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Stabilization and optimization of dynamic property for sub-nanometre resolution on ultraprecision positioning mechanism driven by preloaded ball screw

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Abstract

Dynamic properties for sub-nanometre resolution on ultraprecision positioning mechanism driven by preloaded ball screw are discussed to propose a method of stabilizing and optimizing the positioning behaviour. First, the nonlinear elastic behaviour between torque input and stage displacement was approximated as a linear property within dozens of nanometres, and a 2-mass vibration model was derived as the lowest principal dimension model. Next, a state feedback system and an optimal regulator were constructed to stabilize and optimize the positioning motion. Residual vibration was attenuated to 1/3 of its RMS value, and a ball screw mechanism with a model-based control system enabled ultra-fine positioning with sub-nanometre resolution.

Keywords: Positioning control, Ball screw, Sub-nanometre, Residual vibration, State feedback, Optimal regulator

1. Introduction

Recently, the resolution of linear encoder has improved to the pico-metre level, and positioning performance with sub-nanometre resolution can be expected in mechanisms using ball screws [1]. In the previous report, we discussed the dynamic properties of the mechanism and its settling stability in experiments under sub-nanometre-level motion [2]. To attenuate the residual vibration, an oil film damper was applied, and ultra-fine positioning was achieved. However, the motion speed is limited by the oil film damper. In this report, a state feedback system and an optimal regulator are constructed to stabilize the vibration and to optimize positioning motion in the sub-nanometre range. The performance of the control system is evaluated by actual positioning experiments.

2. Experimental apparatus and property of mechanism

Figure 1 shows the experimental positioning system schematically. The stage is driven by a preloaded ball screw with a 5 mm lead and supported by aerostatic guideways with a stroke of 100 mm. A linear encoder with a resolution of 0.069 nm measures stage displacement. A new ultra-fine rotary encoder optical disc is mounted on the screw shaft to directly measure the angle of rotation with a resolution of 0.0277 μrad.

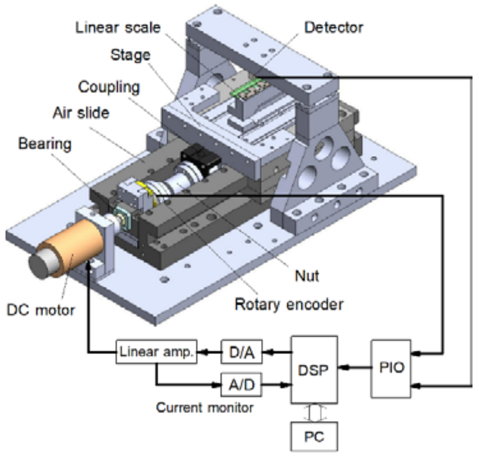
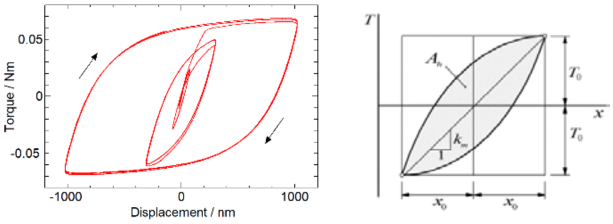
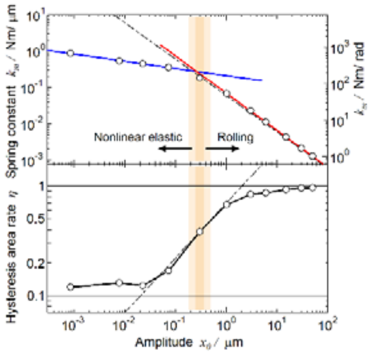


Figure 1. Experimental apparatus

The mechanism has rolling elements of ball screw and bearings that support the rotating shaft and contain nonlinear rolling friction [3, 4]. Figure 2 shows the quasi-static property of this mechanism. (a) is an example of the experimental results of the relationship between the sinusoidal torque input from the motor to the screw shaft and the response of the stage displacement, for different amplitudes. They draw their own hysteresis loops and become almost linearly related as the amplitude decreases. Here, the parameters of the hysteresis loop are defined as shown in (b): the gradient of the straight line between its vertices of the loop is defined as a mean spring constant k_m, and the ratio of the hysteresis loop area A_h to the rectangular area determined by a diagonal between its vertices

