Dynamic Characteristics Analysis of Ball Screw Based on Workbench

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Abstract

The ball screw is widely used in CNC machine tools with high precision, high efficiency, high sensitivity and other advantages. However, the ball screw has the shortcomings of low stiffness. This paper researched the single ball screw, built the ball screw model with three-dimensional modeling software Solidworks, and did the statics analysis, modal analysis and harmonic response analysis respectively using the model which was imported into finite element analysis software ANSYS Workbench, got the natural frequencies and the corresponding vibration type and the response characteristics under the rated load, which provides a basis for the transmission accuracy and structural design of ball screw.

Keywords: ball screw, statics analysis, modal analysis, harmonic response, vibration type

1. Introduction

The ball screw, which can transform the rotation of the servo motor into linear motion of machine tool worktable, tool or other components, or the torque into axial cyclic force, is the most commonly used transmission element in CNC machine tool, and has characteristics of high precision, reversibility and high efficiency[1]. However, the ball screw has the shortcomings of low stiffness and can't bear the large load, which produce deformation, vibration and noise and even resonance under the external force. Therefore, in-depth analyses are extradordinary important to the dynamic characteristics of ball screw.

Ansys is a large general-purpose finite element analysis software includes structure, electric field, magnetic field, fluid field analysis, and is widely used in civil engineering, geology and mineral resources, water conservancy, machinery, railway, automobile transportation, defense industry, aerospace, chemical industry, light industry and other industrial fields[2]. It interfaces with most CAD software to realize data sharing and exchange, is one of the most widely used CAE tools in modern product design.

Modal analysis is a method to study the structure dynamic characteristics, and the basics of the structure dynamics analysis. Harmonic response, transient response analysis must be carried out after modal analysis [3]. Modal is the natural vibration characteristics of the mechanical structure, each mode has a specific natural frequency, damping ratio and mode of vibration. Modal analysis can be used to determine the structure of the natural frequency and vibration mode. Modal analysis of ball screw, can provide the basis for structural vibration analysis, vibration fault diagnosis and prediction and structure optimization design[4].

This paper analyzed the dynamic characteristics of the vertical screw which is in the traction mechanism detection system of low-voltage electrical appliance reliability (Figure 1). Screw statics analysis and modal analysis and harmonic response analysis were carried out mainly indicated the equivalent strain, modal and the dynamic response under the sine load, got the natural frequency and vibration type of the ball screw, harmonic response characteristics.

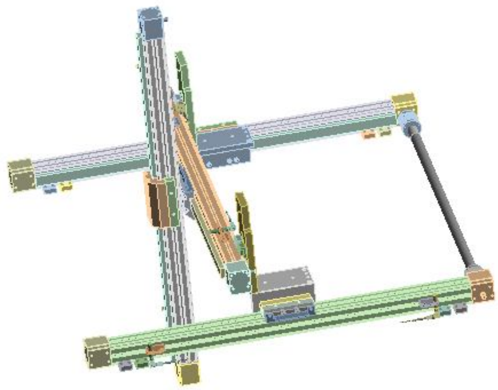


Figure 1: Simplified Model of Traction Mechanism

2. Statics Analysis of Screw

2.1 Sets of Material Parameters

First of all, define the screw model material properties, real constants and material unit type properties. The screw is made of 45 steel, through the look-up table to obtain the desired material parameters, and the specific value of the material parameters are shown in table 1.

Table 1: Material Parameters

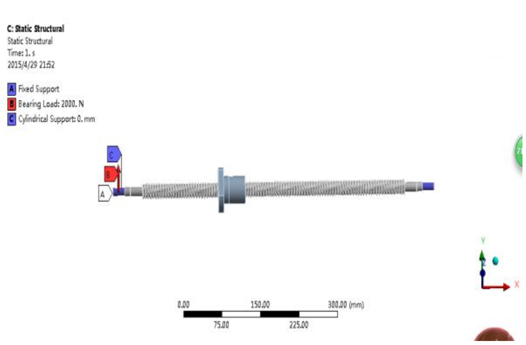
Attribute name	Attribute value
Modulus of elasticity /（Pa）	2.06×10^{11}
Poisson's ratio	0.3
Density /（kg/m*3）	7800

2.2 Mesh and Constraint Handling

The mesh methods in Workbench contains two types: automatic and manual methods. Because the manual workload is enormous and unreasonable division is prone to deformity of grid[5], so this paper adopts the automatic division method of meshing screw. Set screw unit size is 5mm, the size of the nut unit is 7mm. Automatic method means that automatically set tetrahedron or sweep meshing geometry, if cannot be swept, the program will automatically generate tetrahedral, vice versa hexahedral. The mesh produced a total of 66638 nodes, 39050 units.

