Dynamic Characteristics Analysis of Ball Screw Pair Based on Joint Stiffness

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Abstract

In this paper, a certain type of ball screw pair is taken as the research object. Firstly, the stiffness of the ball screw joint is calculated by Hertz contact mechanics theory, and then the dynamic model is established by mechanical system dynamics. Finally, the 3D software model is built using 3D software, and the model is simplified by reasonable. Using the pre-processing function of hypermesh to divide the grid, the finite element model of the ball screw pair is accurately established under the condition of considering the influence of the joint on the dynamic performance. The theoretical modal analysis of the ball screw pair is carried out in the abques. And the results of the theoretical modal analysis are compared with the results before the equivalent, and the conclusion is drawn.

Keywords

Ball screw pair, Finite element analysis, Modal analysis.

1. Introduction

As a common mechanism in the modern machine tool feeding system, the ball screw pair has the advantages of high precision, high rigidity and compact structure. It is the bottleneck that must be overcome in the development of modern CNC machine tools to high speed and high precision. Therefore, the dynamics of the ball screw pair Performance has also raised higher requirements. In some large horizontal machining centers, the table travel is longer for smaller machines, and the lead screw is correspondingly longer. Due to the elasticity, the dynamic performance of the entire feed system is poor, and machine resonance is prone to occur. Processing accuracy does not meet the requirements and other issues [1]. This not only affects normal work production but also increases equipment maintenance and repair costs. Therefore, it is necessary to conduct a more in-depth study on the dynamic performance of the ball screw pair. Although many experts and scholars have carried out a series of dynamic performance studies on it, since the characteristics of the joint of the ball screw pair are not fully considered, the ball screw joint is equivalent to the spring damping unit on this basis. Free modal analysis of a certain type of ball screw pair using the finite element method.

2. Theoretical calculation of contact stiffness of ball screw joint

2.1 Hertz contact theory

Hertz contact theory is widely used to calculate elastic contact deformation and contact stress under the action of mutual contact forces [2], but the theory must be applied to satisfy the Hertz contact between the two interacting bodies. As shown in Figure 1-1, the Hertz contact under the action of force F needs to satisfy the following assumptions: (1) the contact system consists of two materials with uniform and isotropic properties; (2) the contact surfaces of the two objects are smooth, only With normal force, there is no tangential friction, and the deformation of the contact object is a small deformation that can be predetermined by the contact point; (3) the size of the contact surface is much smaller than the radius of curvature of the surface of the contact object and the contact surface is elliptical (4) The relationship between stress and strain takes a linear relationship. And for the ball screw pair, the centrifugal force and torque of the ball rotation are very small, which is more in line with the Hertz contact theory.

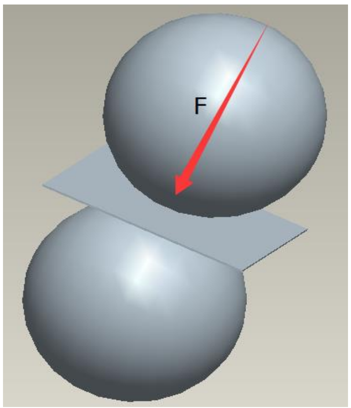

Figure 1. A schematic view of two elastic body contact

According to the Hertz contact theory, the distance between the two contact bodies in the center of the contact area due to the elastic deformation is:

$$\delta_i = \frac{2K_i}{\pi a_i}\left\{\frac{1}{8}\left[\frac{2}{3}\left(\frac{1-u_1{}^2}{E_1}+\frac{1-u_2{}^2}{E_2}\right)\right]^2\right\}^{\frac{1}{3}} \times (\sum\rho)^{\frac{1}{3}} \times Q^{\frac{2}{3}} \tag{1}$$

2.2 Calculation of contact stiffness of ball screw joint under dynamic condition

The ball screw pair of the machine feed system is preloaded by means of misalignment preloading, ignoring the influence of external axial load during operation. Assuming that the axial load is evenly distributed between the loaded balls and ignoring the rotation of the balls in the operating state, the axial stiffness of the ball screw joint can be calculated based on the Hertz contact theory. The normal force of a single ball to nut and screw race is P,The pressure angle at which the ball contacts the raceway is β.δ_1， δ_2 are the contact deformation of the ball and the nut and the screw raceway[3].

