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Modeling analysis and experimental study for the friction of a ball screw

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ABSTRACT

This paper aims to develop a new systematic creep analysis model to calculate the friction of a ball screw. In order to investigate the friction behavior better, a proper transformed coordinate system was established. Through the creep analysis and the principle of force balance, the creep parameters can be easily obtained, such as the vertical creep ratio, the horizontal creep ratio and the spin ratio acting on three contact areas. Based on roll contact theory, the ball screw friction can be predicted more accurately. The effectiveness of the creep analysis model is verified through experiments. Furthermore, the influence of the creep parameters on the ball screw friction and friction distribution will be discussed. The study not only provides a new perspective and approach for the study of ball screw friction, but also provides the theory basis for reasonably reducing the friction and improving the mechanical efficiency of a ball screw.

1. Introduction

Due to the relatively low cost and insensitivity to inertia variation and external forces, the application of ball screws in the positioning machine tool has been promoted further especially in the aspects of high speed and precision. This has led to increasing attention being paid to the influence of ball screw friction on precision and mechanical efficiency [1]. After considerable research, it has been gradually realized that the influence of the friction element on the dynamic performance of ball screws cannot be ignored especially under the condition of high precision and speed [2].

The friction of ball screw is defined as movement resistance caused by all kinds of friction factors in a ball screw, which lead to a reduction of the mechanical efficiency of the ball screw with a loss of energy and positioning accuracy with the thermal deformation. The friction model should be quicker and more efficient to predict the energy loss and temperature rise rates. Due to similarity, there is certain inheritance between the analysis of ball screws and ball bearings, and research into ball bearings can be taken as a reference point when researching ball screws. The kinematics and dynamics analyses of ball screws should be investigated first. Jones [3] introduced the raceway control theory in the process of studying dynamics on ball bearings. In Harris's paper [4], it was demonstrated that the raceway control theory is generally valid for high-speed ball bearings and the friction behavior between a ball and the inner raceway of ball bearings was analyzed. Harris believed that the friction is generated by pressure on the ball's surface and deemed this friction behavior would lead to abrasion of the ball bearing. Based on Harris's research, Lin and Wei et al. [5] proposed a systematic theoretical method to investigate the kinematics of a ball screw using Frenet–Serret coordinates, in which the Coulomb model is used to analyze the friction between the ball and screw (or the nut). Aiming at increasing the accuracy, Olaru D et al. [6], suggested

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an improved Coulomb friction model. Based on Kamalzadeh A's [7] research, Su [8] found that the improved Coulomb friction model proposed in [6] still cannot predict the ideal result for a high-precision ball screw.

Numerous studies indicated that most of the calculations of ball screw friction were based on Coulomb friction model assuming that all balls were equally loaded and the friction between balls were ignored. In general, these methods can well meet the requirements of engineering practice under low and medium precision conditions, which have a certain application market. However, there are certain limitations to the Coulomb friction model in non-planar situations, which mean that the Coulomb model cannot essentially be used to improve the precision of ball screw friction calculations. Considering the influence of gyroscopic effect on quasi statics balance of ball bearing, Kalker [9–12] did a series of kinematics analysis on ball bearings with unlubricated contact. The model Kalker produced is not perfect enough, but it does provide an effective solution to the existing problem of ball the screw.

In order to improve the accuracy of ball screw friction calculations and to solve the above problems, the roll contact theory is used in this paper to analyze ball screw friction. The friction between the balls in the ball screw is taken in consideration and the problem of stress inequality in every circle of a ball screw is discussed. This paper is organized as follows. The homogeneous coordinate transformation systems and the ball screw friction calculated using the creep analysis model is given in Section 2. The results of the friction torque calculated by creep analysis model and the experimental measurements are compared and discussed in Section 3. The influence of the creep parameters on the friction distribution on the slipping area is also presented in Section 3. Finally, we summarize the main findings of this work and draw conclusions in Section 4.

2. Theoretical analysis

In order to calculate the friction of a ball screw, three coordinate systems are established first: global coordinate system, Frenet–Serret coordinate system and contact coordinate system. The global coordinate system, (x, y, z), is fixed at the center of the nut chassis, the screw axis is in the same direction with z axis. The Frenet–Serret coordinate system [13], (t, n, b), is fixed at the ball center whose moving trajectory is in line with the t axis direction. The contact coordinate system, $(e_\lambda, f_\lambda, g_\lambda)$, is fixed at the contact points between the ball and raceway and the contact point pointing to the ball center is coincident with the g_λ axis direction. Here, $\lambda = A$ represents the contact point between the ball and nut raceway, and $\lambda = B$ represents the contact point between the ball and screw raceway. The relationship of contact coordinate system with Frenet–Serret coordinate system and global coordinate system is shown in Fig. 1.

As shown in Fig. 1, the angle between b-axis and z-axis is α, which has the same value of helix angle. The angular velocity of screw and nut are defined as ω and ω_N, respectively. β_B and β_A represent the contact angle of the ball with respect to the screw and nut, respectively. r_b is the radius of ball.

2.1. Homogeneous coordinate transformations

In order to facilitate the systematic study of the theoretical model, the transformation relationships between the different coordinate systems must be established. The homogeneous coordinate transformations between the two coordinates (t, n, b) and (x, y, z) can be obtained through three transformations. One, the origin of the global coordinate system is translated to the intersection point H along the helix line, which is marked as $Trans(r_m \cos\theta, r_m \sin\theta, r_m\theta \tan\alpha)$. Two, the global coordinate system is rotated around the z axis by $(\theta + \pi/2)$-degree to make x and y axes coincident with t' and n' axes which are the projections of t and n axes on the $x - y$ plane, and is marked as $Rot(z, \theta + \pi/2)$, as shown in Fig. 2(a). Three, the global coordinate system is rotated around y axis by $(2\pi - \alpha)$-degree, which is marked as $Rot(y, 2\pi - \alpha)$, as shown in Fig. 2(b).

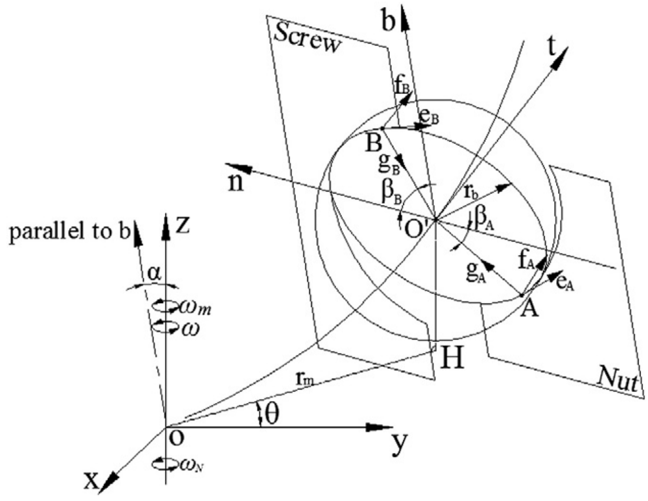

Fig. 1. Three coordinate systems.