SIMPLE AND PRACTICAL CONTROL METHOD FOR ULTRA-PRECISION POSITIONING - APPLICATION TO A BALLSCREW MECHANISM

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INTRODUCTION

Precision positioning systems are essential in precision industry. These positioning systems often have one or more elements that introduce friction. Friction is well known to cause steady-state errors and limit cycles, and to slow the motion of the mechanism. Thus, it is important to consider friction compensation in controller design. Simple controllers like PID controllers do not offer the best possible performance for the mechanisms. Thus the use of advanced controllers such as controllers including model based compensators and variable structure controllers is increasing. However the advanced controller design usually requires the identification of mechanism characteristics and sufficient knowledge of the control theory.

Ballscrew mechanisms have friction characteristics and are widely used in precision positioning systems. In this research, a conventional ballscrew mechanism is used as a positioning mechanism. Although some studies have achieved nanometric accuracy with a ballscrew mechanism, this research differs significantly in the ease of design and controller structure. The NCTF (nominal characteristic trajectory following) controller, has a simple structure and its design procedure does not require exact parameter identification, which makes it easy to design, understand, and adjust [1-3].

In this paper, first, the concept and the design procedure of the NCTF control method are introduced. Next, the NCTF control method is implemented to a conventional ballscrew mechanism and the positioning performance of the controller is examined. The controller is designed without any exact identification of parameters or modeling.

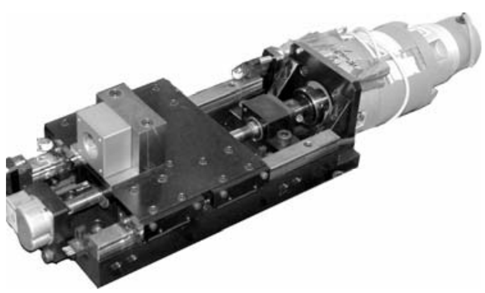


Figure 1. Experimental ballscrew mechanism

EXPERIMENTAL SETUP

Figure 1 shows a picture of the ballscrew mechanism, which is the controlled mechanism in this study. Its table mass is 3.57kg. The mechanism has several sources of friction: the DC motor, the preloaded double-nut, the linear ball guides, and the ball bearings supporting the screw shaft. Friction and damping characteristics tend to vary and depend on the warm-up condition.

The PWM power amplifier is used as a driver unit. The controller sampling frequency is 5 kHz. The feedback position is determined by a laser position sensor with resolution of 1.24 nm. The lead of the ballscrew is 2 mm/rev.

CONCEPT OF NCTF CONTROL MEHTOD

Figure 2 shows the basic structure of the NCTF

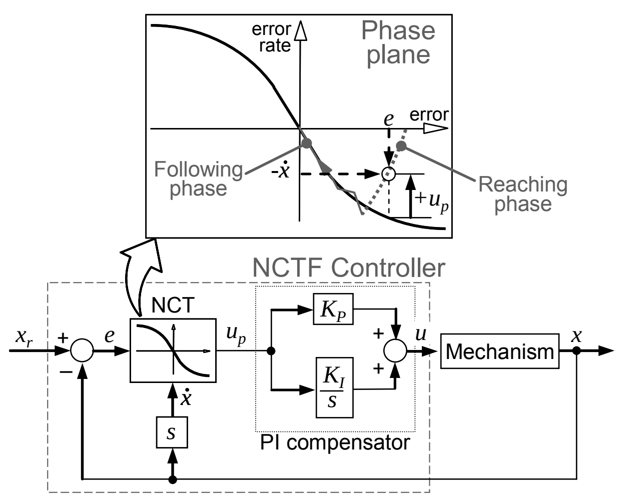
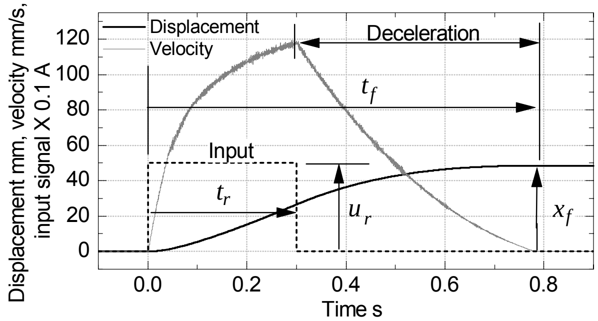
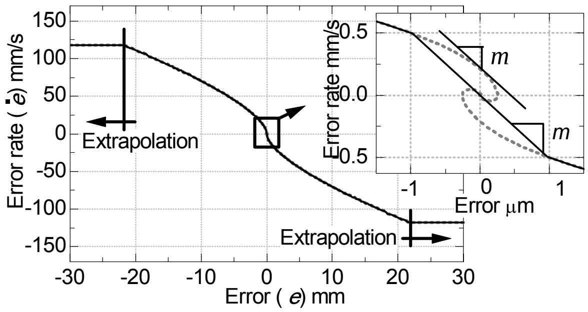