2.3 Static Structure Analysis

The motion performance of screw depends on static and dynamic performance. Firstly, the paper carried out the static analysis of screw, applied the bearing load to 2000N at both ends of the cylindrical surface. In order to achieve higher stiffness to screw and displacement accuracy, both ends of the screw adopted bearing support form of double push – push[6]. So set the fixed support, selected both ends of the screw section, and constrained the direction of three translational degrees of freedom. At the same time, selected the cylindrical surface of screw thread at both ends, and adopted cylindrical support constraints which set for the axial and radial displacement constraint. The finite element model with constraints on the screw in the following was shown in figure 2. From Figure 3 we can see the static analysis of screw strain, the maximum deformation occurred in the edge of the screw nut, and the deformation was 0.020009mm



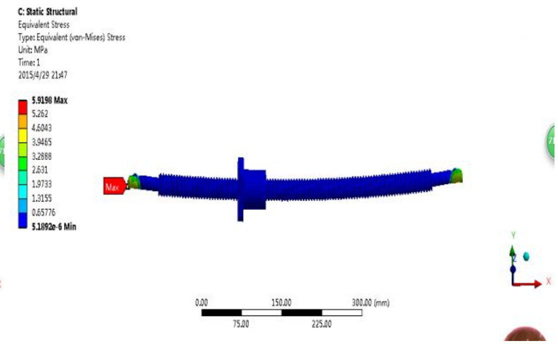


Figure 2: Screw Model with Adding Constraints Figure 3: Screw Static Analysis of Equivalent Stress

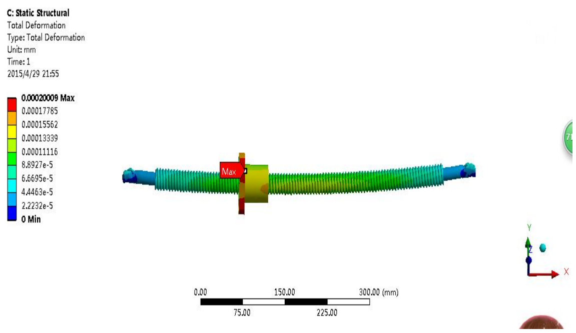


Figure 4: Static Analysis of Screw Deformation

3. Modal Analysis

3.1 The Basics of Modal Analysis

Modal analysis is determined by the characteristics of the material properties and structure of its own, which has nothing to do with the external conditions. The core content of the modal analysis is to identify the modal parameters of the structure, according to the D. Alembert principle, the dynamics of elastic body is simplified as a static problem, the differential equations of motion for structure:

$$[M]\left\{\ddot{q}\right\}+[C]\left\{\dot{q}\right\}+[K]\{q\}=\{F(t)\} \qquad (1)$$

Where: [M], [C], [K] respectively mean the quality matrix, the stiffness matrix and damping matrix of the system, {q}, {F(t)} respectively refers to the system displacement response vector of all points and the external excitation vector of system. Free vibration is happened excluding the effect of damping, which means: [C], {F(t)} are 0, and the differential equations of motion is changed:

$$[M]\left\{\ddot{q}\right\}+[K]\{q\}=\{0\} \qquad (2)$$

Assume the solution of equation is harmonic motion:

$$\{q\}=\{Q\}e^{jwt} \qquad (3)$$

Where :the elements in {Q} represent the amplitudes of each point in the system. Then turn equation (3) into equation (2), get:

$$\left([K]-\omega^2[M]\right)\{Q\}=(0) \qquad (4)$$

In order to make the equation with non-zero solution, then:

$$\left|[K]-\omega^2[M]\right|=0 \qquad (5)$$

[M] and [K] are positive definite matrices. Expand equation (5) and get N eigenvalues $\omega_r^2 (r = 1,2 \cdots N)$, the square root ω_r is the natural frequency of the system. In order of size: $\omega_1 < \omega_2 < \cdots \omega_N$, are respectively called the 1 order, 2 order... N order natural frequency. Turn each eigen value into equation (5) and get corresponding vector $\{\Phi\}_r$, which is the so-called modal(mode shape), and also known as the vibration shape because it is the deformation shape of system modal vibration.

