TRACKING CONTROL OF THE BALL BEARING GUIDED LINEAR STAGE IN HIGH VACUUM

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INTRODUCTION

Recently, there are increasing needs for precision stages with vacuum compatibility in such as lithography equipment for wafer or mask manufacturing, mask mastering equipment for optical data storage and scanning electron beam inspection for semiconductor process. The precision stage in vacuum can have several types of bearing: vacuum compatible air bearing, magnetic bearing and vacuum compatible ball bearing. The vacuum compatible air bearing and magnetic bearing have frictionless motion and a few advantages such as smooth motion control result and controllable parasitic direction stiffness. However, these bearings require a complex bearing component design and a control method and an unstable motion can occur when abrupt motion is applied to air bearing stage due to degraded vacuum-ambient equilibrium. A ball bearing is used in high vacuum with proper material selection and surface finish or treatment. A simpler design, a high stiffness and a lower cost can be achieved by adopting ball bearing in high vacuum (~10\(^{-5}\) Torr). The ball bearing in vacuum also has friction and wear problems as in ambient air and when tracking control is performed, friction can make the tracking error higher and there may be a cold-weld phenomenon between ball and rail surface in high vacuum. Therefore, an adequate control method should be used for tracking control of the ball bearing stage especially in high vacuum. In case of higher speed tracking, tracking error will be increased due to fast desired path and in case of lower speed control, there will be control problems due to frictional forces between ball and guide surfaces. Therefore, a controller which is robust to parameter variation and which has fast tracking capability is needed.

The feedforward controller, ZPETC (Zero Phase Error Tracking Controller), will be adopted for minimizing tracking phase error. The ZPETC control method implements pole-zero cancellation and zero phase tracking error is achieved theoretically [1]. However, the servo loop should have enough robustness for ZPETC to operate properly and therefore TDC (Time Delay Control) control method will be adopted simultaneously (exactly, in series with ZPETC). The TDC can make a stage follow a predetermined reference-model although there are uncertainties in model parameters and unpredictable external disturbances [2]. A pre-study with conventional PID controller was performed and in that case the control system showed somewhat poor performance which may be by friction existence of the ball bearing. In order to decrease friction, special surface finish, DLC (Diamond Like Carbon) film coating, is to be done on the surfaces of bearing component by sputtering deposition for vacuum compatibility.

Figure 1 shows the picture of the linear stage in a vacuum chamber. The linear stage was designed with linear motor and ball bearing guide (THK HR series). The linear motor is a...
coreless type motor and the linear position is measured by linear encoder (Heidenhain LIP481) and the encoder can have 1.25 nm resolution and the moving range of stage is 250 mm. Generally special lubricating grease, which has very low vapor pressure, is used in vacuum. However, this vacuum compatible grease generally makes bearing setup difficult and cause more friction on the stage movement. When the movement speed of the linear stage is below about 1 mm/s, it is too slow for the stage to have heat generation and wear problem. The surface of the bearing and guide is cleaned by solvent solution in order to remove any organic grease or inorganic dirt. And therefore, the surface contact between guide and bearing is a kind of dry-contact type. There was a research report regarding dry condition metal contact (that is two stainless steel contact) and it showed that there is little possibility for contact surface to have cold-welding [3]. However, when higher speed tracking, heat generation and wear problem will cause worse motion precision and bad control performance. In order to overcome these problems, special surface finish, DLC (Diamond Like Carbon) film coating, is to be done on those surfaces of the bearing component by sputtering deposition. The sputtered DLC film has high stiffness, high hardness, low friction coefficient and high atomic structural stability in vacuum.

**PID Control Experiment**

Figure 2 shows multistep control results. The control method is conventional PID control and the control gain is varied according to the motion step size as predicted. Many previous research results reported that physical models are different from each other when the movement range is above and below a certain value. When the moving range is long enough the control plant can be thought of as a system that has a mass and a damper. However, the system has an energy conservative model element, just like a spring component, when below a few micrometer movement and the controller gain need to be set higher. And in case of sub-micrometer movement the settling time increases because of abrupt model change which is a nonlinear burden to control system. The tracking control experiments are performed with various following speed in two environments of vacuum and ambient air. Figure 3 shows the result when 5 μm/s speed tracking control was performed and somewhat better tracking performance can be observed in case of vacuum environment. With the experiment in vacuum the control gains needed to be

![Figure 2](image1.png)

**FIGURE 2.** Multi-step control results at various single step amounts. A step control result as low as 10 nm is achieved.