Figure 2. Basic structure of the NCTF control system



(a) Open-loop response for the NCT construction.



(b) NCT constructed from the open-loop response.

Figure 3. Open-loop response and construction of the NCT

control system. The controller is composed of a nominal characteristic trajectory (NCT) and a PI compensator. The objective of the PI compensator is to make the mechanism motion follow the NCT, finishing at the origin of the phase-plane. The output of the NCT is a signal, which is the difference between the actual error rate of the mechanism and the error rate of the NCT. On the phase-plane, the table motion is divided into a reaching phase and a following phase. During the reaching phase, the compensator controls the table motion to achieve the NCT. The next step is the following phase, where the PI compensator causes the mechanism motion to follow the NCT, leading it back to the origin of the phase-plane.

The design of the NCTF controller is comprised of three steps:

(i) The mechanism is driven with an open-loop step input while its displacement and velocity are measured.

(ii) The NCT is constructed on the phase-plane using the displacement and velocity of the mechanism during the deceleration.

(iii) The PI compensator is designed using simple response results and the NCT information.

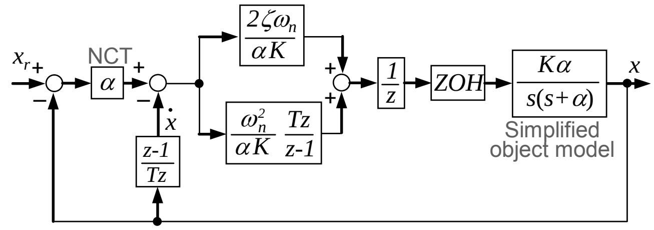


Figure 4. Digital NCTF control system

Since the NCT is constructed from the actual response of the mechanism, the actual nonlinear friction effects are included in the NCT. Thus, the actual friction characteristics are part of the control law.

DESIGN OF PI COMPENSATOR

Stability Condition Based on Linear System

When the ball screw has sufficient stiffness, the mechanism can be approximately linearized as follows;

$$\ddot{x} + \alpha\dot{x} = K\alpha \cdot i \tag{1}$$

Where, x and i represent a table displacement and a motor current, respectively. α and K are model parameters. In this case, the nonlinear friction effects are reflected on α and the NCT.

Figure 3(a) shows the open-loop response used to construct the NCT. Figure 3(b) shows the NCT constructed from the open-loop experiment. The vertical axis is constructed from the measured velocity during the deceleration. The horizontal axis is constructed from the measured displacement during the deceleration. The inclination of the NCT near the origin m coincides with -α. The detail shows that a spring-like behavior manifests near the origin of the NCT as a circling motion. This circling motion has negative effects on positioning and the NCT is linearized with a straight line close to the origin. The inclination of the line is chosen to be the same as the tangential line of the NCT just before the spring-like behavior begins. K is expressed as Eq. (2) using parameters in Fig.3.

$$K = \frac{x_f}{u_r t_r} \tag{2}$$

The PI compensator gains K_P and K_I are expressed as Eq. (3), using compensator parameters ζ and ω_n.

$$K_P = \frac{2\zeta\omega_n}{K\alpha}, \quad K_I = \frac{\omega_n^{\;2}}{K\alpha} \tag{3}$$

Figure 4 shows the block diagram of the digital NCTF control system near the origin of the NCT. T is the sampling time of the controller.

