the effectiveness of the proposed methods.

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1. Introduction

Linear motors are widely used in many aspects of production and life especially in semiconductor manufacturing area because of their high speed and fast response. Photo etching is the chief technology of silicon die. Lithography is the key equipment to process the silicon chip. In general, lithography can be divided into two different types: one is step & repeat system, also referred to as stepper and the other is step & scan system, also referred to as scanner. With the rapid development of photolithographic technology, scanners take the place of steppers progressively because of its unique superiority \cite{1}.

From the view of motion control the major difference between steppers and scanners is as follows: During the exposures on a stepper system, the wafer does not move. It stays as accurate as possible in one
position. When the exposure is finished, the wafer stage will travel to the next position to place the next section of the wafer underneath the projection lens for exposure. A scanner’s stage does not stand still while the exposure takes place, but it moves at a constant speed throughout the exposure. So the demand of control accuracy for a scanner is much higher than that of a stepper. And its output is obviously higher than a stepper’s. The position tracing accuracy of a stepper is chiefly assured just when it is in still position. The stage of a scanner assures the position tracing accuracy not only in its still position but also in its constant speed phase.

The widely used control method in present for linear motors is PID control. But the general PID control is not fit for the demand of lithography stage precision position control system since its low tracing accuracy and long dynamic response time. Feedforward control has certain foresight. The combination of PID and feedforward forms ‘PID + feedforward’ whose position tracing accuracy can be improved and a faster dynamic response can be obtained. But the position tracing accuracy in constant speed is just 3 to 4 microns [2] and does not satisfy the demand of lithography stage.

By observing track of lithography wafer stage we have found that the Y direction moving track of a stage (either a stepper or a scanner) can be regarded as a periodic function whose period is a certain time interval. Fig. 1 shows the track path schematic diagram of a scanner when it processes a wafer. The arrowhead solid line in vertical direction represents the Y direction track path of the stage while the dashed line in horizontal direction represents the X direction track path of the stage. We can conclude from the figure that the motion of the wafer stage in the same horizontal line is to-and-fro periodic motion composing of a positive Y direction motion and a negative Y direction motion. By altering the track (circle) of two axial (X and Y) to two separate uniaxial motion, the motion of the wafer stage in Y direction is turned into a motion consisting of a positive Y direction motion and a negative Y direction motion. So repetitive control can be used in wafer stage of lithography. By combining common PID, feedforward and repetitive control, a new control method named ‘repetitive plus PID plus feedforward’ is proposed that is applicable to the linear motor whose motion track has periodic rule.

2. The Linear Motor of Wafer Stage

2.1. The Introduction to lithography wafer stage
The motion system of a lithography wafer stage consists of two long stroke linear motors that cross perpendicularly and short stroke Lorentz motor (see Fig.2). The whole system can be divided into a coarse stage and a fine stage. The coarse stage consists of an X direction permanent magnet linear synchronous motor and a Y direction permanent magnet linear synchronous motor. The stator of Y direction linear motor is fixed on the rotor of X direction linear motor. The stator of X direction linear motor is fixed on a great flat marble. Hall element and magnet are set in the linear motor and stator of the Lorentz motor respectively and form a sensor named difference sensor that is used to measure the distance of linear motor relative to Lorentz motor. The core of fine stage is the planar motor which is set on the rotor of the Y linear motor. It is a dualistic motor which is used to assure the accurate position in X, Y and θz direction. And it uses a 3-axis laser interferometer as its position test device. It is worth mentioning all motors above whose rotors are guided by air-bearings.

2.2. The mathematical model of linear motor

When linear motor is at work, there is driving force (F) and guide friction force (FL) acting on its rotor. The motion equation of a linear motor is:

\[ m \ddot{x} + c \dot{x} = F \]  

(1)

where \( \ddot{x} \) and \( \dot{x} \) are acceleration and velocity respectively. \( c \) is the viscid damp coefficient. \( F_L = c \dot{x} \) is frictional resistance.

Owing to using air bearing the linear motor is regarded as a double differential system. Equations (1) can be expressed as:

\[ m \ddot{x} = F \]

(2)

From Eq.(2), the Laplace motion equation can be obtained:

\[ ms^2 X(s) = F(s) \]

So the mechanical transfer function of the linear motor is:

\[ G_p(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2} \]

(3)

3. Repetitive PID control

3.1. Principle of repetitive control

Repetitive control, which is based on the internal model principle proposed by Francis and Wonham [3], has been proved to be a useful control strategy for the system that involves periodic reference and/or disturbance signals [3-5]. In a stable closed loop, it sets an internal model which can generate the signal whose period is equal to that of the reference input. Consequently the closed loop can realize asymptotically tracing to external periodic reference signal.

By implementing a periodic signal generator in the repetitive controller, the repetitive control system can significantly improve the performance of tracking and/or rejecting periodic references and/or disturbances.

