Modeling and Control of Macro-micro Dual-Drive High Acceleration and High Precision Positioning Stage Using for IC Packaging

Yanjie Liu, Teng Li, and Lining Sun

State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, China
yjliu@hit.edu.cn

Abstract. Macro-micro dual-drive positioning stage has particularly good potential application in high acceleration and high precision positioning stage using for IC packaging. In this paper, the positioning stage which is composed by VCM (voice coil motor) as macro driver and PZT as micro driver is used. Coupling characters of the stage are discussed by analyzing dynamic model firstly, then models of macro drive positioning stage and micro drive positioning stage are built separately which both contain mechanism and driver part. Finally, a control structure, micro drive positioning stage dynamic compensate the positioning error produced by macro drive positioning stage, is proposed, in this control structure, LQG control method is used to control macro drive positioning stage, and PID control method is used to control the micro drive positioning stage. Detailed designs are conducted for the proposed approach, and the simulation results demonstrate the good performance of the proposed controller.

Keywords: macro-micro dual-drive, positioning stage, motion couple, modeling, LQG.

1 Introduction

IC (integrated circuit) manufacturing technique is developed rapidly, the integrated level of IC chip is improving and its volume is reducing with the increasing I/O leg wires' density. So high machine accuracy and high productivity are urgently required for package equipment.

Positioning stage with high acceleration and high precision, as a central component in the package equipment, plays a key role. In package process, the positioning stage is required to run and stop frequently with high acceleration, such that the system must have high bandwidth, so many structures have been proposed to solve the problem. Presently, macro-micro dual-drive technique, which is proved an effective method to achieve long stroke, high acceleration and high precision, is presented by some institutes and scholars [1, 2]. This structure uses two independent mechanisms for a single degree of freedom motion, it can widen the bandwidth of system and reduce the effective inertia of end effectors [3, 4], but the motion coupling of the two positioning stages effects the performance of the whole positioning stage, and

C. Xiong et al. (Eds.): ICIRA 2008, Part II, LNAI 5315, pp. 269–278, 2008.

performance of this system may vary depending on the control method employed. So, in this paper, system's coupling characters are analyzed firstly, according to the results, the system can be treated as two separate positioning stage and models can be built separately. Based on the model, macro positioning stage has vibration, so PID controller in forward path plus LQG controller in the feedback loop is proposed to satisfy the track following performance and restrain vibration simultaneously.

This paper is organized as follows: in section 2, structure of the dual-drive positioning stage is displayed and in section 3, motion coupling between two positioning stage is analyzed by dynamic equation, in section 4, whole models for two positioning stage are built, which contain driver and mechanism part, then the control structure is constructed and controllers are designed in section 5, and the simulation results are shown, finally, in section 6, conclusions are drawn.

2 Structure of Macro-micro Dual-Drive Positioning Stage

Usually, the positioning stage for IC packaging has two degrees-of-freedom, and each has the same structure and characters, so here we use a single axis as an example to discuss. Fig.1 shows the structure of single axis macro-micro dual-drive positioning stage. VCM together with the PZT are adopted to drive the macro positioning stage and micro positioning stage, high resolution grating scale is integrated into the close-loop feedback of macro drive positioning stage and capacitance micrometer is used to measure the displacement of micro drive positioning stage.

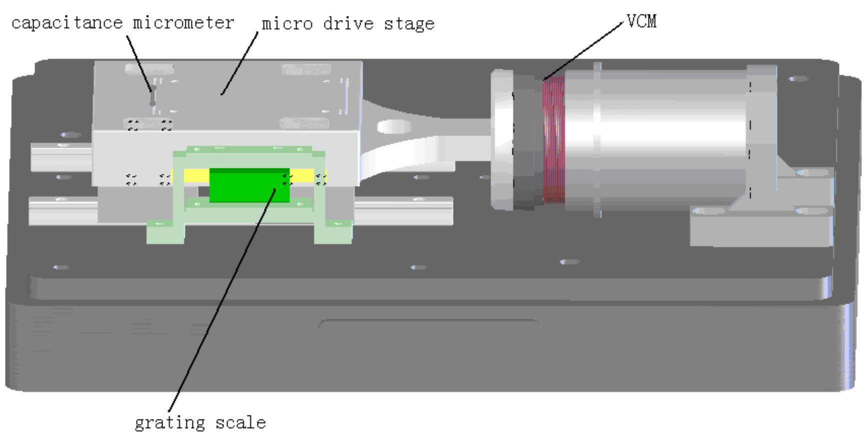

Fig. 1. Structure of macro-micro dual-drive positioning stage

The micro drive positioning stage is working at a nanometer level resolution and positioning accuracy via the double layer elastic hinges driven by PZT. The simplified structure of the micro drive positioning stage is shown in Fig.2.

