Dynamic Behavior Analysis of Feed Drive System Using Linear Guideways with Different Ball Diameters

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Abstract. The feed drive system for machine tool consist of rolling elements such as ball screw and linear guides. It is well known that in the positioning of linear guides using steel ball rolling, the contact surface has nonlinear spring characteristics. This phenomenon is deteriorating the accuracy of the machine tool. In this study, we have manufactured a feed drive system in which the physical contacts are only linear guides by using a linear motor as actuator. At first, we measured the responses to some fine feed amount for feed drive system. Next, the same experiment was performed by changing the linear guideways. This paper presents the transition of nonlinear spring characteristic region by considering the response to linear guides under different conditions.

1. Introduction

In recent years, positioning systems consisting of mechanically non-contact elements are increasing. There elements include the drive mechanism using the linear motor, and hydrostatic guideways using air or oil pressure. However, it is still dominant the positioning systems have contact element such as ball screw, guideway using rolling and sliding for the cost and usage conditions [1]. The increase in the physical elements of the system means the increase in the elements to be considered in improving the accuracy of the system. The friction and spring behavior caused by the mechanical contact of the elements have nonlinear characteristics, and the responses of positioning system are changed by element size and displacement amount. For the reason, several studies improve the positioning accuracy by tuning the input force or control parameters, and compensating for friction, respectively [2, 3].

In rolling guides, which are often used as guideways for machine tools, it is well known to have three different spring characteristics depending on the displacement [4]. According to a study by Futami et al. decreasing the displacement, the hysteresis loop of displacement and friction force transit from steady rolling to nonlinear spring characteristics. If the displacement is further reduced, the relationship becomes not the hysteresis loop but linear. Similar analysis of rolling guideways using sinusoidal displacement is well done [5-8].

Since these studies are considering characteristics (hysteresis loop) for one linear guide, the spring characteristics when changing the linear guide have hardly studied. In addition, it is also reported that the nonlinear friction zones appear frequently when switching the forward and reverse rotation in sinusoidal displacement [9]. The positioning accuracy is evaluated for step input; it is considered necessary to clarify the behavior for microscopic displacement.
In this study, we will compare and consider the transition of spring characteristics caused by changing the size of the linear guideways (ball diameter) for the step input. Specifically, entering different steps of displacement for the two guideways, NS15 (preload 294 N) and NS25 (preload 98 N) made in NSK, the transition of nonlinear spring characteristics is discussed from their dynamic behavior.

2. Experimental Device

2.1. Feed Drive Mechanism
The drive device used in this paper is shown in figure 1. This device consists of a table, a linear motor (made by GMC Hillston, S200Q), a guide rail, and a base. This drives the table one axis. The guideways details used in this paper shown in table 1. The device table is attached with an encoder scale (made by HEIDENHAIN, LIP201, grid scale pitch is 512 nm) for displacement measurement, and an encoder head (made by HEIDENHAIN, AK LIP 21) at the base using a jig. Guideways on height adjustment rails, encoders are mounted to achieve specified torque and parallelism.

2.2. Control Device
The experimental device configuration is shown in figure 2. In this experiment, two feed drive devices using different guideways are put on the same surface plate. These two feed drive devices use a common control configuration system by switching the connection with the linear motor and the encoder from the servo amplifier. For control, Programmable Multi Axis Controller (made by OMRON, CKE3E-1210, after this it called PMAC) is used as a host device, and PMAC is operated by the software of the PC. PMAC is operated by PC and torque commands from PMAC are transmitted to the servo amplifier, the servo amplifier supplies power to the linear motor to drive the table. The encoder reads the displacement, and the signals passing through the multiplier (made by HEIDENHAIN, maximum 16384 divisions) are fed back to the servo amplifier and PMAC.

2.3. System
The control system installed in PMAC is shown in figure 3. PMAC can select either velocity or torque control. In this experiment, position loop and velocity loop are performed by PMAC, it is torque control that to transmit current signals to the servo amplifier. The current loop is performed by the servo amplifier, which supplies power to the linear motor.