![Figure 3](image2.png)

**FIGURE 3.** Tracking control experiment results: tracking speed is 5 μm/s. (a) in air (b) in vacuum
FIGURE 4. Tracking control experiment results: tracking speed is 5 mm/s in air and in vacuum.

increased higher possibly due to friction. A cold weld phenomenon could affect the control or dry contact condition could be a cause. When the tracking speed is about 5 mm/s the control performance is much worse in ambient air than that is in vacuum. This result can be explained by the existence of the adsorbed layer between guide rail and bearing surface in ambient air environment.

TRACKING CONTROLLER DESIGN: ZPETC+TDC

The TDC controller uses time delay estimation of the control plant model from the measured output. Therefore, the TDC is robust to plant parameter variation. The TDC controller makes the system follow the pre-determined reference model, which can be written as below [4],

\[
\frac{d^2e}{dt^2} + K_p \frac{de}{dt} + K_p e = 0 \tag{1}
\]

With these \(K_D\) and \(K_p\) parameters one can define the reference model and generally critical damping condition is applied to the model. And the TDC digital controller can be written as follows,

\[
u(k) = u(k-1) + \left( \frac{MK_D}{t_s} + \frac{MK_p}{t_s} + \frac{M}{t_s^2} \right) e(k) - \left( \frac{MK_D}{t_s} + \frac{2M}{t_s^2} \right) e(k-1) + \frac{M}{t_s} e(k-2) \tag{2}\]

The \(u(k)\) is control input at the \(k\)th control event, \(t_s\) is the sampling time, \(M\) is the assumed coefficient value of the second order term of the system and \(e(k)\) is the error input at the \(k\)th control event. At the start of control, the initial conditions of those \((k-1)_{th}\) and \((k-2)_{th}\) values are set to zero. The Z-Transform result of the TDC controller is shown below,

\[
C(z) = \left[ \frac{MK_D}{t_s} + \frac{MK_p}{t_s} + \frac{M}{t_s^2} \right] z^2 - \left( \frac{MK_D}{t_s} + \frac{2M}{t_s^2} \right) z + \frac{M}{t_s} \right] \frac{1}{z^2 - z} \tag{3}\]

With the \(C(z)\) controller and the plant model the closed loop system transfer function can be obtained. The ZPETC feedforward controller uses inverse model of the total closed loop system. The closed loop system transfer function can be written as equation (4).

\[
G_{closed}(z^{-1}) = \frac{z^{-d}B_c(z^{-1})}{A_c(z^{-1})} \tag{4}\]

\(z^{-d}\) is a d-step plant delay. And the \(G_{closed}(z^{-1})\) can have unstable zeros (out of unit circle in the Z complex domain) and ZPETC is designed with the following equation,

\[
r(k) = \frac{A_c(z^{-1})B_c^u(z)}{B_c^u(z^{-1})[B_c^g(1)]^2} y_d(k+d) \tag{5}\]

\(B_c(z^{-1})\) is divided into \(B_c^u(z^{-1})\) and \(B_c^g(z^{-1})\) and upper character \(u\) means unstable zeros and upper character \(g\) means stable zeros. In the denominator \(B_c^g(1)\) means the DC gain value. The \(y_d(k+d)\) is the desired position at \((k+d)_{th}\) control event and \(r(k)\) is the input to the closed loop system. With the above ZPETC formula it has been theoretically proved that the ZPETC controller make the controlled system have zero phase following performance.
CONCLUSION
A vacuum compatible precision linear stage was designed and its control performance was investigated with conventional PID controller. And ZPETC+TDC controller was proposed for linear stage tracking in vacuum. The DLC coating on guide-rail is in process and with the designed ZPETC+TDC controller it is an ongoing procedure to investigate tracking control performance in high vacuum.

REFERENCES