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Measurement and analysis of friction fluctuations in linear guideways

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ABSTRACT

This paper addresses the analysis of friction fluctuations in linear guideways, which influence positional deviations of machine tool drives. Several measurement experiments evaluate the influence of contact conditions and ball circulation conditions, and fluctuations in the measured friction forces for several guideways were compared. The amplitude spectra for motion wavelengths clarified the reduction of friction fluctuations for different experimental parameters.

1. Introduction

The major function of machine tool guideways is to support a driven object, such as a table, saddle, or spindle unit, providing smoothness in the direction of motion and stability in orthogonal directions. Stiffness and damping are also essential functions of high-productivity machining [1]. Linear guideways are widely used in various machine tool drives, as they do not require special fluid lubrication equipment. Although they promote cost-effectiveness in design and fabrication, applications of high-precision drives have several drawbacks, including wave-like motion perpendicular to the direction of motion, which comes from load fluctuation with ball circulation. Guideways that do not produce such wave-motion, which employ smaller balls, have improved straightness to the order of tens of nanometers [2]. However, friction due to the rolling and circulation of balls deteriorates the trajectory accuracy of feed motion.

Many studies have analyzed and investigated compensation of friction forces in guideway systems. Transient friction changes with motion reversal prevent a driven object from moving, which causes quadrant glitches in circular motions [3]. To compensate for glitches, transient changes in friction have been analyzed and modeled. Canudas et al. proposed the LuGre model [4], which is represented by a differential equation with a Stribeck curve. Al-Bender et al. proposed a generalized Maxwell–Slip friction model [5] to emulate the complicated characteristics of hysteresis for compensation [6]. Dong et al. proposed a compliant joint mechanism to robustly reduce quadrant glitches using feedforward friction compensation [7].

For ultra-smooth motion, positional deviation from fluctuations in guideway friction must also be reduced. Friction fluctuation tends to occur in infinite-circulation linear guideways, in which balls circulate from a return tube to a groove space. This paper addresses the analysis of friction fluctuations in linear guideways, which influence positional deviations of machine tool drives. Measurement tests were designed to clarify the effect of ball contact and circulation conditions, where guideway parameters, e.g. preload, the surface profiles of guideway grooves, and ball setting were changed. Analysis of amplitudes and wavelengths of measured friction fluctuations was conducted to find key conditions to obtain ultra-smooth motion.

2. Experiment design

2.1. Tested guideways

Fig. 1 illustrates the causes of friction fluctuations in linear ball guideways. The main fluctuations come from rolling and slipping motions of preloaded balls that contact the track groove. In infinite circulation guideways, friction is also caused by ball circulation conditions because rolling balls must offer the driving force of balls in the return mechanisms. As one guideway unit has several tracks, interference becomes complicated.

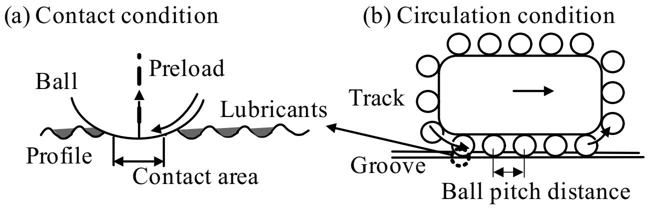

Fig. 1. Causes of friction fluctuations.

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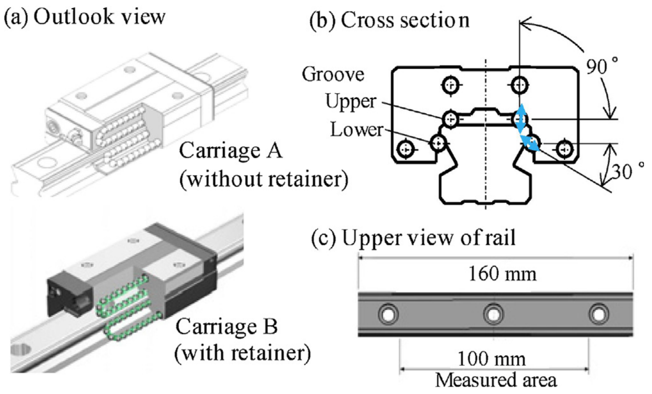

Fig. 2. Schematic of linear guideways.