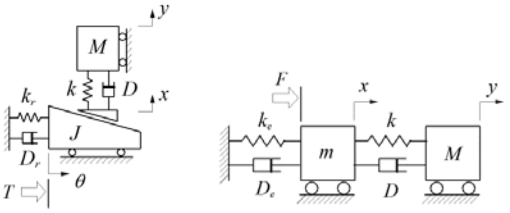


(a) Example of experimental result (b) Definition of parameters



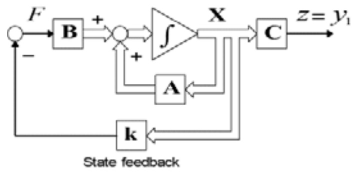
(c) Transition of property

Figure 2. Nonlinear elastic property within microscopic range

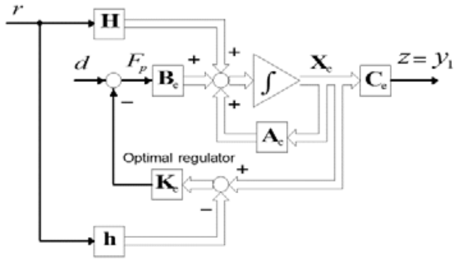


(a) Structure Screw mechanism (b) two-mass model

Figure 3. Dynamic model of controlled object



(a) State feedback for vibration damping



(b) Optimal regulator and positioning system

Figure 4. Control system

is defined as a hysteresis area ratio η ($=A_h/4T_0\cdot x_0$). (c) shows transitions of k_m and η as the function of displacement amplitude x_0. It is considered that behaviour of the ball screw mechanism shifts from a macroscopic rolling state to a microscopic nonlinear elastic state when the motion amplitude is less than 0.3 μm, and that the property becomes nearly linear when the amplitude is less than 50 nm where η reaches a micro value of about 0.1, and the spring constant is nearly constant in that micro range. Therefore, it is possible to consider the mechanism as a linear dynamic system.

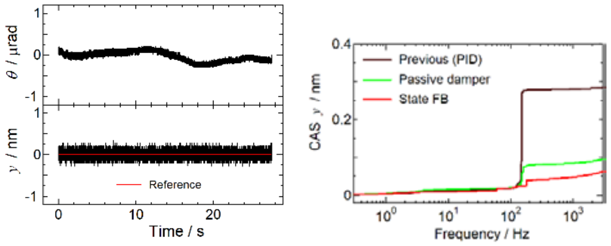
3. Modelling and control system

The mechanism can be modelled as a six-mass model, as discussed in the previous report. However, the major vibration modes in the micro motion range are originated from the compliance $1/k$ of the coupling between the nut and stage and the nonlinear elastic properties of the ball screw mechanism. Furthermore, the nonlinear elastic behaviour can be described by the spring constant k_r, since it can be regarded as linear as mentioned above. The mechanism was then modelled as the lowest principal dimension model, as shown in Figure 3(a). Using the constraint condition of screw, the model was described by the two-mass model as shown in (b). Therefore, the positioning mechanism was modelled as a state variable model expressed in Eq. (1) using a simplified two-mass model that includes the elastic properties of the rolling elements [5].

$$\left.\begin{aligned}\dot{\mathbf{X}} &= \mathbf{AX}+\mathbf{B}F\\ z=y &= \mathbf{CX}\end{aligned}\right\} \qquad (1)$$

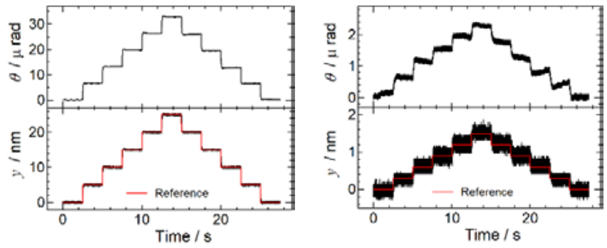
$$\mathbf{X}=\begin{pmatrix}\mathbf{x}_1\\ \mathbf{x}_2\end{pmatrix}=\begin{pmatrix}x\\ y\\ \dot{x}\\ \dot{y}\end{pmatrix},\ \mathbf{A}=\begin{pmatrix}\mathbf{0} & \mathbf{I}\\ -\mathbf{\Omega} & -\mathbf{\Lambda}\end{pmatrix},\ \mathbf{B}=\begin{pmatrix}0\\ 0\\ 1/m\\ 0\end{pmatrix},\ \mathbf{C}=\begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}.$$

First, a state feedback control system was constructed as shown in Fig. 4(a) using the four-component state variables in Eq. (1). To stabilize the vibrations in the sub-nanometre range, the poles of the system were assigned to appropriate positions on the complex plane and the corresponding feedback gains were determined. Next, a positioning system using integral control of stage position was constructed to derive the optimal regulator as shown in (b). The weighting parameters of the quadratic performance index were determined for the ideal positioning motion of a normal mass-spring system.



(a) Residual vibration (b) CAS of residual vibration

Figure 5. Vibration under controlled settled condition



(a) 5 nm step (b) 0.3 nm step

Figure 6. Multi-step response

4. Experimental results

Several positioning experiments were performed. Figure 5(a) shows the response of stage displacement and screw shaft rotational angle when the reference value of stage displacement was set to zero. Residual vibrations of displacement are maintained in the sub-nanometre range. The CAS of the residual vibrations from the experiment are shown in (b) compared with the previous results. Controlled by the state feedback system, RMS value of residual vibration is suppressed to 1/3 of the previous value with PID controller, and stable settling is achieved equivalent to that of previous passive damper. Figure 6 shows the results of positioning experiment for step widths of (a) 5 nm and (b) 0.3 nm. The ball screw mechanism with model-based control proposed here enables ultra-fine positioning at the sub-nanometre level.

The next works need to evaluate the reproducibility of the nonlinear property in long term, and to establish a robust control system for reliable navigation from macroscopic rolling condition to asymptotically stable basin within 50 nm range.

5. Conclusion

It was shown that a mechanism driven by a preloaded ball screw can be considered a linear system in the micro region within dozens of nanometres. The positioning mechanism was modelled as a state variable model using a simplified two-mass model that includes the nonlinear elastic properties of the ball screw. The state feedback system and an optimal regulator suppress residual vibration to 1/3 of its RMS value, enabling ultra-fine positioning with sub-nanometre resolution.

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