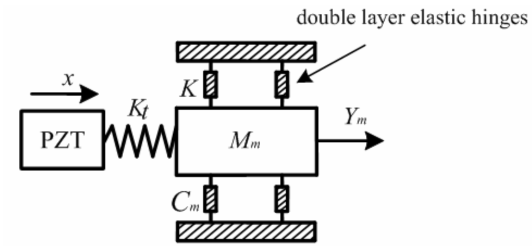

Fig. 2. The structure of micro positioning stage

Where, K_t is the stiffness of transmit part, K is the stiffness of double layer elastic hinges, M_m is the inertia of motion part in the micro stage, C_m is the damping ratio of micro stage, x is the input displacement by PZT, Y_m is output displacement. In our system, $M_m = 0.43kg$, $K = 2.0\times10^7 N/m$, $K_t = 12.0\times10^7 N/m$, and $C_m = 0.02Ns/m$.

3 Motion Coupling of Macro-micro Dual-Drive Positioning Stage

Since the micro drive positioning stage place on the macro drive positioning stage, there is force act on micro drive positioning stage when the macro dive positioning stage is moving, and vice versa, so the motion coupling should be discussed firstly as the guidance of modeling and controller design of the stage. In this paper, the motion coupling is discussed by analyzing dynamic model of the dual-drive stage.

The mechanism parts, as a kind of finite rigid body, have certain flexibility which causes remnant vibration in high-acceleration motion, reduces accuracy of the stage and prolongs the settling time. Therefore, the flexibility of the micro drive positioning stage and guiding plates should be considered. On the basis of the rigid-flexible dynamic analysis of mechanical system, the system can be simplified to a mass-damping system, as shown in Fig.3.

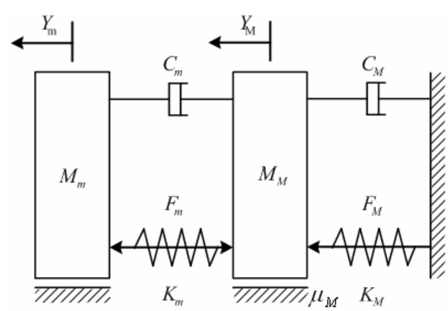

Fig. 3. The rigid-flexible model of dual-drive positioning stage

where, K_M , C_M ,and M_M are the stiffness, damping ration and inertia of stage driven by VCM, K_m ($K_m = K + K_t$), C_m and M_m are the stiffness, damping ration and inertia of stage driven by PZT , μ_M is the coefficient of friction of the linear guide, F_M , F_m are the drive force of VCM and PZT separately, Y_M, Y_m are the corresponding displacements. According to Newton's second law, dynamic differential equation of the macro-micro dual-drive positioning stage can de derived:

$$\begin{cases} M_m \ddot{Y}_m = F_m + K_m(Y_M - Y_m) + C_m(\dot{Y}_M - \dot{Y}_m) \\ M_M \ddot{Y}_M = F_M - F_m - K_M Y_M - K_m(Y_M - Y_m) - C_M \dot{Y}_M - C_m(\dot{Y}_M - \dot{Y}_m) - \mu_M \dot{Y}_M \end{cases} \tag{1}$$

Written in the form of matrix:

$$[M]\{\ddot{Y}\} + [C]\{\dot{Y}\} + [K]\{Y\} = [A]\{F\} \tag{2}$$

where, output vector: $\{Y\} = \begin{Bmatrix} Y_m \\ Y_M \end{Bmatrix}$, input vector: $\{U\} = \begin{Bmatrix} F_m \\ F_M \end{Bmatrix}$, $[M] = \begin{bmatrix} M_m & 0 \\ 0 & M_M \end{bmatrix}$, $[C] = \begin{bmatrix} C_m & -C_m \\ -C_m & C_M + C_m + \mu_M \end{bmatrix}$, $[K] = \begin{bmatrix} K_m & -K_m \\ -K_m & K_M + K_m \end{bmatrix}$, $[A] = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}$. In our system, $M_M = 1.92kg$, $K_M = 6.5 \times 10^7 N/m$, $C_M = 0.05Ns/m$, $\mu_M = 0.03Ns/m$.

