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Research on the dynamics of ball screw feed system with high acceleration

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ABSTRACT

For the ball screw feed system with high acceleration, the large inertial force derived from the moving components may change the real contact state of the system kinematic joints, resulting in the changes of the contact stiffness and hence the dynamic characteristics of the feed system. In this study, an equivalent dynamic model of the ball screw feed system is established using lumped parameter method considering the influence of the acceleration. Equivalent axial stiffnesses of screw-nut joints and bearing joints are both derived based on the contact state due to the variation of inertial force. The experiments on the ball screw feed system driven with different accelerations are also performed to verify the dynamic model proposed. The variation of the contact stiffness of the kinematic joints, transmission stiffness and natural frequency of the feed system are discussed with acceleration and the results show that they all reveal sudden changes when acceleration reaches a certain value. Total load, rated dynamic load and screw tension force have a great effect on the system natural frequency at different accelerations. The largest acceleration the feed system can reach is determined by the smaller one of the two critical accelerations for nut joints and bearing joints.

1. Introduction

Ball screw feed system is popularly used in various kinds of machine tools. Its dynamic characteristics have important influence on the control performance [1], the machining accuracy of workpiece [2–4] and the stability of cutting process [5]. Therefore, the research on its dynamic characteristics has received great attention.

In order to predict the dynamics of machine tool at the design stage, Poignet et al.[6] and Khalil and Gautier [7] established a dynamic model of the machine tool feed system in the transmission direction by using lumped parameter method, containing 8 masses and 7 springs. Pislaru et al. [8], Okwudire and Altintas [9] and Okwudire [10] analyzed the dynamic characteristic of the ball screw feed system by a hybrid model, where the flexibility of the screw shaft was considered. Zaeh et al. [11] employed FEM to investigate the influences of the part stiffness on the dynamic performance by modeling a ball screw feed system. Feng and Pan [12] used lumped parameter method to analyze the influence of preload on the dynamic performance of screw-nut system. Mi et al. [13] analyzed the variation of dynamic stiffness on tool point due to serials of preloads of the screw-nut joint, and found the preload value can greatly change the stiffness in the transmission direction. On the other hand, the friction is also a significant factor for dynamics, which depends on the feed velocity. Verl and Frey [14] experimentally studied the variation of the screw-nut joint's preload with different feed velocities in order to estimate the operating life of a feed drive. For high speed ball screw feed system, Zhang et al. [15] analyzed the variation of the equivalent axial stiffness of individual kinematic joint, the system transmission stiffness and system natural frequency with the different feed rate, and found that the ball screw feed system behaves velocity-dependent dynamics. Chen et al. [16] developed a mechanical model of a ball screw feed-drive system and found the mechanical compliance can cause a significant contouring error at high acceleration.

In high speed machining, high acceleration is also really expected for feed drive system. The inertial force derived from acceleration may change the real contact state of the kinematic joints, resulting in the changes of the contact stiffness of the kinematic joints and the transmission stiffness, which would further affect the dynamic characteristics of the feed system. In this study, an equivalent dynamic model of the feed system was established using lumped parameter method, and the worktable's acceleration was taken into account to influence the contact stiffness of the kinematic joints. The variation of the equivalent stiffness of the kinematic joints, transmission stiffness and natural frequency of the ball screw feed system were discussed.

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2. Dynamic model of the ball screw feed system with high acceleration

2.1. Equivalent dynamic model

A typical ball screw feed system consists of worktable, screw shaft, screw nut, bearings, linear guide and slider, as shown in Fig. 1. Among the three directions (X, Y, Z), the stiffness in the Y direction (transmission direction) is the smallest because of the kinematic joints including screw-nut, screw-bearing and slider-guide. As a result, the dynamic characteristics of the feed system mainly depend on the transmission stiffness. For the feed system with high acceleration, the inertial force should be considered, which would act on the joints of screw-nut and bearings and then affect their contact stiffness. The friction force, however, is neglected here owing to the small value compared with inertial force.

In the dynamic model, screw shaft, screw nut joints and bearing joints are equivalent to lumped spring elements, and worktable is equivalent to a lumped mass element. The equivalent dynamic model of the ball screw feed system is established by ignoring the effect of servo stiffness, as shown in Fig. 2.

In Figs. 1 and 2,

m is the mass of the feed system including workpiece;
a is the acceleration in the transmission direction;
y is the distance between nuts and rear-end support bearing unit;
L is the screw length between rear-end support bearing unit and front-end support bearing unit;
$K_{ls}(y)$, $C_{ls}(y)$ and $K_{rs}(y,p)$, $C_{rs}(y,p)$ are the generalized axial stiffness and damping of the screw shaft on left and right sides of the nuts;
$K_{lb}(m,a,F_{as})$, $C_{lb}(m,a,F_{as})$, $K_{rb}(m,a,F_{as})$ $C_{lb}(m,a,F_{as})$ and $K_{nut}(m,a,P)$, $C_{nut}(m,a,P)$ are the axial equivalent stiffness and damping of the left and right bearing unit joints, the axial equivalent stiffness of the screw-nut joints, respectively;
F_{as} is the screw tension force;
P is the preload of the double nuts.

