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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 11 (4): 492-495, 2012
ISSN 1812-5638 / DOI: 10.3923/itj.2012.492.495

Synchronization Control for Reticle Stage and Wafer Stage Based on Iterative Learning Control

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Abstract: In order to resolve the problem that the reticle stage and the wafer stage must move synchronously during the scanning process, a synchronization controller is designed based on iterative learning control theory. The control system is a typical master-slave synchronization structure and the reticle stage is chosen as the slave system. An open-loop type synchronization learning controller is added to the feedback control system of the reticle stage and the convergence in the iteration domain is proved. Simulation results show that the synchronization learning method can reduce the synchronization error evidently.

Key words: Synchronization error, moving standard deviation, iterative learning control, lithography

INTRODUCTION

Step-and-scan lithography is a kind of IC manufacture equipment. During the exposure process, the reticle stage must scan in the opposite direction and keep synchronization with the wafer stage. The synchronization performance can be described by MA (Moving Mean Difference) and MSD (Moving Standard Deviation) of the position synchronization error (Luce *et al*., 2002; Klaassen *et al*., 2000). Iterative Learning Control (ILC) was introduced by Arimoto *et al*. (1984) and used in the robot control field. The learning control process can improve the control performance iteratively by using the information obtained from previous trials (Xiaoe and Baiwu, 2001; Rong-Hu and Zhong-Sheng, 2007). Because the scanning process is repetitive, ILC method has been successfully implemented in the control systems of the reticle stage and wafer stage and the tracking quality can be improved effectively (Mishra *et al*., 2007; De Gelder *et al*., 2006; Mishra and Tomizuka, 2009).

DYNAMIC MODEL OF THE RETICLE STAGE

The reticle stage is a typical macro-micro structure. The micro stage is six DOF (Degrees of Freedom) and the actuators are six voice coil motors. Figure 1 shows the dynamic structure of the micro stage. The mass and inertia are denoted by m, J_{rx}, J_{ry} and J_{rz}. F_{cg}= $[F_{xcg}\ F_{ycg}\ T_{rzcg}\ F_{zcg}\ T_{rxcg}\ T_{rycg}]^T$ represents a column with the center-of-gravity forces, and F_{act}= $[f_x\ f_{y1}\ f_{y2}\ f_{z1}\ f_{z2}\ f_{z3}]^T$ represents the actuator forces.

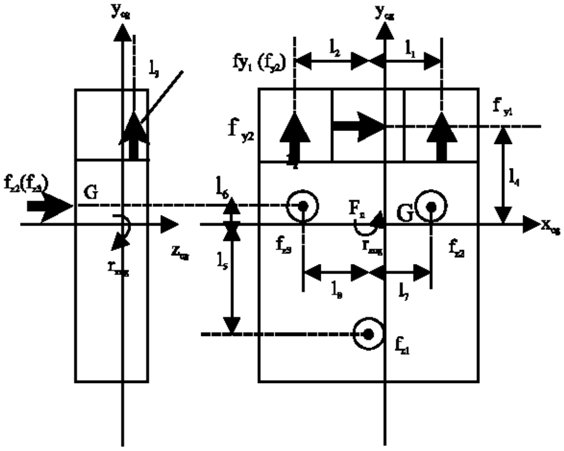

Fig. 1: Dynamic model of the reticle stage

The scanning process is depended on the exposure fields and the controlled object is changing with the set-point variation when the whole silicon wafer is exposed. The relationship between the exposure position Y = $[x\ y\ r_z\ z\ r_x\ r_y]^T$ and the center-of-gravity position Y_{cg} = $[x_{cg}\ y_{cg}\ r_{zcg}\ z_{cg}\ r_{xcg}\ r_{ycg}]^T$ can be shown in Fig. 2 and the dynamic equations are given as follows:

$$F_{cg} = LF_{act} \tag{1}$$

$$Y = QY_{cg} \tag{2}$$

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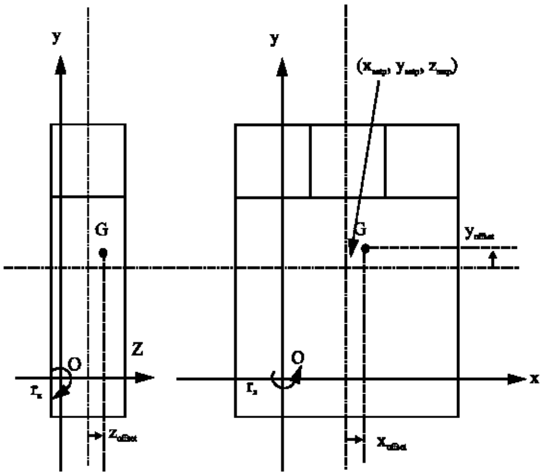