![Figure 1. Drive device.](image-url)
### Table 1. The guideways details.

|                      | NS15     | NS25     |
|----------------------|----------|----------|
| Rail width [mm]      | 15       | 25       |
| Preload [N]          | 294 (middle) | 98 (fine) |
| Steel ball diameter [mm]| 2.7781 (7/64) | 3.9688 (5/32) |

3. Feed Experiments

3.1. Experimental Conditions

The linear scale used in the experiment has a grid scale pitch of 512 nm, and the minimum resolution of 0.03125 nm can be obtained by electrically multiplying this by $2^{14} (=16,384)$. The servo amplifier does not support to this resolution. For this reason, the signals from the multiplier were divided by 16 (ignored 4 bits) and the encoder resolution was set to 0.5 nm.

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512 \times \frac{16}{16384} = 0.5 \text{ nm.} \tag{1}
\]

The servo amplifier and PMAC gains were set to that position loop proportional gain $K_p$ is 0, velocity loop integral gain $K_v$ is 0.013, current loop proportional gain $C_p$ is 1000, and current loop integral gain $C_i$ is 0. The displacement of the step inputs is 10, 5, 1, 0.5, 0.1, 0.05 and 0.1 μm. In this paper, 30 steps of input were performed using the displacement of each step input.

3.2. Comparison of Actual Force for Each Guideway

First, we compared the actual force at each linear guideway for different displacements. Here, the several displacements are extracted, and figure 4(a)-(d) show actual forces at displacement of 10, 1, 0.1 and 0.01μm of one step, respectively. In these figures, the red line is the actual force, the magenta is the average for each step of the actual force, the black is the step input command, the solid line is NS15 and the dotted line is NS25. The left and right axes represent the displacement and the actual force.
The actual force for both guideways are almost constant after the first step input at a displacement of 10μm in figure 4(a). This shows that the spring characteristics are constant because the steel ball is in the steady rolling area at this displacement. In figure 4(b), the actual force for both linear guideways show that the nonlinear spring characteristics up to around 9 μm (9th step). More than this displacement, the actual force for NS15 is increase, but the actual force for NS25 is almost constant. From that, it is considered that range of spring characteristics by linear guideway is different.

The large difference is appeared depending on the spring characteristics by the guideways in the area shown in figure 4(c). In the solid line NS15, the increase in force up to around 500 nm (5th step) is different from after that displacement. On the other hand, the increase in force after the first step is almost constant in the dotted line NS25. This shows that the area of the spring characteristics of NS15 is transitioning around this displacement. In figure 4(d), there is almost no difference between the two actual force, and the increase is almost constant. This indicates that both are linear spring characteristic area in this displacement.

### Table 2. Range of spring characteristics area.

|       | Linear area [μm] | Nonlinear area [μm] | Steady rolling area [μm] |
|-------|-----------------|---------------------|--------------------------|
| NS15 (294 N) | ~0.3            | 0.3~10              | 10~                       |
| NS25 (98 N)  | ~3              | 3~5                 | 5~                       |

**Figure 4.** Comparison of actual force for each guideways.

**Figure 5.** Comparison of actual force for each displacement.
3.3. Comparison of Actual Force for Each Displacement

Second, we compared the actual force at different displacements for each linear guideway. Figure 5(a) and (b) show actual forces at NS15 and NS25 for displacement of 10 μm-10 nm of one step. From figure 5(a), the actual force at the steps input is approximately the same at a displacement of 10 μm. At a displacement of 5 μm, 1 μm and100 nm, the forces converge to around 40 N. This indicates that the drive force becomes constant when the step input is performed multiple times, and it is considered that steel balls are in the steady rolling area for the more than those displacements.

At a displacement of 50 nm, the transition of the spring characteristic area is observed and does not reach the steady rolling area. At a displacement of 10 nm, linear spring characteristics can be observed. From figure 5(b), the actual force at the steps input is approximately the same at a displacement of 10 and 5 μm. At a displacement of 1 μm and, the forces converge to around 35 N, the transition of the spring characteristic area is observed. At a displacement of 100, 50 and 10 nm, linear spring characteristics can be observed.

4. Summary

In this paper, we performed steps input experiments with different displacements using two types of linear guideways. The experimental results were classified by guideways (ball diameter) and displacements, and the actual torque was compared. As a result, each area is summarized as shown in table 2. The linear spring area is smaller in NS15 according to table 2. It is considered that the NS15 which the diameter is small have small elastic deformation until the steel balls roll or slide. On the other hand, NS25 transitions to a steady rolling area at a displacement smaller than NS15. The rolling friction is assumed to be smaller than NS15 because NS25 has a small preload. In the future, we will change the preload of the guideways and to study the transition of spring characteristics in more detail.

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