Analysis and Compensation of Friction Force in High-precision Linear Drive System

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Abstract

The friction force in a linear drive system supported by rolling guideways is analyzed. The present analysis separates the influence of the stick friction and slip friction. The locomotive multi-bristle model is suggested to analyze the friction characteristics. With this model, the motion error compensation is conducted in circular tests. Measured results are compared with the conventional friction compensation.

1 Introduction

The friction force on rolling guideways affects the motion accuracy particularly in high-speed motions. The stick-slip is one of well-known phenomena caused by such a friction. For high-speed and high-precision feed drive systems with rolling guideways, the analysis and the compensation of friction force are clearly important.

Futami [1] reported the hysteresis characteristics of linear ball guideways. According to the authors' previous work, the friction force can be divided into the stick friction component and the slip friction component [2].

From analysis results, many friction models have been suggested for the friction compensation in the literature. Canudas modelled the friction force as a function of the velocity with a single bristle having the spring characteristics with the saturation [3]. Though it is possible to represent the stick friction component with this model, it is difficult to represent the slip fiction characteristics as well.

The objective of this research is to develop a friction compensation methodology to improve the motion accuracy in high-speed circular motions. The friction force in a linear drive system supported by rolling guideways is analyzed. The locomotive multi-bristle model to represent both the stick friction and the slip friction is suggested. Based on this friction model, the motion error compensation is conducted in circular motion. Measured results are compared with the conventional friction compensation method.

2 Locomotive multi-bristle model

Figure 1 shows a schematic of a linear ball guideway and the contact surface modeled with multiple bristles. Balls and the rail are assumed to be in the same contact state. The tangential force at $y=y_o$ is defined a the function in the contact surface coordinate system; $q(x,y_0)$. Bristles have following characteristics:

(1) Every line parallel to x-axis is defined as a stripe. Bristles enter and exit along the stripe. Bristles are deformed by the slip velocity between the ball and the race.

(2) In the stick region, bristles are elastically deformed. When the elastic deformation of each bristle exceeds a threshold, it starts to slip and the elastic force is hold constant (slip region). In the slip region, the tangential force is also affected by the viscosity.

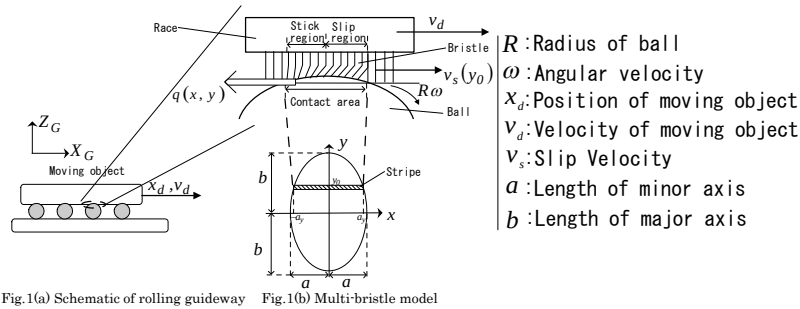

Fig.1(a) Schematic of rolling guideway Fig.1(b) Multi-bristle model

The friction force on contact surface is calculated as follows. Firstly, the tangential force on each stripe is calculated. The slip velocity, $v_s(y)$, is given by:

$$v_s(y) \cong (v_d - \omega R) - \frac{\omega}{2R} y^2 \qquad (1)$$

The tangential force on the stripe is approximated by:

$$q(x,y) = \begin{cases} -k_q \cdot \xi(y) \cdot (x + a_y), & if \quad q(x,y) \le U_{\max} \\ U_{\max} + C_v & otherwise \end{cases} \qquad (2)$$

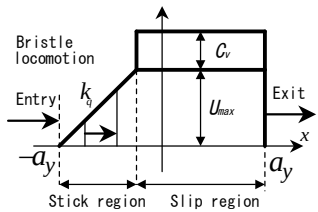

Fig.2 Model of tangential force

Note that $\xi(y)$ represents the ratio between the slip velocity and the velocity of moving object.i.e; $\xi(y) = v_s(y)/v_d$. The distribution of the tangential force is shown in Fig.2.