Fig. 2: Graphical representation of the motion relation between the micro stage and the exposure fields

Where:

$$L=\begin{bmatrix}1&0&0&0&0&0\\0&1&1&0&0&0\\-l_4&l_1&-l_2&0&0&0\\0&0&0&1&1&1\\0&-l_3&-l_3&-l_5&l_6&l_6\\l_3&0&0&0&-l_7&l_8\end{bmatrix},$$

$$Q=\begin{bmatrix}1&0&-y_s&0&0&z_s\\0&1&x_s&0&-z_s&0\\0&0&1&0&0&0\\0&0&0&1&y_s&-x_s\\0&0&0&0&1&0\\0&0&0&0&0&1\end{bmatrix},\ \begin{cases}x_s=x_{setp}+x_{offset}\\y_s=y_{setp}+y_{offset}\\z_s=z_{setp}+z_{offset}\end{cases}$$

The control input is denoted by $U_{ctrl}=[u_{xctrl}\ u_{yctrl}\ u_{rzctrl}\ u_{zctrl}\ u_{rxctrl}\ u_{ryctrl}]^T$ and the actuators force F_{act} can be calculated by:

$$F_{act}=L^{-1}HU_{ctrl} \tag{3}$$

Where:

$$H=\begin{bmatrix}1&0&\frac{my_s}{J_{rz}}&0&0&-\frac{mz_s}{J_{ry}}\\0&1&-\frac{mx_s}{J_{rz}}&0&\frac{mz_s}{J_{rx}}&0\\0&0&1&0&0&0\\0&0&0&1&-\frac{my_s}{J_{rx}}&\frac{mx_s}{J_{ry}}\\0&0&0&0&1&0\\0&0&0&0&0&1\end{bmatrix}$$

H is the decoupling matrix and can been calculated using the set point positions before the scanning process of each exposure field. The long-stroke movement of the reticle stage is only in y translation direction, so x_{setp} and z_{setp} are considered as zero in practice. The matrix H decouples the six DOF system of the reticle stage to six linear time-invariant SISO systems and the six controllers can be designed independently.

SYNCHRONIZATION LEARNING LAW AND THE CONVERGENCE ANALYSIS

The block diagram of the single degree of freedom synchronization control system in *y* translation direction is showed in Fig. 3. The control system is designed based on a master-slave structure and the reticle stage system is chosen as the slave system because it is much lighter than the wafer stage. P_w, P_r are the controlled objects and C_w, C_r are the feedback controllers. $y_w(t)$ and $y_r(t)$ are the position outputs of the wafer stage and reticle stage and r(t) is the desired position trajectory . The reticle stage control input $u_r(t)$ contains a feedback control input $u_{fb}(t)$ and a synchronization control input $u_s(t)$. The feedback controllers can be designed using the traditional PID method.

The MA and MSD of the synchronization error $e_s(t)$ are defined by follow equations:

$$e_s(t)=y_w(t)-\frac{1}{4}y_r(t) \tag{4}$$

$$MA=\frac{1}{t_{sc}}\int_{t_x-\frac{t_{sc}}{2}}^{t_x+\frac{t_{sc}}{2}}e_s(t)dt \tag{5}$$

$$MSD=\sqrt{\frac{1}{t_{sc}}\int_{t_x-\frac{t_{sc}}{2}}^{t_x+\frac{t_{sc}}{2}}[e_s(t)-MA]^2dt} \tag{6}$$

where, t_x is the moment when exposure center is in the middle of the grating, t_{sc} is the scanning time. The state vector of the reticle stage controlled object are denoted by x_r (t). A, b, c and d are constant matrices with appropriate dimensions. $\eta_r(x_r, t)$ represents the control input disturbance and is local Lipschitz continuous in x_r (t). The reticle stage system can be described by:

$$\begin{cases}\dot{x}_r(t)=Ax_r(t)+bu_r(t)+d\eta_r(x_r,t)\\y_r(t)=cx_r(t)\end{cases} \tag{7}$$

