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Positioning error improvement based on ultrasonic oscillation for a linear motion rolling bearing during sinusoidal motion

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ABSTRACT

Friction can be a major disturbance to precision positioning. This study presents a method for improving positioning error in a linear motion rolling bearing based on ultrasonic oscillations. Experiments were conducted in which a single-axis linear motion rolling bearing was driven in a sinusoidal motion to simulate circular motion. Two ultrasonic actuators excited both the rail and the carriage of the guide to create relative displacements between raceways and rolling elements. The carriage of the linear motion rolling bearing was driven by a frictionless voice coil motor (VCM). The displacement of the carriage and the friction force were measured by a springless linear encoder and the VCM's current, respectively. The early stages of the experiments focused on several oscillating patterns, and their consequent impacts on positioning error during sinusoidal motion were investigated. Finally, the oscillating pattern that maximally improved the positioning error was proposed and tested. By applying the proposed pattern, the maximum displacement error, exhibited just after velocity reversal, was reduced by approximately 40%, while the average error was reduced by 26%.

1. Introduction

For linear motion drives, there are many types of linear bearings currently available on the market, including sliding bearing, rolling bearing, aerostatic bearing, hydrostatic bearing and electromagnetic bearing. Engineers select bearing type based on specific criteria to meet their manufacturing purposes and budget. In recent years, the demand for high-precision and high-accuracy machines has been increasing; this has often made frictionless bearing a likely and suitable choice. However, these types of bearings have some drawbacks. Aerostatic bearings are smooth in motion but lack rigidity and damping. On the other hand, hydrostatic bearings have higher stiffness and damping compared to aerostatic bearings, but require the use of lubricating oil that has raised environmental concerns. Meanwhile, electromagnetic bearings have many advantages, including being frictionless, lubricant-free and highly resistive toward temperature and pressure changes. They are, however, complex systems that are costly to produce.

A survey conducted by the Japan Society for Precision Engineers [1] indicates that despite the increased use of frictionless bearings, sliding and rolling bearings remain popular. Among the reasons are their high stiffness, ability to tolerate heavy loads, low cost, and comparatively uncomplicated and robust system. Moreover, the linear motion rolling bearings commercially available are improved with better performance. The main problem remains, however, of the friction force between the rolling element and raceway, even though this friction force is much lower than the friction force exists with the sliding bearings.

A great deal of work has focused on the friction problem, particularly on velocity reversal, which consists of deceleration and acceleration at very low velocity. Fig. 1 shows the circular motion error of a machining center, measured using a double ball bar [2]. In the figure, protrusions can be seen occurring at the quadrant change, caused by stick-slip at very low speed during velocity reversal. This stick-slip phenomenon has been thoroughly explained in several publications [3,4]. Vielsack [5] investigated stick-slip instability at decelerative motion, and concluded that the phenomena mainly depend on the properties of the mechanical system, especially the drive, and not on the different characteristics of friction laws. Mei et al. [6] proposed a simple approach to compensate for the friction error in a high precision table using rectangular compensation curves.

The friction force generated during reverse motion is one of the principle factors influencing contour accuracy; several methods

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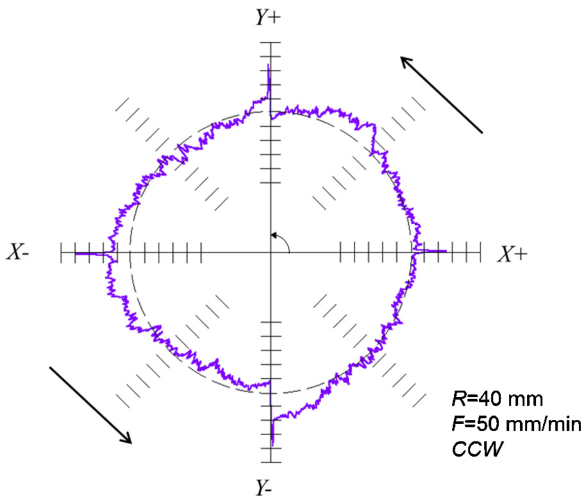

Fig. 1. Circular motion error of a machining center measured using double-ball bar [2].

have been developed to overcome the problem. The testing method for circular contour error was investigated and reported many years ago. Nakazawa [7] proposed a method that used a circular master and two-dimensional probe. Bryan [8] developed the double ball-bar (DBB), and used it to inspect the performance characteristics of two simultaneously driven linear axes. Kakino [9,10] also used the DBB to diagnose motion error origins rapidly by comparing the measured error plots with a set of reference trace patterns. Finally, Knapp and Matthias [11] introduced a circular test to demonstrate the influence of single machine errors. There have also been several approaches that investigated circular motion error [12–14].