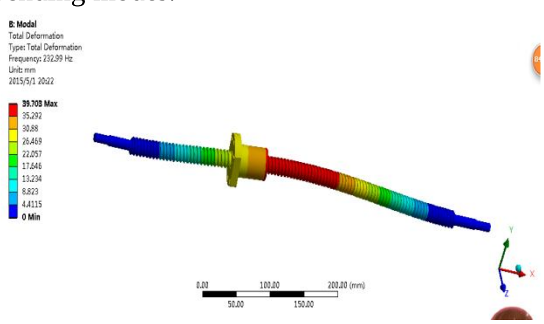
3.2 Modal Analysis of Screw

The paper adopted Block Lanczos modal extraction method. This method is mainly suitable for Large Symmetric Eigenvalue Problem, which not only can deal with rigid body modes, but also is very effective in solving the large, medium model[7]. It is a powerful method. Because low order modes play the greatest important role in the working process of lead screw and high order modes are complex, away from the band[8], so the first four modes were extracted for analysis, and the first 4 order natural frequency and vibration mode were obtained. The first four order natural frequency and vibration types were listed in Table 2.

Table 2: Ball Screw Inherent Frequency and Vibration Types

order	Natural frequency/Hz	Modal description
1	232.99	The first order bending in y axis
2	233.44	The first order bending in z axis
3	681.03	The second order bending in y axis
4	683.36	The second order bending in z axis
5	697.2	The first order torsion
6	1385.5	The third order bending in y axis
7	1392.3	The third order bending in z axis
8	2351.7	The fourth order bending in y axis
9	2361.7	The fourth order bending in z axis

According to the workbench bending deformation nephogram and screw deformation animation, screw bending in the direction of Y axis in the first order modal which is called the first order bending since there is only one extreme point. The natural frequency is 232.99 Hz, the maximum deformation occurs in the central section of screw, and the deformation is 0.39703 mm. The second step is the first bending mode in the direction of z axis, which natural frequency is 233.44 Hz. The two mutually orthogonal modal which natural frequency are very close, is likely to produce resonance. Screw bending in the direction of y axis in the third order modal which is called the second order bending since there were two extreme points. The natural frequency is 681.03 Hz, the maximum deformation occurs at the right side near the screw portion and the value is 0.48277 mm. The natural frequency of the fifth order screw modal which is the first torsion mode is 697.2Hz , serious torsion and expansion are happened in addition to screw and nut. The actual use should be avoided to the external excitation frequency and the inherent frequency. In addition to the fifth order modal, the other adjacent modals are orthogonal bending modes.



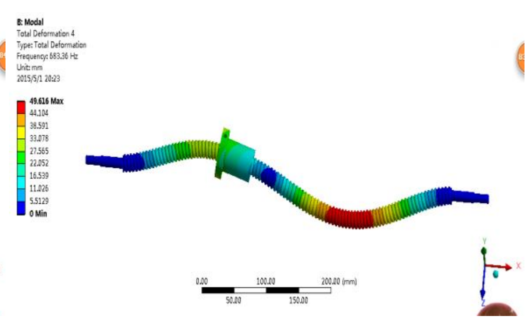
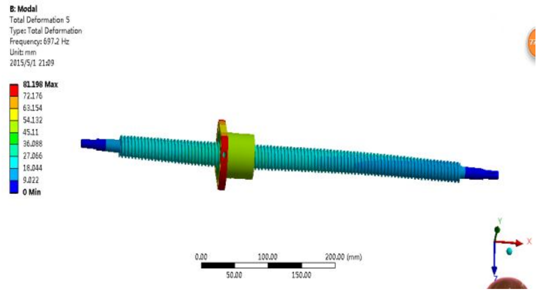