Considering the relative degree of the reticle stage system is 2, the ILC synchronization control law can be constructed as follow:

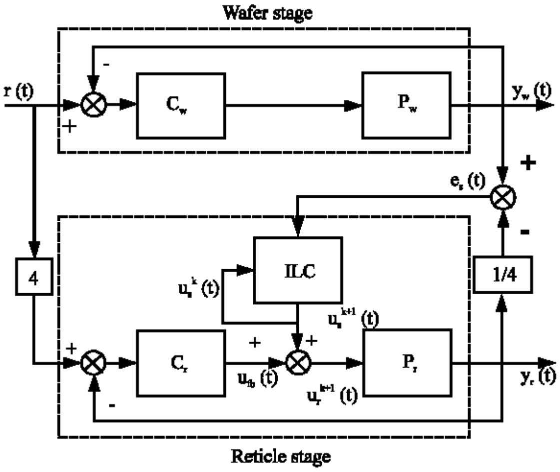

Fig. 3: Block diagram of the synchronization control system in *y* translation direction

$$u_s^{k+1}(t) = u_s^k(t) + q\ddot{e}_s^k(t) \tag{8}$$

where, q is a positive constant.

Theorem: Suppose that the initial synchronization error $e_s^k(t)$ satisfies $e_s^k(0) = \dot{e}_s^k(0) = 0$ for all k. Then $e_s^k(t)$ converges uniformly to 0 as k→∞, if:

$$|1 - \frac{1}{4}qcAb| < 1 \tag{9}$$

Proof:

$$\begin{aligned}\ddot{e}_s^{k+1}(t) &= \ddot{y}_w(t) - \frac{1}{4}\ddot{y}_r^{k+1}(t) = \ddot{y}_w(t) - \frac{1}{4}cA^2x_s^{k+1}(t) - \frac{1}{4}cAbu_r^{k+1}(t)\\ &= (1 - \frac{1}{4}qcAb)\ddot{e}_s^k(t) - \frac{1}{4}cA\Delta^{k+1}(t)\end{aligned} \tag{10}$$

Where:

$$\Delta^{k+1}(t) = A[x_r^{k+1}(t) - x_r^k(t)] + d[\eta_r^{k+1}(x_r^{k+1},t) - \eta_r^k(x_r^k,t)] \tag{11}$$

With the assumption that $x_r^k(0) = 0$, $x_r^{k+1}(t)$ can be described as:

$$x_r^{k+1}(t) = \int_0^t \dot{x}_r^{k+1}(\tau)d\tau = \int_0^t [Ax_r^{k+1}(\tau) + bu_r^{k+1}(\tau) + d\eta_r^{k+1}(x_r^k,\tau)]d\tau \tag{12}$$

Substituting Eq. 12 into Eq. 11:

$$\Delta^{k+1}(t) = \int_0^t A\Delta^{k+1}(\tau)d\tau + \int_0^t qAb\ddot{e}_s^k(\tau)d\tau + d[\eta_r^{k+1}(x_r^{k+1},t) - \eta_r^k(x_r^k,t)] \tag{13}$$

Taking norm of both sides of Eq. 13:

$$\|\Delta^{k+1}(t)\| \le \int_0^t \|A\|\|\Delta^{k+1}(\tau)\|d\tau + \int_0^t \|qAb\|\|\ddot{e}_s^k(\tau)\|d\tau + \|d\|\|\eta_r^{k+1}(x_{k+1},t) - \eta_r^k(x_k,t)\| \tag{14}$$

There exists an unknown positive constant γ satisfied:

$$\|\eta_r^{k+1}(x_r^{k+1},t) - \eta_r^k(x_r^k,t)\| \le \gamma\|x_r^{k+1}(t) - x_r^k(t)\| \le \int_0^t \gamma\|?^{k+1}(\tau)\|d\tau + \gamma\|qb\|\int_0^t \|\ddot{e}_s^k(\tau)\|d\tau \tag{15}$$

Substituting Eq. 15 into Eq. 14, it follows that:

$$\|\Delta^{k+1}(t)\| \le \int_0^t (\gamma\|d\| + \|A\|)\|\Delta^{k+1}(\tau)\|d\tau + (\gamma\|d\|\|qb\| + \|qAb\|)\int_0^t \|\ddot{e}_r^k(\tau)\|d\tau \tag{16}$$

