Journal of Mechanical Science and Technology 32 (6) (2018) 2723~2734
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-018-0529-6

Improved friction model for the roller LM guide considering mechanics analysis †

De-Jun Cheng, Tae-Jo Park and Su-Jin Kim*

Department of Mechanical Engineering, Gyeongsang National University, Jinju, Korea

(Manuscript Received June 11, 2017; Revised February 26, 2018; Accepted February 28, 2018)

Abstract

In machining centers, investigating friction force in the linear motion (LM) guide is important in improving the positioning performance of the center. We analyzed the contact force and the contact pressure between the roller and raceway via the Palmgren formula and Hertzian contact theory, respectively. Based on Albrecht's friction model, an improvement model for calculating friction force was proposed which takes into consideration the bearing's geometrical parameters, the contact force and the changes in grease viscosity with pressure and temperature. The coefficients in the improved model were obtained from previously published experimental results. The improved model was verified by comparison to previous empirical equation results and the experimental results. The analysis showed that the improved model predicts the friction force more accurately compared to the previous model, and it will lay the theoretical foundation for predicting friction behavior in the linear motion guide.

Keywords: Roller linear motion guide; Improved friction model; Contact force; Contact pressure; Grease viscosity

1. Introduction

The roller linear motion (LM) guide has advantages in high positioning accuracy, high rigidity, good precision retaining ability, and long-term maintenance-free operation; thus, roller linear motion guides are a key feature of computer numerical control machining (CNC) equipment. However, in the machining center, the friction force in the LM guide has an effect on the machining performance of a machine tool and accuracy of positioning. Therefore, investigating friction force is important in optimizing the control system and improving the positioning performance of the roller linear guides.

Elastohydrodynamic lubrication (EHL), as the main lubrication mechanism of rolling bearing, has been extensively studied. In engineering practice, no surface is ideally smooth, and surface roughness is often of the same order of magnitude as, or greater than, the average lubricant film thickness, so that a complete separation between the two surface seldom occurs. Mixed EHL is a model in which both EHL films and surface asperity contacts coexist and neither can be ignored [1]. With the development of EHL theory, a great deal of theoretical and experimental work has been published on both film thickness and traction in rolling and/or sliding contacts. The study of frictional resistance has been addressed for different types of rolling bearings, such as tapered roller bearings, angular contact bearings and thrust ball bearings and so on. Various analytical models have been suggested for calculating hydrodynamic rolling force in the full film lubrication regime [2-7].

There has been a great deal of research conducted in relation to the modeling of non-linear friction characteristics, such as ball screw and rolling ball guide. Some researchers [8-12] studied the behavior of friction force in a linear rolling guide under various constant velocities, and the non-linear friction characteristic was reported and described using Stribeck friction curve. Generally, these models include three kinds of forces: Coulomb friction, Stribeck friction, and viscous friction. Moreover, Albrecht [13] introduced an improved friction model that includes Coulomb friction, Stribeck friction and one more component in viscous friction to compensate the total friction force. Jang [14] experimentally investigated the friction force of an LM ball guide using Box-Behnken design (BBD) of response surface methodology for various velocities, preloads and external loads. Experimental results show a typical Stribeck friction curve corresponding to the velocity (as shown in Fig. 3 from Ref. [14]), an increasing of the velocity lead to a decreasing of the friction force, but only to the velocity of 0.02 m/s. over this velocity, an increase of the friction force is obtained. Olaru [15] conducted the forces and moments theory in the ball linear motion guide system based on the friction models of rolling bearings, and predicted the variation of friction coefficient with the velocity and the influence of ratio C/P. Compared with experimental results obtained from Jang [14], under the same load ratio of C/P: 4 and the range of 0.1 ~ 0.4 m/s, the friction coefficient decreases as

*Corresponding author. Tel.: +82 55 772 1636, Fax.: +82 55 772 1577
E-mail address: sujinkim@gnu.ac.kr
† Recommended by Associate Editor In-Ha Sung

speed increases, which is opposite of Jang's [14] results. The comparison results show that the equilibrium of forces and moments theory by used the existing friction model cannot well describe the frictional behavior of linear motion guide. It can be concluded by reviewing the literature that the existing friction equation of the LM guide is only derived from experimental results, and these equations have some restrictions for application in a wide range of operating conditions due to their derived under limited model factors such as velocity, preload and external load. Thereby, it is still a hot topic to accurately predict the frictional behaviors in the LM guide.