The block diagram of general repetitive control is shown in Fig.3. A positive feedback time delay system which can generate any periodic signal is set in a closed loop, which forms an agonic (no deviation) servo tracing system that can trace any periodic reference signal (whose period is T). The feedforward item \( a(s) \) is used to improve rapidity and stability of the system. Transfer function \( F(s) \) which
is set in front of the time lag is a lowpass filter that is used mainly to improve stability of the system. Its cut-off frequency is determined by the working band of the system. C(s) is stabilization compensator.

![Structure of general repetitive control](image)

**Fig. 3** Structure of general repetitive control

### 3.2. Repetitive PID control

PID control is widely used in many industrial control areas, especially in deterministic control system whose accurate mathematical model can be built up because of its simple algorithm and good reliability. So it is quite common in linear motor control. But general PID control does not satisfy the demands in some situation such as lithography which has a strict demand for position tracing accuracy. ‘PID plus feedforward’ can improve the position tracing accuracy and shorten the dynamic response time, but the position tracing accuracy in constant speed is just 3-4 microns. There still exists room to improve.

We combine repetitive control to ‘PID plus feedforward’ and form a ‘repetitive plus PID plus feedforward’ control. Since the linear motor used in lithography have air bearing. So the feedforward is only acceleration feedforward. Acceleration feedforward is used to improve the tracing accuracy and to shorten the adjusting time. The low pass filter in PID controller is used to eliminate the disturbance of high frequency noise. To eliminate the disturbance in some specific frequency, a notch filter is used.

Transfer function of notch filter is:

\[
H(s) = \frac{\omega_{pole}^2}{\omega_{zero}^2} \frac{s^2 + 2\zeta_{zero}\omega_{zero}s + \omega_{zero}^2}{s^2 + 2\zeta_{pole}s + \omega_{pole}^2}
\]  \(\text{(4)}\)

where \(\omega_{zero}\), \(\omega_{pole}\), \(\zeta_{zero}\) and \(\zeta_{pole}\) are the zero frequency, pole frequency, zero damping factor and pole damping factor respectively.

### 4. MATLAB simulation

Firstly, a MATLAB simulation was done in a PC. Fig.4 is the simulink block diagram. The ‘pos’ and ‘acc’ represent the set point position and acceleration of linear motor. In order to achieve the better accelerating/decelerating effect the S curve accelerating/decelerating is used.

According to the conditions of the experiments, the mass of the linear motor rotor is 45 kilograms, and the feedforward coefficient is 42.

PID parameters: \(K_p=4.6e4\), \(K_i=1.8e7\), \(K_d=1.3e6\).

The position tracing errors of the linear motor in two situations (‘PID plus feedforward’ and ‘repetitive plus PID plus feedforward’) are shown in Fig.5. The errors denoted in green line and in red line are in ‘PID plus feedforward’ control and ‘repetitive plus PID plus feedforward’ control respectively. From the figure we can see that the position tracing error will stabilize just in 2 periods with ‘repetitive plus PID plus feedforward’ control. The error during stabilization is 45% less than that of in ‘PID plus feedforward’ control. The absolute value is less than 2 microns.
5. Experiments and Conclusion

The experiments have been carried out in the linear motor of ARNOLD [USA] with air bearing. The position measurement device is an encoder of 1 micron resolving power. The motor constant is 63 N/A. We have conducted the experiments for many times with different distance and different speed. All the results of the experiments validate the results of MATLAB simulation.

The position tracing error of the linear motor which has the periodic motion track can decrease obviously with the ‘repetitive plus PID plus feedforward’ control method proposed in this paper. That has a active significance to the linear motor whose motion track has periodic rule.

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References

[1] Liu Dan, Cheng Zhaoyu. Process of wafer stage and reticle stage for step-and-scan-lithography system[J]. Laser & Optoelectronics Progress, 2003, 40(5): 14-20(in Chinese).

[2] Hou Bojie, Li Xiaoqing, Zhou Yunfei, Teng Wei, The Development of Feedforward Plus PID controller for Linear Motor, Machine tool & hydraulics, 2009, 37(2): 56-58(in Chinese).

[3] Francis BA, Wonham WM. The internal model principle of control theory. Automatica, 1976;12:457-65.

[4] Doh T-Y, Ryoo JR, Chung MJ. Design of a repetitive controller: An application to the track-following servo system of optical disk drives. IEEE Proceedings - Control Theory and Applications 2006;153(3):323-30.

[5] Moon J-H, Lee M-N, Chung MJ. Repetitive control for the track-following servo system of an optical disk drive. IEEE Transactions on Control Systems Technology 1998; 6(5):663-70.

[6] Dong F, Wang Y, Zhou J. Track following control design for ODDs by employing repetitive two-degree-of-freedom control scheme. IEEE Transactions on Consumer Electronics 2003; 49(4):1186-95.