This can be obtained by analyzing the force of the nut in the axial direction:

$$F_a - PZ\sin\beta\cos\emptyset = 0 \tag{2}$$

The combined curvature of the ball-nut contact point is:

$$\sum\rho_1 = \frac{2}{d_b} + \frac{2}{d} - \frac{1}{d_b f_1} - \frac{2\cos\beta\cos\emptyset}{d+d_b\cos\beta} \tag{3}$$

The combined curvature of the ball and screw contact point is:

$$\sum\rho_2 = \frac{2}{d_b} + \frac{2}{d} - \frac{1}{d_b f_2} - \frac{2\cos\beta\cos\emptyset}{d+d_b\cos\beta} \tag{4}$$

The axial displacement of the nut relative to the lead screw is obtained by the geometric relationship:

$$\delta_a = \frac{(\delta_1+\delta_2)}{\sin\beta\cos\emptyset} \tag{5}$$

After the data is substituted, the axial stiffness of the ball screw joint can be calculated as:

$$K_a = \frac{F_a}{\delta_a} \tag{6}$$

3. Ball screw pair dynamic model establishment

3.1 Physical parameter identification and modification

There are two main methods for identifying and modifying the modal parameters of the ball screw joint system[4]:

(1) Now identify the modal parameters of the system, such as natural frequency, modal mass, modal damping, modal stiffness, modal shape, etc., and then convert to the required physical parameters.

(2) Firstly, the finite element three-dimensional analysis model of the system is established, and all physical information parameters are initially determined by analysis software simulation or static test, and then the analysis model is corrected by the results of the vibration test. Finalize the physical parameters of the system.

Here we choose the second method.

3.2 Three-dimensional model establishment of ball screw

Establishing a correct finite element model directly determines the accuracy of finite element calculation。The ball screw model studied in this paper is W4008C-54ZY-C3Z。Specific parameters are shown in the table .1:

Table.1

Elastic Modulus/MP_a	Poisson's ratio	Density/t/mm^3
2.09E+9	0.281	7.81E-9

Before drawing a 3D model, a simple analysis of the overall structure of the ball screw pair is required to simplify the model, such as removing some process holes, chamfering, rounding, and removing the ball in the thread raceway and the nut. This makes the generated finite element mesh shape more reasonable and improves the calculation accuracy.

3.3 Finite element calculation

The ball screw is a key function of the CNC machine tool. Among them, the screw shaft and the nut belong to a typical movable joint, which is one of the main sources of damping and compliance of the machine tool. Establishing a complete and accurate ball screw dynamics model is beneficial to a more realistic understanding of the dynamics of the ball screw joint, which provides a powerful guarantee for data analysis[5]. According to the finite element model, the ball screw is simplified into a mass unit according to the structural characteristics of the ball screw, and the ball of the nut and the screw contact area is replaced by a spring damping unit. as the Figure 3-4-1 shows:

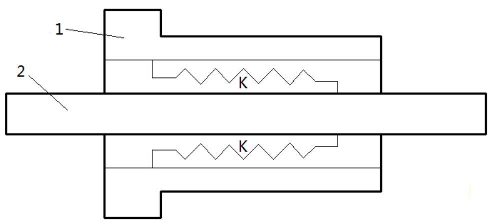

Figure 2 Spring damping unit 1-Nut;2-Screw

3.4 Finite Element Dynamics Calculation of Ball Screw Pair

After the grid drawn in Hypermesh is output as an inp file, open it with abques for dynamic calculation. Before calculating, you can set parameters such as material properties, which can be obtained by querying NSK's product manual. After the parameters are set, a spring resistance unit is added between the ball and the screw, and parameters such as stiffness and damping of the spring resistance unit are input[6].