Then, the friction force on each stripe is calculated by integrating this tangential force. Finally, the total friction force on the contact surface is obtained by integrating the friction force on the each stripe.

3 Analysis of friction characteristics

To build the present friction model, the following experiments are conducted. A feed drive moves by 0.2 mm and takes a short pause. This operation is repeated 20 times for one direction. Figure 3(a) shows the measured friction characteristics.

Simulation parameters are identified by measured friction profile. Figure 3 (b) shows the simulated friction characteristics. In Fig.3 (a), circles represent averaged frictions when the drive is stationary (v_s=0), and the curve connecting the circles shows an inner hysteresis loop. The inner hysteresis loop represents the stick friction. The difference between the inner loop and the outer loop shows the slip friction. The simulated result also shows the same friction characteristics.

In the conventional friction compensation, the magnitude of the outer hysteresis loop is commanded as the compensation force. However, when the command includes the dwell, the slip friction becomes zero. Therefore, the compensation command may become larger than the actual friction force.

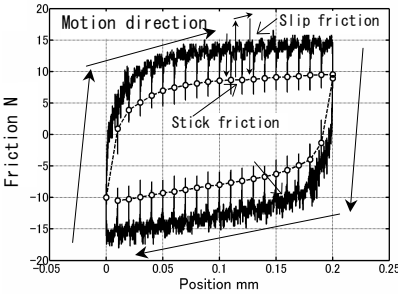

Fig.3 (a) Measured friction force

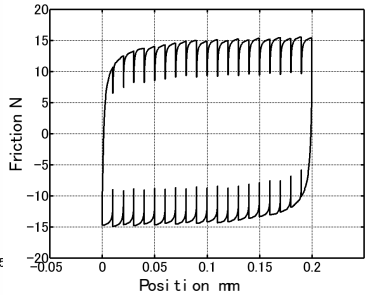

Fig.3(b) Simulated friction force

4 Compensation of friction force

The friction compensation is tested in a circular motion. In this compensation, the friction model is simplified as a function of the table position. In the stick region, the simplified friction model commands compensation force proportional to the position. In the slip region, a constant compensation force is commanded.

The following three cases are compared; Condition A performs no compensation, Condition B assumes spring constant of 40 N/μm in the stick region, and gives constant command of 26 N in the slip region. Condition C assumes spring constant of 40 N/μm and constant command of 20 N. The radius of circular path is 20mm and

commanded feed rate is 3.6 m/min. Two tests are conducted under: 1) continuous circular motion and 2) circular motion with shortly stopping at a quadrature point.

Figure 4 (a) and (b)shows measured contour error profiles under 1) the continuous circular motion and 2) the circular motion stops at the quadrature point for 0.5 sec, respectively. Note that contour errors are magnified 5000 times. In Condition B, the maximum contour error is less than 0.1 μm in the continuous circular motion. However, in the circular test with the quadrature stop, the contour error exceeds 0.3 μm. This is because the slip friction became zero when the table stopped, which caused the over-compensation. In Condition C, which gives smaller constant command, the contour error became about 0.1 μm in Fig. 4(b), while it is 0.2 μm in the continuous circular motion in Fig.4 (a). It is necessary to modify the compensation condition for higher accuracy.

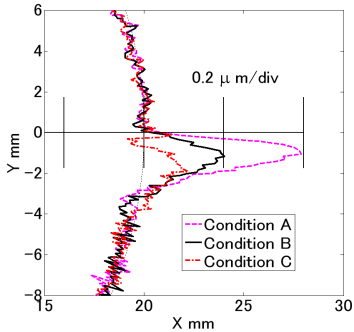

Fig.4(a) Continuous circular motion

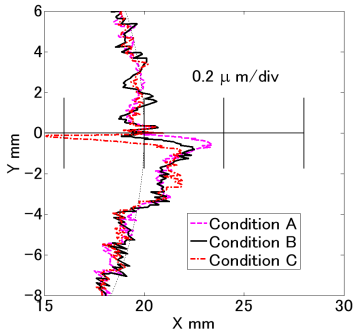

Fig.4(b) Circular motion with dwell

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