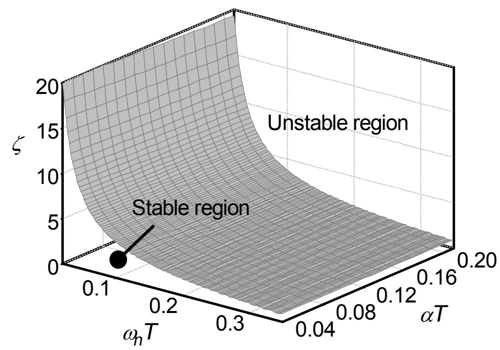


Figure 5. Stability limit of the linear digital system with PI element

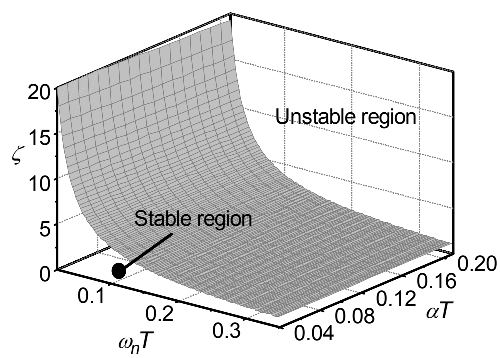


Figure 6. Stability limit of the linear digital system with P element

The stability of the linear digital NCTF control system is dependent on the parameters αT, $\omega_n T$, and ζ. Applying the Jury's test, a numerical plot of the stability limit is shown in Fig. 5. The linear stability limit has negligible variations on the αT axis. The linear stability condition is approximately expressed as:

$$\zeta > \frac{0.383}{\omega_n T} \tag{4}$$

The PI compensators determined under Eq. (4) make the control system stable. However the condition is too excessive for the mechanism with friction.

Stability Condition for Actual System

Coulomb friction is known to increase the stability of the system, allowing for the use of higher gains than those predicted by a linear analysis. This subsection introduces a simple method to find the practical stability limit of the NCTF control system.

Figure 6 shows the case in which the stability analysis is conducted with the integral gain set to zero. Comparing with the surfaces of Figs.5 and 6, it is observed that the integral gain has little effect on the linear digital stability analysis.

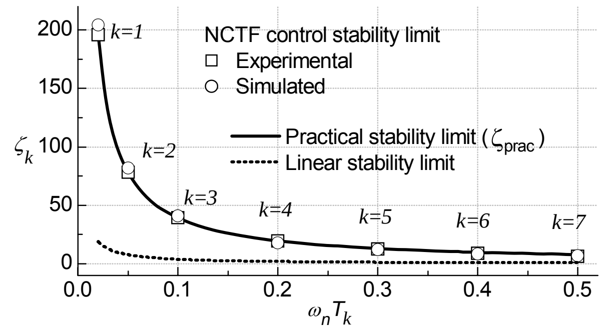


Figure 7. Practical stability limit compared to experimental and simulated results

From the comparison, it is observed that the integral element has a negligible influence on the stability of the linear system. For the following analysis, it will also be assumed that the integral element has a negligible influence on the stability of the actual system. Experiments and simulations will show that this assumption is valid.