Many of the studies on friction compensation and improvement of positioning accuracy have required a sufficient friction model and control method. However, it is difficult to deal with the problem of friction in the control field due to its deteriorating effect on precise positioning control and highly nonlinear performance in low velocity [15]. Tarng and Cheng [16] used a nonlinear model, and demonstrated that stiction-induced errors at quadrant positions can be effectively suppressed by appropriately tuning the velocity loop integral gain. Mei et al. [17] used a mathematical model to predict friction error and its characteristics in the course of feeding for a high-speed, high-precision feed servo table. Chen et al. [18] analyzed the friction force of rotating ball bearings and proposed a combination model, which consists of a non-linear spring and a plastic element to represent various hysteresis characteristics. Kaneko et al. [19] proposes a mathematical model of a feed drive system consisting of a cylindrical linear motor and linear ball guides, and clarified that quadrant glitches do not appear in the microscopic displacement region.

In terms of the characteristics of presliding friction at velocity reversal, Park et al. [20] used the estimated transition time from presliding regime to sliding regime as a criterion for distinguishing the regime of friction. Tsai et al. [21] implemented a complete feedforward compensator to compensate for machine errors caused by servo lag and friction, while Jamaludin et al. [22] evaluated friction and cutting force compensation techniques on a linear drive *XY* table using feedforward compensation based on the advanced GMS friction model. Sato and Tsutsumi [23] investigated a new generation mechanism of quadrant glitches and clarified that the generation mechanism does not depends on the velocity. Xi et al. [24,25] demonstrated a feedforward compensation method by improving circular contouring accuracies for a biaxial CNC machine. The static friction compensation was divided into two phases, which were during the presliding regime and in the sliding regime. Meanwhile, Fujita et al. [26] characterized a disturbance force in a linear drive system with high-precision linear motion rolling bearing, dividing it into a friction component and other disturbance forces. Most of this research, however, involved complicated and tedious control methods. In the current study, we propose a simpler way to reduce positioning error using ultrasonic oscillation.

2. Application of oscillation in reducing friction force

The earliest work on the influence of vibration on static friction was carried out by Fridman and Levesque [27]. They investigated vibrations of varying frequencies (6–42 Hz) normal to the contact plane by vibrating a plate while they pulled a block over it. They found a decrease of approximately 100% in the static friction coefficient with increasing amplitude. Pohlman and Lehfeldt [28] then investigated the influence of ultrasonic vibrations on friction for different vibration directions. He used a device similar to a record player needle to test the effect of ultrasonic vibration on friction, and found that when the vibration direction was parallel to the friction direction, and the velocity of the vibrating point was faster than the contact velocity, the reduction of the friction factor was significant. Lenkiewicz [29] analyzed the influence of external vibrations on dry static and kinetic friction. He reported a distinct effect of induced vibrations on the values of the force of friction for low sliding speeds, which resulted in a decrease in the friction force values of up to 15% of the original value.

Within a few decades, ultrasonic oscillation has become a major application in various fields. Kutomi et al. [30] reported that ultrasonically excited nanoscratch tests have revealed changes in the friction coefficient, and are now sought as fast qualitative/quantitative techniques for overcoat films. Sinn et al. [31] performed an ultrasonically assisted experiment in woodcutting. Results showed a reduction in cutting forces on the order of 50% was achieved at relatively small vibration amplitudes. In rolling-element linear bearings, Oiwa [32] conducted several experiments in which ultrasonics oscillation was applied to the linear motion rolling bearing. He reported that the frictional force between the rail raceways and bearing balls was reduced by approximately 25%. Finally, Teidelt et al. [33] reported the influence of ultrasonic on static and sliding friction. They reported that the frictional force typically decreased with increasing oscillation amplitude, and the decrement was larger at smaller sliding velocities.

Fig. 2 shows the rolling model. Theoretically, the bearing ball used in the linear motion rolling bearing geometrically contacts the upper and lower race at “points”. In reality, however, due to the existence of preload, the bearing ball does not undergo perfect rolling. It can be imagined as being compressed by the upper and lower races, which results in the elastic deformation of the roller and ball [34]. Instead of point contacts, the bearing ball should be assumed to have a plane contact, as may be seen in the figure. For this reason, to some extent, the friction behavior of a rolling bearing is considered to have a typical behavior with sliding friction.

Despite the abundance of studies on the influence of oscillations on friction, only a few have considered ultrasonic application on a linear motion rolling bearing using a bearing ball. In terms of sliding friction, Kumar and Hutchings [35] studied the friction between metallic surfaces in the presence of ultrasonic vibration. Fig. 3 is an illustration of body *A*, which is assumed to slide with a constant velocity V_s, on body *B*, which has an oscillatory motion of amplitude a and angular frequency ω in parallel and perpendicular direction to V_s. Significant reduction in sliding friction was observed for both methods, although the reduction for perpendicular oscillation was less than for parallel oscillation. During the perpendicular oscillation, when the instantaneous velocity of **B**,