By applying the Bellman-Gronwall lemma to Eq. 16, we have:

$$\|\Delta^{k+1}(t)\| \le \xi\int_0^t e^{(\gamma\|d\|+\|A\|)(t-\tau)}\|\ddot{e}_s^k(\tau)\|d\tau \tag{17}$$

Where:

$$\xi = \gamma q\|d\|\|b\| + q\|Ab\|$$

Taking the norm of Eq. 10 and combining Eq. 17:

$$\|\ddot{e}_s^{k+1}(t)\| \le \rho\|\ddot{e}_s^k(t)\| + \frac{1}{4}\xi\|cA\|\int_0^t e^{(\gamma\|d\|+\|A\|)(t-\tau)}\|\ddot{e}_s^k(\tau)\|d\tau \tag{18}$$

Where:

$$\rho = |1 - \frac{1}{4}qcAb|$$

Taking the λ-norm operation lead to:

$$\|\ddot{e}_s^{k+1}(t)\|_\lambda \le (\rho + \frac{1}{4}\xi\|cA\|\frac{1 - e^{(\gamma\|d\|+\|A\|-\lambda)T}}{\lambda - \gamma\|d\| - \|A\|})\|\ddot{e}_s^k(t)\|_\lambda \le \overline{\rho}\|\ddot{e}_s^k(t)\|_\lambda \tag{19}$$

Where:

$$\overline{\rho} = \rho + \frac{1}{4}\xi\|cA\|(1 - e^{(\gamma\|d\|+\|A\|-\lambda)T})/(\lambda - \gamma\|d\| - \|A\|), \quad t \in [0,T]$$

Since, $\rho<1$ we can find a $\lambda > \gamma\|d\| + \|A\|$ which makes $\rho<1$. It is easy show that $\ddot{e}_s^k(t) \to 0$ as k → ∞. Since $e_s^k(0) = \dot{e}_s^k(0) = 0$ the synchronization error $\ddot{e}_s^k(t) \to 0$ uniformly converges to 0 as k →∞.

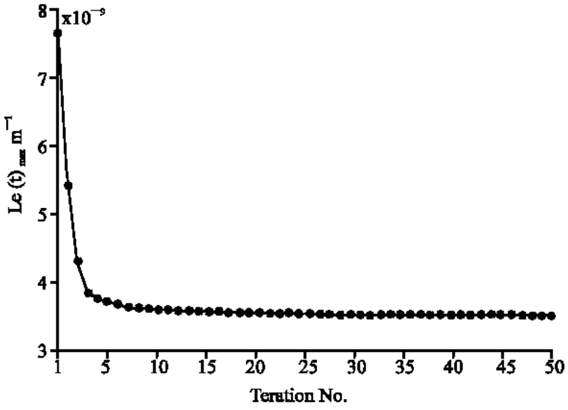

Fig. 4: Maximum synchronization error in the iteration domain

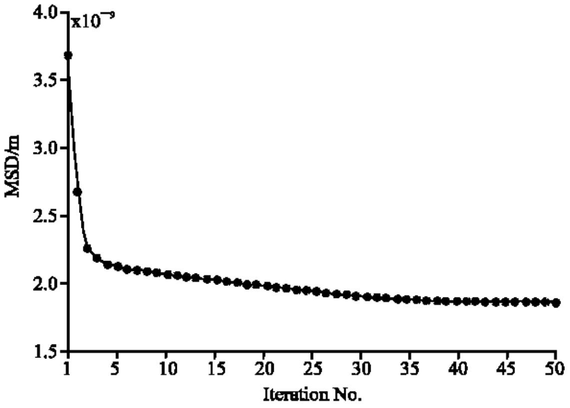

Fig. 5: MSD in the iteration domain

SIMULATION RESULTS

Figure 4 and 5 show the maximum synchronization error and the MSD along the iterative times. After fifty trials, $|e(t)|_{max}$ and MSD are 3.1 nm and 1.9 nm and they are reduced by 53.9% and 49.3%. The synchronization performance has been improved significantly and the synchronization control system of the reticle stage can ensure the exposure effect.

CONCLUSION

A synchronization control system is designed to ensure the synchronization between the wafer stage and the reticle stage using a master-slave structure. A synchronization learning law is proposed based on the iterative learning method. The feedback controller achieves good tracking performance while the ILC controller reduces the synchronization error. Simulation results show that the synchronization error and its MSD decrease significantly and the synchronization performance can be effectively improved.

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