Rewrite the above equation after do the Laplace transform on both side of it, the transfer function matrix can be obtained:

$$\begin{bmatrix} Y_m \\ Y_M \end{bmatrix} = \begin{bmatrix} \dfrac{1}{M_m s^2 + C_m s + K_m} & 0 \\ \dfrac{1}{C_m s + K_m} & \dfrac{1}{M_M s^2 + (C_M + C_m + \mu_M)s + K_M + K_m} \end{bmatrix} \begin{bmatrix} F_m \\ F_M \end{bmatrix} \tag{3}$$

Form (3) the motion coupling of macro drive positioning stage and micro drive positioning stage is:

$$Y_M = \frac{1}{C_m s + K_m} F_m \tag{4}$$

Do the inverse Laplace transform of it:

$$Y_M(t) = \frac{1}{C_m} e^{-\frac{K_m}{C_m}t} F_m(t) \tag{5}$$

K_m is far greater than C_m, so $Y_M(t) \approx 0$, that is, the motion coupling of the two stage can be neglected, the dual-drive stage can be treated as two single-drive positioning stages.

4 Modeling of Macro-micro Dual-Drive Positioning Stage

In this section, models of macro drive positioning stage and micro drive positioning stage are constructed. The model includes the mechanism part and the driver part.

4.1 Modeling of Macro Drive Positioning Stage

From electrical equivalent model of VCM and Kirchhoff law, the voltage balance equation can be written:

$$U = U_R + U_L + U_B \tag{6}$$

where, U is the overall voltage in coil, $U_R = Ri$ is the voltage in resistance, the induction voltage is $U_L = L(di/dt)$, the back electromotive force by coil's motion is $U_B = K_B V$, i is circuit current, V is motion speed, K_B is the back electromotive force constant. So we have:

$$U = Ri + L(di/dt) + K_B V \tag{7}$$

The force balance equation is:

$$F_M = M\ddot{Y}_M + (C_M + \mu_M)\dot{Y}_M + K_M Y_M \tag{8}$$

where, $F_M = K_F i$, K_F is force sensitivity of VCM, $M = M_M + M_m$, that is, micro drive stage is treated as one of the loads of macro drive stage.

According above two equations, the block diagram transfer function of macro drive stage is shown in Fig.4.

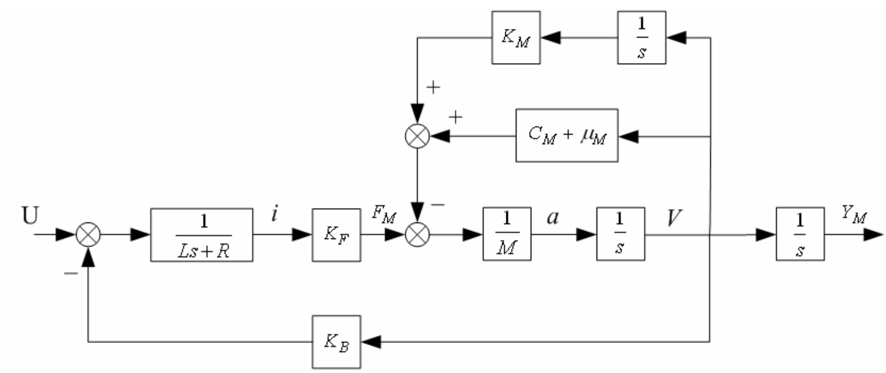

Fig. 4. Block diagram transfer function of macro drive positioning stage

So the transfer function of macro drive stage is:

$$G_M(s) = \frac{Y_M(s)}{U(s)} = \frac{K_F}{LMS^3 + (LC_M + L\mu_M + RM)s^2 + (K_M L + RC_M + R\mu_M + K_F K_B)s + RK_M} \tag{9}$$

In our system, $L = 2.5mH$, $R = 2.4\Omega$, $K_F = 21.35N/A$, $K_B = 21.36V/m/s$.