Here we extract the first 6 modes, as the Figure 3 shows：

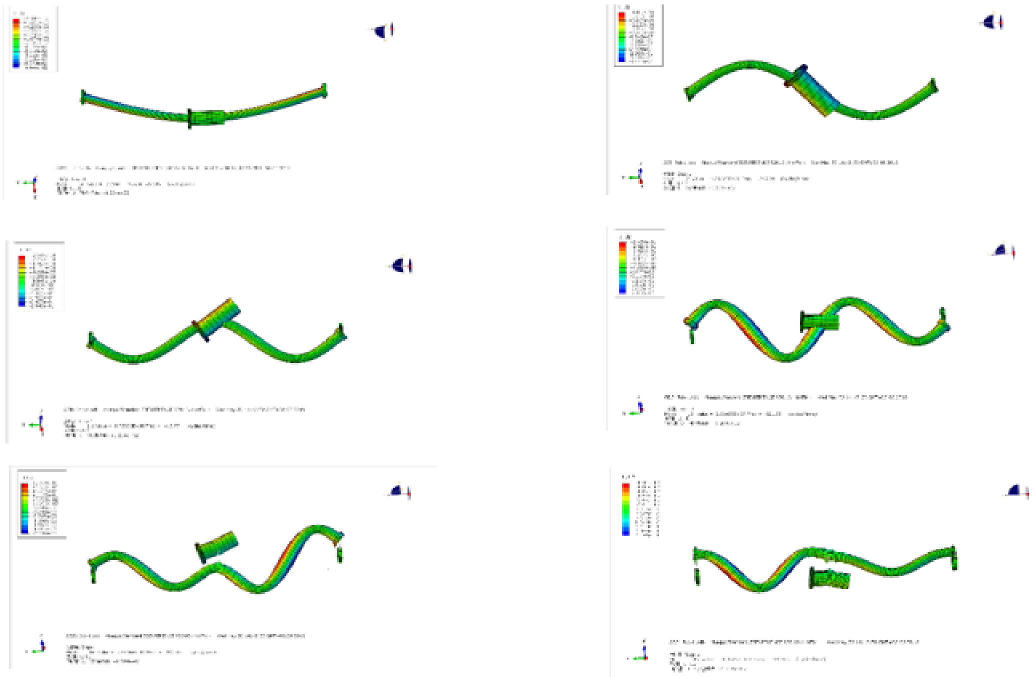

Figure 3 the first 6 modes

4. Experimental modal analysis

4.1 Modal analysis

The modality is the natural vibrational characteristics of the mechanical structure, including natural frequency, modal mass, modal damping, modal stiffness, and modal shape[7]. The mechanical properties of structural or machine components are often determined by modal analysis in mechanical and structural dynamics and are the basis for other dynamic analyses. After the finite element model of the ball screw pair is established and the mesh is divided by hypermesh software, the calculation can be performed. The position of the nut calculated here is the movement of the nut to the middle of the screw, followed by modal analysis in the abques software[8].

This analysis takes the axial dynamic stiffness of the ball screw joint as the research object, and the pre-tightening force is set to one-third of the maximum axial load., The experimental frequency range is 0~1200Hz, Sampling frequency is 1Hz。

Using the hammer module, the point excitation is used as the excitation mode to collect the acceleration signal of the deployed point.

After the modal experiment, the frequency response function curve is obtained. According to the expected effect, the appropriate window function is selected to make the coherence function as close as possible to 1.It can be concluded from the graph that the natural frequency is 213.34Hz. This order natural frequency corresponds to the axial vibration caused by the ball screw. The ball screw joint frequency response function curve is shown in Figure 4-1. Some dynamic experimental data after changing the ball screw material properties and spring damping unit parameters are shown in Table 4.1:

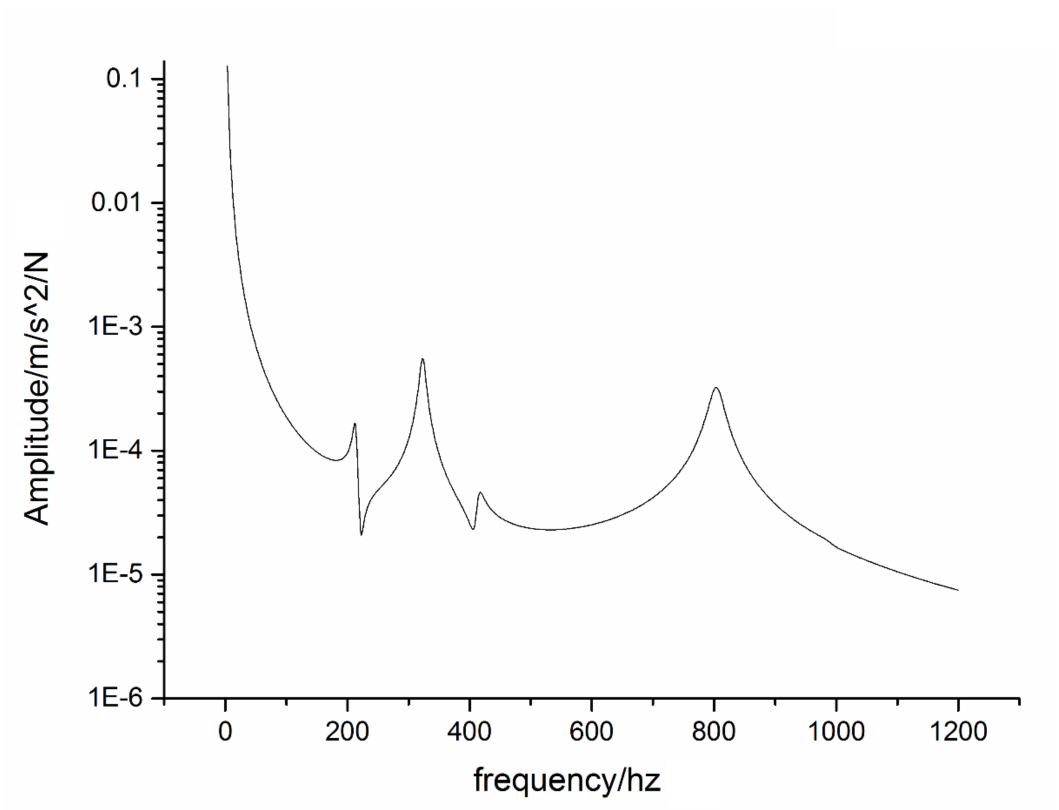

Figure 4 Curve of the axial vibration frequency response of the ball screw

Table 2 Change Material Properties and Spring Damping Unit Parameter Data Sheet

calculate data		Experimental data	
frequency	Damping ratio	Stiffness	Damping
1125.26	0.6454	2.5419E8	1.3656E3
1452.68	0.5477	2.1536E8	1.2365E3
1875.44	0.5013	1.9752E8	2.3613E3
2138.94	0.4536	1.8973E8	1.8462E3
2765.51	0.4078	2.3455E8	2.0215E3

4.2 Data analysis

By comparison, it can be found that the first six natural frequencies of the ball screw pair are too large when the rigid connection is adopted. This is mainly due to the use of rigid connections to simulate the stiffness of the joint between the bearing and the screw and the stiffness of the joint between the screw and the nut is greater than the stiffness of the joint under actual conditions. In practice, the stiffness of the two joints It is not so large, so the use of the spring damping unit to simulate the joint is more in line with the actual situation, and its accuracy is higher than the calculation accuracy of the rigid connection.

5. Conclusion

When the joint is rigidly treated, the natural frequency of the ball screw pair is obviously increased. In practice, the rigidity of the joint is not so large, so the elastic treatment of the joint is more in line with the actual situation; as the nut reciprocates on the screw The natural frequencies of the ball screw pairs show different trends. The natural frequency of the ball screw pair is sensitive to changes in joint stiffness. As the stiffness of the screw nut joint increases, the natural frequency of the ball screw pair also increases, but the increased amplitude is not significant.

Acknowledgements

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