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Dynamic analysis of high-speed spindle-bearing system subject to tilting motion

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***Abstract*—Spindle bearing system is one of the key components whose dynamics have a great influence on overall performance of the high-speed machine tools. This study investigated the dynamic characteristics of a high-speed spindle system supported by angular contact bearings (ACBBs) considering the effect of the spindle tilting motion. The bearing stiffness, bearing fatigue life and spindle natural frequency were estimated subjected to varying tilting speed of spindle. Computation results showed that the spindle tilting motion has significant impacts on overall performance of spindle system.**

***Keywords*—Spindle, tilting motion, angular contact ball bearing, gyroscopic moment, fatigue life, natural frequency**

I. Introduction

High-speed spindles are being developed in modern machine tools. To meet the demands for increasing productivity, spindles are often designed to increase its flexibility so that the attached tools can perform cutting at different positions. Consequently, the spindle usually performs not only the rotational motion around its axis, but also the tilting motion so that it is able to approach different the cutting positions from different angles. Because of the tilting motion, additional gyroscopic moment is induced in the spindle, which may affect the characteristics of the bearings, and thus change the dynamic characteristics of the spindle. However, available studies in literature often analyzed the spindle with single spindle rotational speed [1-5]. There is very few research on the characteristics of bearing and spindle subjected to such tilting motion.

In this paper, the dynamic characteristics of a high-speed spindle ACBB system were analyzed subjected to the gyroscopic moment induced by tilting motion of the spindle. First, the additional moment loads acting on the spindle caused by its tilting motion was determined. Then, the reaction loads at the supporting bearings were calculated using an iterative method. Subsequently, the stiffness and basic reference rating life of the ACBBs were calculated. Finally, The spindle natural frequency was analyzed subject to a wide range of tilting speed of the spindle.

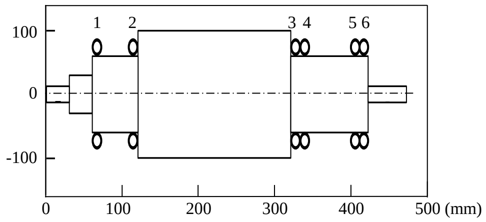

Figure 1. Spindle-bearing system model

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II. Modeling of spindle bearing system

Figure 1 shows the spindle system, which is supported by six ACBBs type B7012E. The gyroscopic moment induced by the spindle tilting, which is assumed to be applied at the center of gravity of the shaft, is calculated by

$$M = I\omega_s\omega_t \qquad (1)$$

where ω_s and ω_t are the angular speed and tilting speed of the spindle. I is the polar mass moment of inertial of spindle. The equilibrium of the system should be characterized first to derive the reaction loads at individual bearings, which are then used to determine the bearing stiffness, fatigue life and the spindle natural frequency. Because the spindle is supported by multiple bearings, the system is indeterminate. Under gyroscopic moment, loads developed at the supporting bearings include radial and moment loads that can result in the shaft radial deflection and bending. Consequently, determination of spindle equilibrium requires an iteration procedure as presented in Figure 2 [6]. In this figure, the bearing displacements, stiffness, and induced moment loads are determined by using a five degrees-of-freedom quasi-static bearing model as indicated in Figure 3. Details of the bearing model can be found in Refs. [7, 8].