4.2 Modeling of Micro Drive Positioning Stage

The equivalent circuit of PZT is shown in Fig.5, R_i is the inner resistance of PZT power supply, R_p and C_p is the resistance and capacitance of PZT, and $R_i << R_p$, U_i is the input voltage of PZT power supply and U_p is the voltage act on PZT.

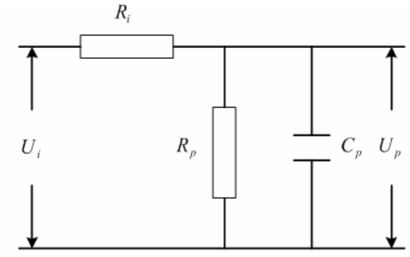

Fig. 5. The equivalent circuit of PZT

So the transfer function can be written as:

$$\frac{U_p(s)}{U_i(s)} = \frac{1}{R_i C_p s + 1} \tag{10}$$

According to the electric displacement character of PZT, and ignoring the nonlinearity of PZT, the displacement of PZT is proportional to the U_p , that is:

$$x = aU_p \tag{11}$$

a is the ratio coefficient, so

$$\frac{X(s)}{U_i(s)} = \frac{a}{R_i C_p s + 1} \tag{12}$$

Then from Fig.2 the force balance function of micro drive positioning stage is:

$$K_t x = M_m \ddot{Y}_m + C_m \dot{Y}_m + (K_t + K)Y_m \tag{13}$$

So that, the transfer function of micro drive stage is:

$$G_m(s) = K_p \frac{Y_m(s)}{U_i(s)} = \frac{aK_t K_p}{(R_i C_p s + 1)(M_m s^2 + C_m s + (K + K_t))} \tag{14}$$

K_p is the magnification of PZT power supply. In our system, $a = 0.267 \times 10^{-6} m/V$, $K_p = 15$, $R_i = 11\Omega$, $C_p = 14.5\mu F$.

5 Control of Macro-micro Dual-Drive Positioning Stage

The classic method using for control macro drive stage is PID, but for our system, from the transfer function above we know that the damping ratio is small, so the system will vibrate seriously while motion. The design of vibration damping controller is formulated as a standard LQG problem [5, 6]. In this paper, we design LQG controller as the feedback part to restrain vibration, and PID controller in forward path to ensure the track following character. The controller structure is shown in Fig.6.

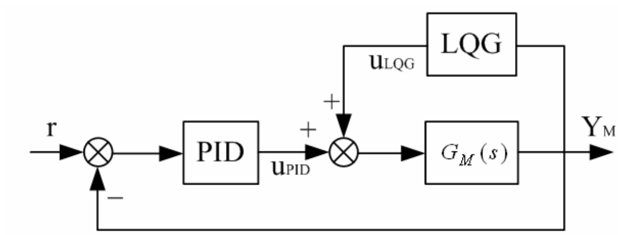

Fig. 6. Control structure of macro drive positioning stage

First, the state space model of macro drive stage is written:

$$\begin{pmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \\ \dot{x}_3(t) \end{pmatrix} = \begin{bmatrix} -\frac{LC_M + L\mu_M + RM}{LM} & -\frac{LK_M + RC_M + R\mu_M + K_F K_B}{LM} & -\frac{RK_M}{LM} \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{pmatrix} + \begin{pmatrix} \frac{K_F}{LM} \\ 0 \\ 0 \end{pmatrix} u(t) \tag{15}$$

$$y(t) = x_3(t)$$

where state vector $\begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \end{pmatrix} = \begin{pmatrix} \ddot{Y}_M(t) \\ \dot{Y}_M(t) \\ Y_M(t) \end{pmatrix}$.

The covariance of disturbance in state equation and measurement noise in observation equation for Kalman filter model are 1 and 0.01.