The practical stability limit is found by driving the mechanism with the NCTF controller using only the proportional element. The value of the proportional gain is increased until continuous oscillations are generated. The determined proportional gain K_{Pu} represents the actual ultimate proportional gain. Using Eq. (3), the practical stability limit ζ_{prac} is given as

$$\zeta_{prac} = K_{Pu} \frac{K\alpha}{2\omega_n} \tag{5}$$

Equation (5) represents the maximum values allowed for a given ζ, before the control system becomes unstable. In order to prove the suitability of ζ_{prac}, the NCTF controller (using the proportional and integral elements), is designed as follows: for a fixed value of $\omega_n T_k$ (where k = 1...7), the compensator gains are calculated from Eq. (3). The parameter ζ_k is increased until the system achieves instability. The points defined by ζ_k and $\omega_n T_k$ are plotted in Fig. 7. The procedure performed both experimentally and by simulations using the mechanism model which is similar to that in [4]. As the results show, ζ_{prac} fits closely to all the points representing the NCTF control stability limit. In addition, it is observed that ζ_k represented by the linear stability limit curve is much smaller than the ζ_k determined by the practical stability limit.

Based on the above discussion, the step (iii) in the NCTF controller design is carried out as follows:

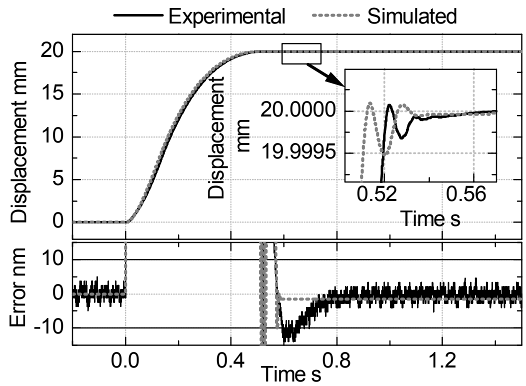


Figure 8. Response of the NCTF control system to a 20mm step input

(iii-1) The mechanism is driven with the NCTF controller using only the proportional element. The value of the proportional gain is increased in order to determine the ultimate proportional gain (K_{Pu}).

(iii-2) ζ_{prac} is obtained by using K_{Pu} with Eq. (5).

(iii-3) $\omega_n T$ and ζ are chosen within the stable region delimited by ζ_{prac}.

(iii-4) The compensator gains are calculated using parameters $\omega_n T$ and ζ with Eq. (3).

It should be noted that this procedure can be completed without any previous information about the model parameters.

EXPERIMENTS

Figure 8 shows the positioning performance for a step input of 20 mm. The compensator used in this figure is chosen to have 40% of the values of ζ_{prac}, so that the margin of safety of the design is 60%. The controller also includes the conditional freeze integrator. The achieved positioning accuracy is less than 10 nm.

Figure 9 details the positioning resolution of the control system. Stepwise inputs of 5 nm are used as reference, and the experiment is repeated for two different frictional conditions: before and after warming up. The warm-up condition is achieved by driving the mechanism with a sinusoidal reference of 20 mm in amplitude at a frequency of 0.6 Hz over 40 seconds. After the warm-up, the Coulomb friction and viscous friction were reduced by 13% and 24%, respectively. In spite of the changes in friction, a positioning resolution of 5 nm is still maintained, proving that the designed NCTF controller is robust against friction variations.

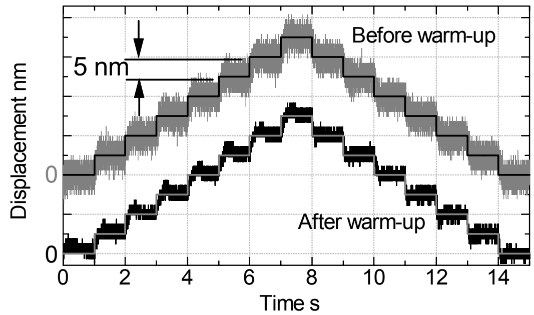


Figure 9. Positioning resolution under two frictional conditions

CONCLUSIONS

In order to clarify a simple method for ultra-precision positioning with a ballscrew mechanism, the NCTF control was introduced and improved more practically. The NCTF controller was designed without any exact identification of parameters or modeling. The practical stability limit was used to restrict the choice of two kinds of design parameters within the stable area. The designed control system achieved a positioning accuracy on the order of nanometers. The positioning resolution of the control system is 5 nm even when friction changes.

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