Figure 5: The First Order Bending in y Axis Figure 6: The First Order Bending in z Axis



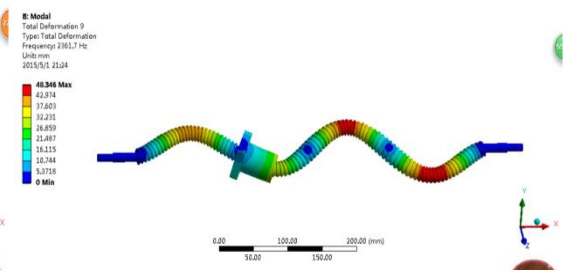


Figure 7: The First Order Torsion Mode Figure 8: The Fourth Order Bending in z Axis

4. The Harmonic Response Analysis of Screw

4.1 The Basics of Harmonic Response Analysis

The harmonic response analysis process is to apply dynamic load force of a specific frequency to ball screw, and analyze the steady-state response amplitude and phase angle of screw[9]. It shows the relationship between the amplitude and frequency of the screw steady-state response through applying dynamic load in different frequency on the screw. Therefore, it 's more clearly to analyze the vibration of ball screw under the dynamic load.

This is the harmonic response analysis motion equation:

$$([K]+\mathrm{i}\omega[\mathrm{C}]-\omega^2[M])(\{X_1\}+\mathrm{i}\{\mathrm{X}_2\})=\{F_1\}+\mathrm{i}\{F_2\} \qquad (6)$$

Where: F1 is the real part of the excitation force, F2 is the imaginary part of the excitation force, I is the imaginary unit, ω is the excitation frequency, X_1 is the real part of the displacement amplitude, X_2 is the imaginary part of the displacement amplitude.

4.2 Analyze Process

The screw rod is motivated by the motor through the shaft coupling, which drives the screw rod to rotate, drives the nut moves, converting rotary motion to linear motion. In order to simulate the actual working condition of screw better, 2000 N Bearing Load was applied on both ends of the cylindrical surface, and the frequency was set at a range of 0~2000 Hz. Selected thread surface which was essential to get the deformation, set the corresponding parameters in Workbench, and analyzed the response of harmonic screw. The deformation frequency response function curve was obtained, as shown in figure nine.

It was indicated in the figure, the deformation of screw was relatively small at the frequency range of 0Hz to 500Hz, the deformation increased sharply at the frequency range of 500Hz to 700Hz where the deformation reached the maximum, the deformation decreased rapidly at the frequency range of 700Hz to 800Hz and the deformation at the frequency range of 800Hz to 2000Hz is very small. Screw reached the maximum deformation in 700Hz frequency excitation force, which coincided with the three and fourth modes of screw. Therefore, we should avoid the screw work in the environment which frequency was near the 700Hz, to prevent the occurrence of resonance phenomenon and affect the normal operation of the feed system etc.

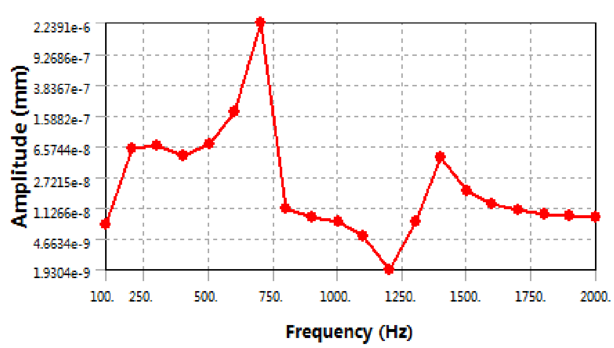


Figure 9: The Deformation Frequency Response Function Curve

4. Conclusion

Static structural analysis of the screw which ascertained the deformation and stress under rated load has been investigated. The modal analysis of the screw has been done to ascertain the first 4 order natural frequency and vibration modes, which provided the theoretical basis for the design improvement of screw. The same frequency interference or other vibration caused by screw resonance can be prevented, the highest speed frequency can also be calculated through bend frequency to determine the normal working condition of screw. The harmonic response analysis of the screw, which makes sure the sinusoidal excitation at 700Hz that the maximum deformation is close to the third and fourth order mode.

5. Acknowledgment

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