The cost function for this LQ design is:

$$J = \int_0^t (Y_M^2(t) + u_{LQG}^2(t))dt \tag{16}$$

Fig.7 and Fig.8 show the step response of system under PID controller and PID plus LQG controller. From the figure we can see that the system has a certain following ability under PID controller, but vibration is obvious, by adding the LQG feedback controller, the vibration is restrained assuredly.

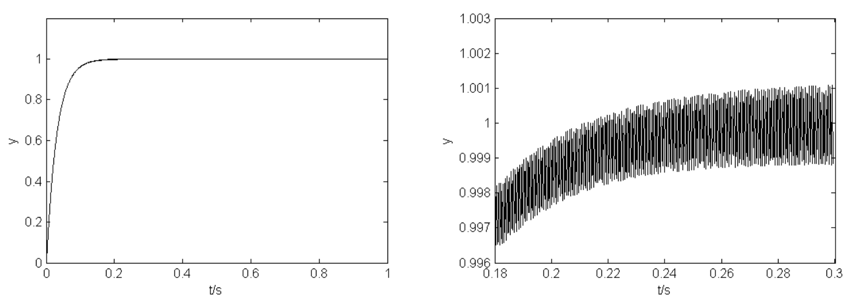

Fig. 7. Step response of macro drive positioning stage under PID controller

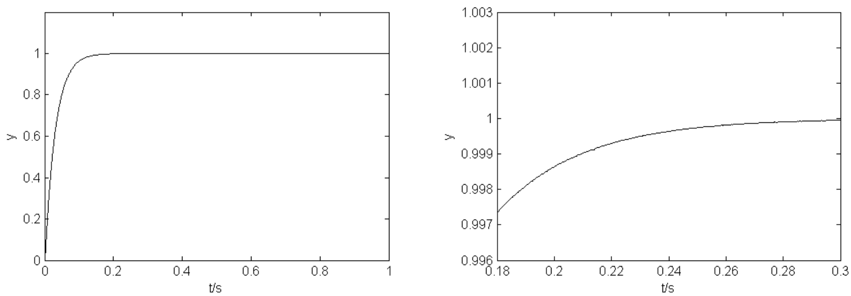

Fig. 8. Step response of macro drive positioning stage under PID plus LQG controller

For the PZT drive positioning stage, though the output displacement of PZT is proportional to input voltage, because of the nonlinear character of PZT, using the open-loop controller would not obtain good performance, so with the capacitance micrometer the micro drive positioning stage can form closed-loop control structure in our system.

Fig.9 shows the proposed controller structure for macro-micro dual-drive positioning stage. r_M is the reference input which is a periodic signal for IC packaging application, r_m is the reference input of micro stage, which is the error signal of macro drive positioning stage. In this structure, micro drive positioning stage dynamic compensate the positioning error of macro drive positioning stage, so the positioning error of the whole system is reduced by adding micro drive stage.

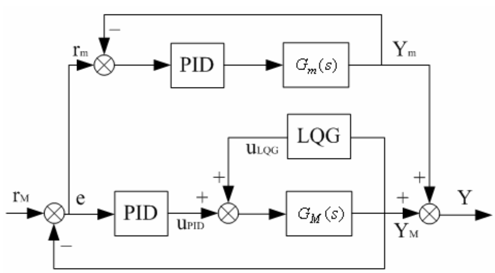

Fig. 9. Control structure of macro-micro dual-drive positioning stage

Sine wave, amplitude is 2mm, frequency is 10rad/s, and use absolute value of the negative part, is used as reference signal, which is similar to the periodic signal in IC packaging. Fig.10 and Fig.11 show the response curve of the system without micro drive stage. From these two figures, we can see that by adding micro drive stage, the positioning precision is an order of magnitude greater than the positioning stage driving only by macro driver.