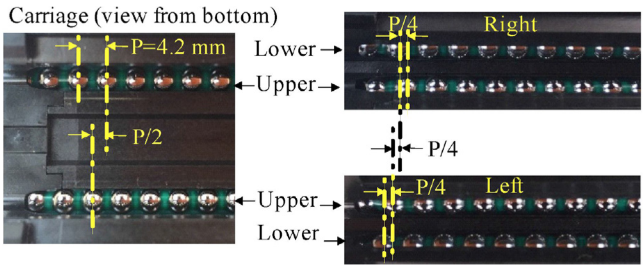

Fig. 3. Quarter-pitch-shift arrangement for retained balls in four tracks.

To investigate the effect of contact and circulation conditions on friction fluctuation, actual guideway systems shown in Fig. 2 were utilized. The guideway was a normal type with a moderate load capacity consisting of balls as rolling elements, ball retainers, a carriage, and a rail. The rail has two grooves on the upper surface and one groove on each lower slanted surface. The carriage has corresponding grooves and ball-return sections to share four infinite circulation tracks. To analyze the effect of ball circulation, two types of carriages that can and cannot accommodate the retainer—called types A and B, respectively—were selected. In the type B carriage, the relative positions of balls retained at each track were shifted by a quarter of the ball pitch distance, as shown in Fig. 3. This arrangement reduces the number of balls that enter (or exit) the grooves simultaneously. For comparison, a zero-pitch-shift arrangement was also tested.

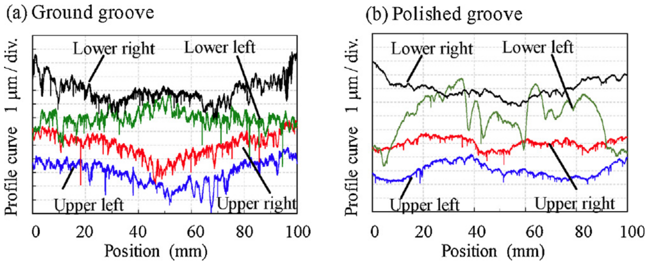

Fig. 4. Profile curves of grooves on rails.

To change the contact conditions, the grooves of carriage and rail were polished and compared with ground ones. The effect of preload was investigated by changing the ball sizes. The guideways were given from combinations of the aforementioned elements, as shown in Table 1. Fig. 4 shows the profile curves of rail grooves in the rolling direction measured with a contact profile measurement device. Although the lower-left groove seems to be polished considerably, the polished grooves have smoother profiles than the ground ones.

2.2. Experiment system

To measure the friction force of the rolling ball and circulation, together with the positional deviation induced by friction, the X axis of a high-precision machine tool was used. Fig. 5 shows a schematic view of the measurement system. While the rail of a tested guideway was placed on the X-axis table, the carriage was fixed to the Z-axis table. A force sensor, which measures the friction associated with motion, was inserted between the carriage and Z-axis table. The X-axis table was supported by an air guideway and driven by a linear motor to provide ultra-smooth motion. A linear encoder with a 500-nm resolution detected the table position. Position data was fed back to a CNC, which controls the drive with cascade P–PI control. Position deviations in this control system could be obtained from the CNC. The position signal, together with force signals, were captured by a monitoring PC. Motion and measurement conditions are shown in Table 2. For the measurements, the carriage was moved back and forth three times.

To compare the results produced by different guideways, preloads were estimated from the average friction force. The relationship between the preload and friction was obtained via a different measurement system, in which balls were placed only on the upper track of the rails and the preload was given by pushing the carriage to the rail side.

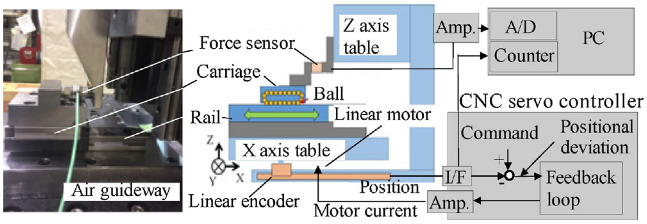

Fig. 5. Schematic of drive control and measurement system.

Table 2
Motion and measurement conditions.

Feed rate mm/min	120, 300, 600
Travel distance mm	50
Lubricant	Industrial multipurpose oil (VG100)
Motion repetitions	3

Table 1
Specification of tested guideways.

Type		AG	BG	BP
Ball	Nominal diameter	3.969 mm		
	Diameter difference from gauge ball	−4, . . . ,+7 µm	−4, . . . ,+7µm	0, . . . ,+10µm
	Number	28		
Carriage	Type	A	B with retainer	
	Size	48 mm wide × 33 mm high × 83 mm long		
Groove	Radius	2.065 mm		
	Rail	Ground		Polished
	Carriage	Ground		Polished

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