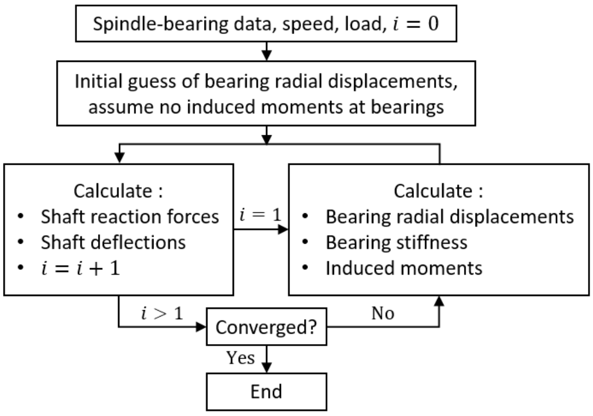


Figure 2. Overall calculation of spindle-bearing system equilibrium

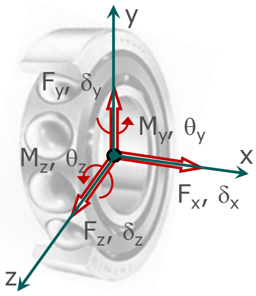


Figure 3. Bearing model with loading and displacements

Once the reaction loads at all bearings are available, the fatigue life of each bearing can be calculated. In this study, fatigue life is investigated in terms of basic reference rating life. Because all bearings are subjected to combined radial, axial, and moment loads, the calculation method provided by ISO 16281-2008 standard [9] is adopted to estimate the basic rating life of bearing under constant loading conditions. With the effect of the gyroscopic moment caused by tilting motion, the bearings are under variable loading conditions. To include such effect, the bearing fatigue life of the bearing was calculated by the following manner [10]:

$$L_{10} = \frac{1}{\sum_{k=1}^{N} \frac{U_k}{L_{10\_k}}} \qquad (2)$$

where U_k represent the interval fraction calculated as the ratio between interval time of operating condition k over total operating cycle of the spindle. $L_{10\text{-}k}$ is the basic rating life under constant operating condition k. N is the total number of interval fractions.

The natural frequency of the system is calculated by using the finite element method [11-13]. Bearings are assumed to be located at nodes. The mass, stiffness matrices of all elements and bearings are identified and then assembled to give the mass and stiffness matrices for the whole system. The rotational speed effects on the system natural frequencies are considered: bearing stiffness change and spindle gyroscopic effect. Then the eigenvalue problem is solved for the system equations to obtain the system natural frequencies.

III. Numerical results

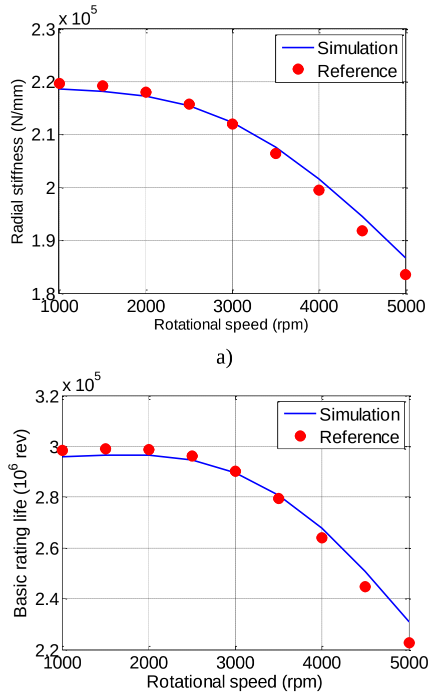
In this section, verification of the model is made by comparing the calculated bearing stiffnesses with those from a commercial program [14]. Then, the effect of spindle tilting motion on bearing stiffness, fatigue life and the spindle natural frequency are investigated.

A. *Model verification*

Figures 4 and 5 compare the radial stiffness and fatigue life of ACBB #3 estimated by the current model and the commercial code as a function of rotational speed. It is observed that the computational results match well with the data obtained from the commercial program thus successfully verifying the presented bearing model. The spindle natural frequency estimated by the current model and commercial code are shown in Figure 6. As expected, the difference between the two calculation methods is minor with the maximum difference of 2.11%. Therefore, the spindle model is proved sufficiently accurate.