2.2. Motion equation considering the influence of acceleration

As described in Section 2.1, the frequently changed acceleration would lead to the variation of stiffness. Therefore, according to the equivalent dynamic model and D'Alembert principle, a variable-coefficient dynamic equation of the feed system is established as:

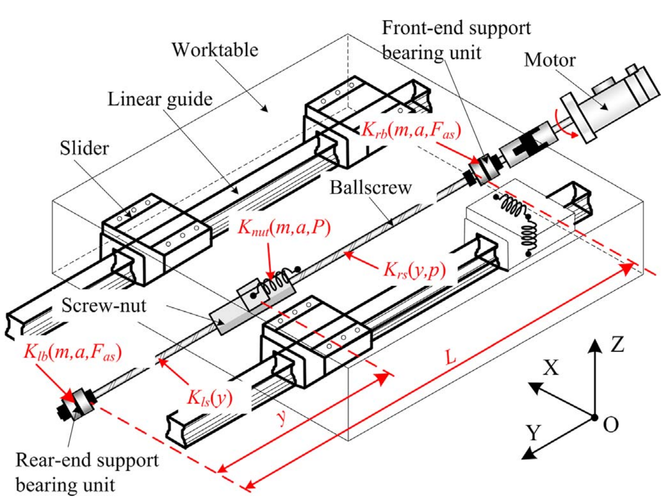

Fig. 1. The structure of a ball screw feed system.

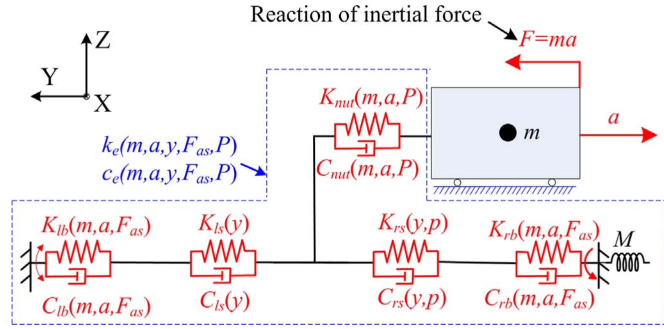

Fig. 2. Equivalent dynamic model of the ball screw feed system with high acceleration.

$$m\ddot{x} + c_e\dot{x} + k_e(m,\, a,\, y,\, F_{as},\, P)x = 0 \tag{1}$$

where k_e is the total stiffness coefficient determined by the acceleration, mass and position of the worktable and screw tension force. In this study, only natural frequency of ball screw feed system is considered and thus the damping coefficient c_e is neglected.

2.3. Calculation of the stiffness coefficients

2.3.1. Equivalent axial stiffness of screw-nut joints

Fig. 3 shows the cross-section of the gasket-type double-nut ball screw joints. It is assumed that only the balls between screw-shaft and screw-nuts produce the elastic deformation, which can be calculated by the Hertz contact theory [17]. The initial normal force and deformation of each ball are obtained by Eq. (2) if no external load is applied on the nuts.

$$\begin{cases} P_A = P_B = \dfrac{P}{N\cdot \sin\alpha\cdot \cos\varphi} = \dfrac{P_d\cdot c_p}{\left(i\cdot \frac{\pi\cdot d_{s0}}{d_{sb}\cdot\ \cos\varphi}\right)\cdot \sin\alpha\cdot \cos\varphi} \\ \delta_A = \delta_B = \left(\dfrac{1}{K_h}\right)^{2/3}\cdot {P_A}^{2/3} \end{cases} \tag{2}$$

where

d_{s0} and d_{sb} are the diameters of screw and ball, respectively;
α is the contact angle between the ball and the race;
φ is the lead angle of the screw;
i is the total number of load bearing ring of the single nut;
N is the number of bearing balls;
P_d is the rated dynamic load of screw-nut joints;
P_A and P_B are the ball's initial normal forces of nut A and nut B, respectively;
c_p is the coefficient of the rated dynamic load;
δ_A and δ_B are the ball's normal deformation of nut A and nut B.

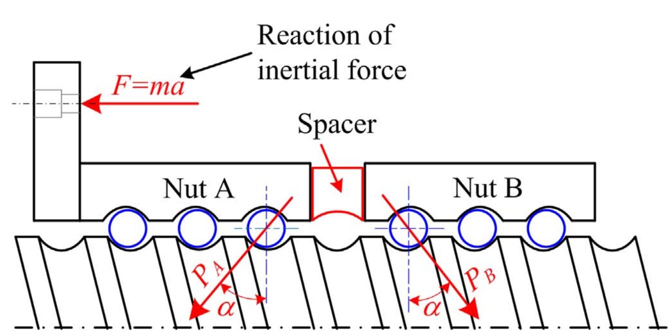

Fig. 3. Cross-section view of a gasket-type double-nut ball screw joints.