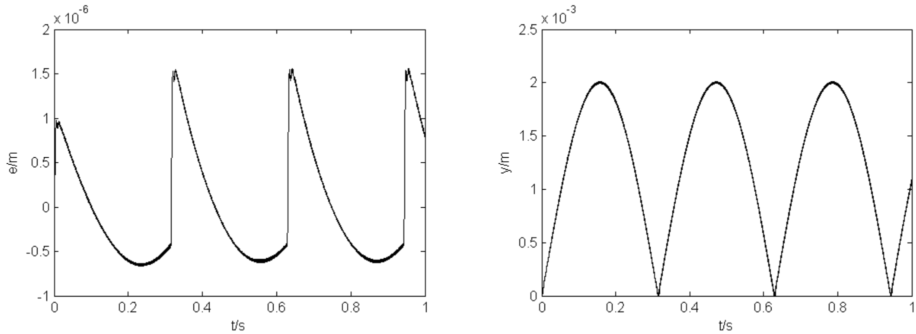

Fig. 10. Response of macro-micro dual-drive positioning stage to sine wave, the left figure is error curve of the whole positioning stage, the right figure is the response curve. In the right figure, the solid line is the reference input, and the dashed line is the response curve.

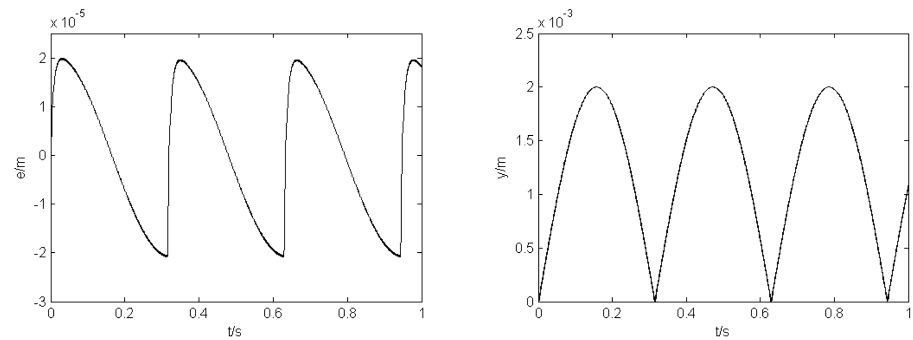

Fig. 11. Response of macro drive positioning stage to sine wave, meaning of figures are similar with Fig.10

6 Conclusions

In this paper, model building and controller design of macro-micro dual-drive positioning stage are discussed. Mechanism structure that this paper studied is composed by a VCM and a PZT, and both of them have displacement sensors. By analyzing dynamic model of the whole system, motion coupling of the two positioning stage is discussed, which conclude that the coupling action of two positioning is so small that can be neglected. Basing on the result, models of two positioning stage are built, both including mechanism part and driver part. From the model of macro positioning stage, we known that vibration is an important character of it, so we proposed a controller contain PID and LQG to satisfy the tracking following performance and improve vibration damping ability, simulation results verify the proposed controller. For the dual-drive positioning stage, we proposed a control structure that micro drive positioning stage dynamic compensate the positioning error produced by macro drive positioning stage, the simulation results also shows the good performance of it.

Acknowledgment

This paper is supported by the Cheung Kong scholars creative team plan IRT0423, the National Natural Science Foundation of China under Grant 50705027 and the National High Technology Research and Development Program of China (863 Program) under Grant 2007AA04Z315.

References

1. Sangjoo, K., Wan, K.C., Youngil, Y.: On the Coarse/Fine Dual-stage Manipulators with Perturbation Compensator. In: The 2001 IEEE International Conference on Robotics & Automation, Seoul, Korea, pp. 121–126 (2001)
2. Heui, J.P., Dong, S.L., Jong, H.P.: Ultra Precision Positioning System for Servo Motor-piezo Actuator Using the Dual Loop and Digital Filter Implementation. International Journal of Machine Tool & Manufacture 41, 51–63 (2001)
3. Sharon, A.: The Macro/Micro Manipulator: An Improved Architecture for Robot Control. Degree of Doctor of Philosophy, Thesis, Mechanical Engineering Department, Massachusetts Institute of Technology (1988)
4. Khatib, O.: Reduced effective inertia in macro-mini Manipulator Systems. In: Fifth Int. Symp. on Robotics Research, pp. 279–284 (1990)
5. Li, Y., Marcassa, F., Horowitz, R., Oboe, R.: Track following control with active vibration damping of a PZT actuated suspension dual-stage servo system. In: Proc. Am. Control Conf., pp. 2553–2559 (2003)
6. Huang, X., Horowitz, R., Li, Y.: Track-following control with active vibration damping and compensation of a dual-stage servo system. Microsyst. Technol. 11, 1276–1286 (2005)