B. *Effect of tilting speed on ACBB fatigue life*

It is assumed that the interval fraction for tilting motion is 0.2, i.e., The spindle spends 20% of total working time of spindle for performing the tilting motion. The remaining 80 % of the life cycle is subjected to constant loading conditions. Figure 6 shows the fatigue life of the ACBB #3 as a function to the tilting speed. It is clear that the bearing life significantly decreases as the tilting speed increases.



a)

b)

Figure 4. Bearing stiffness and fatigue life validation (calculating for ACBB #3): a) a) Radial stiffness k_{yy}, Basic rating life

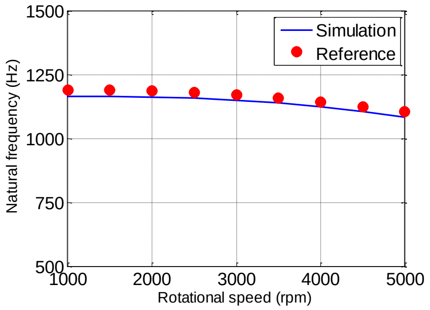


Figure 5. Spindle natural frequency validation

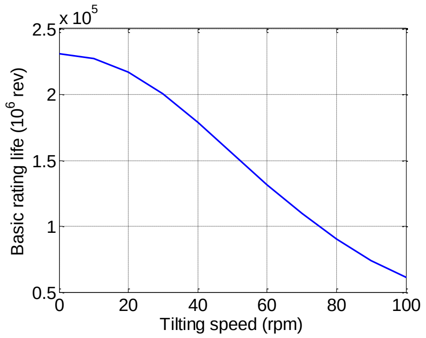
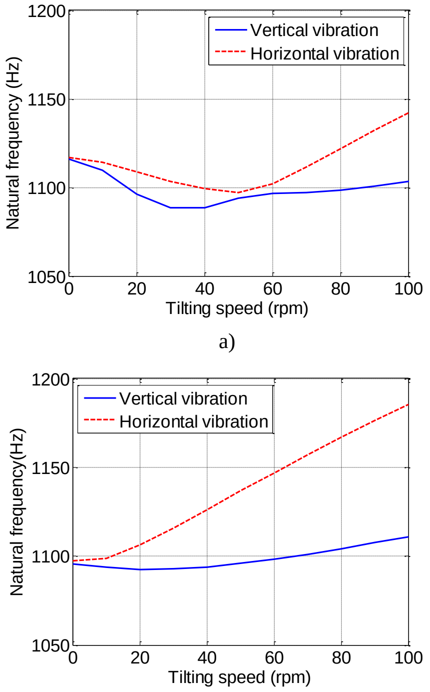


Figure 6. Effect of tilting speed on fatigue life of ACBB #3

C. *Effect of tilting speed on spindle natural frequency*

Figure 7(a) shows the effect of tilting speed on the spindle natural frequency. The spindle runs at constant rotational speed of 5000 rpm without any external radial load. As shown in the Figure 7(a), tilting motion introduces anisotropic behavior in the vibration response of the spindle system. It is clearly seen the difference in vertical and horizontal natural frequencies. The system natural frequencies decrease in the low tilting speed but increase in the higher tilting speed.

Figure 7(b) shows the system natural frequency with radial load as a function of tilting speed. In this case, a radial load of F_r = 10 kN is applied at the right-hand end of the spindle, representing for a cutting force at the attached tool tip. The application of radial load alters the system natural frequencies along with the tilting speed effect.



a)

b)

Figure 7. Spindle natural frequencies as a function of tilting speed: a) No radial load, b) Radial load F_r = 10 kN

IV. Conclusions

An efficient model for dynamic analysis of high-speed spindle with ACBBs subject to tilting motion has been presented and verified. The effects of tilting speed on the characteristics of the bearing and spindle were investigated. The following conclusions were obtained:

(1) Tilting motion induces additional moment acting on the spindle thus changing the reaction forces and moments at the supporting bearings of spindle.

(2) Increasing tilting speed significantly decreases the bearing fatigue life.

(3) Tilting motion leads to anisotropic behavior in vibration of spindle system. The spindle natural frequencies reduce in the low tilting speed but increase in the higher tilting speed.

Further investigations can be made as a future work with regard to the effects of spindle tilting speed profiles on the mechanical behavior of the system.

Acknowledgment

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