We [16, 17] already investigated the frictional behavior in roller linear motion guide experimentally and derived an empirical friction equation through experimental results. In this paper, we studied the complex friction behavior of the roller linear motion guide during various operations. Especially, the analysis of contact force, pressure and viscosity was used to improve the LM friction model. Based on theory of contact analytical mechanics and the Palmgren formula, we obtained the normal contact force between the roller and raceway and the deformation of the roller. The pressure distribution between the roller and raceway was analyzed via the Hertzian contact theory. Also, the viscosity model used in this study includes the parameters of lubricant, temperature and pressure. An improved model for calculating friction force in the roller linear motion guide is proposed from the Albrecht friction model, which takes into consideration the bearing's geometrical parameters, the contact force and the changes in grease viscosity owing to pressure, lubricant and temperature. The experimental constant values in the proposed model are obtained from previous published experimental results. Afterward, the improved model is verified by the comparison of our calculated results to those of previous published model and as well as to experimental results. Further analysis investigates the importance of operating parameters on the friction force response of the roller LM guide.

2. Mechanics analysis of the roller LM guide

2.1 Contact force between the roller and raceway

In an actual machine center, relationships between the loads and deflections of all components involved when considering the elasticity of the rollers and the raceways are very complex. It is a kineto-elasto-dynamical (KED) problem with various contact constraints. In this study, following the contact analytical method of linear rolling guide proposed in Refs. [18, 19], the contact deformation of the linear rolling guide is represented by the equivalent contact deformation of the rollers between raceways due to the direct and simple relationship between them [18, 19]. However, the governing equation for a system of rollers in an actual linear guide of a machine center is required to consider the KED problem. This issue will be addressed in our future research.

From THK catalog (Sec. A-1 pp. 412-441) [20], roller LM guide that consists of rail and block is transported by four rows of rollers and each row has many rollers. Each row of rollers is arranged at a contact angle of 45° so that the LM block receives an equal load rating in all four directions, as shown in Fig. 1.

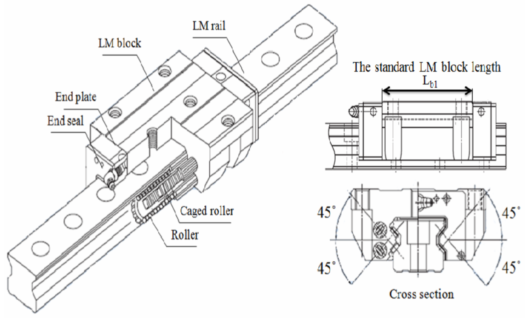

Fig. 1. Schematic of the roller linear motion guide [20].

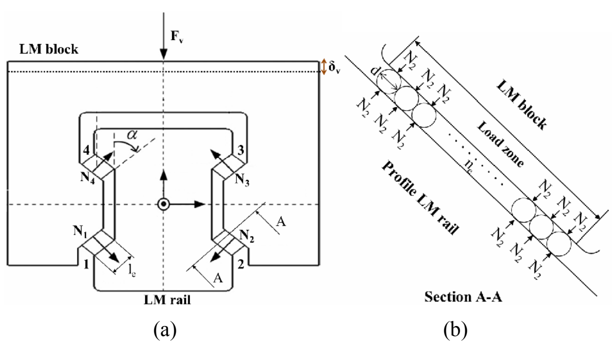

Fig. 2. Contact force of the roller linear motion guide and Sec. AA along the perpendicular direction.

In the LM guide system, preload is an internal load applied to the rolling elements (roller) in advance to increase the rigidity of the LM block. The elastic deformation between roller and roller grooves under preload is named as initial deformation δ_0. The magnitude of deformation of each row of the roller under loading can be calculated based on contact mechanics. Fig. 2 shows the applied vertical load on the roller linear guide and the contact force on the roller from the contact surface of the block. The vertical load F_v is applied on the LM block. The normal contact force on each roller of the i-th row from the contact surface of the block is $N_i (i = 1,2,3,4)$. By setting the displacement of the block in the vertical direction is δ_v. We obtain the deformation amount of δ_i of the roller of the i-th row:

$$\delta_i = \delta_0 + \delta_V \cos\alpha, \qquad i = 1,2 \tag{1}$$

$$\delta_i = \delta_0 - \delta_V \cos\alpha, \qquad i = 3,4 \tag{2}$$

where α is the angle between the normal direction of the contact surface and the vertical axis direction. When under the effect of vertical load, contact deformation occurs between the roller and raceway. This contact deformation can be regarded as an elastic deformation between an elastic cylinder with a finite length and a rigid plate; this deformation can be modeled by using the Palmgren formula [21]: