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Radiation noise of the bearing applied to the ceramic motorized spindle based on the sub-source decomposition method

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ABSTRACT

This paper mainly focuses on the calculation and analysis on the radiation noise of the angular contact ball bearing applied to the ceramic motorized spindle. The dynamic model containing the main working conditions and structural parameters is established based on dynamic theory of rolling bearing. The sub-source decomposition method is introduced in for the calculation of the radiation noise of the bearing, and a comparative experiment is adopted to check the precision of the method. Then the comparison between the contribution of different components is carried out in frequency domain based on the sub-source decomposition method. The spectrum of radiation noise of different components under various rotation speeds are used as the basis of assessing the contribution of different eigenfrequencies on the radiation noise of the components, and the proportion of friction noise and impact noise is evaluated as well. The results of the research provide the theoretical basis for the calculation of bearing noise, and offers reference to the impact of different components on the radiation noise of the bearing under different rotation speed.

1. Introduction

The ceramic motorized spindle has higher precision and reliability over traditional spindles, and has been widely used in high speed machining. Y.H.Wu and K. Zhang have conducted several researches on the mechanical and thermal properties of ceramic motorized spindles [1,2]. However, the noise radiated while working has a great effect on the acoustical environment, and hinders the further increase of rotation speed. As an important component of the ceramic motorized spindle, the bearing also radiates considerable noise in rotation. Bearing noise takes a large part in the overall noise of the spindle, and varies greatly with the change of rotation speed. Therefore, the calculation on the bearing noise can help predict the surrounding acoustic field distribution of the ceramic motorized spindle, and is of profound significance for the improvement of high speed machining industry.

Bearings applied on the ceramic motorized spindle are mostly angular contact bearings, which work under time-varying internal and external excitation in axial and radial directions. The change of any working parameter might have impact on the

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dynamic response of bearing, and then modifies the radiation noise. In addition, the bearings applied on the ceramic motorized spindle are made of ceramic, of which the elasticity and hardness are different from those of traditional steel bearing. The influence of each parameter on the radiation noise is very complex, and theoretical analysis on the acoustical performance of ceramic bearing is quite rare so far to the author's knowledge.

In 1990, T.C.Lim and R. Singh first built the model of rolling element bearing which clearly demonstrated thethe coupling between the shaft bending motion and the flexural motion on the casing plate. And then a numerical scheme was involved for the estimation of the stiffness coefficients given the mean bearing load vector [3,4]. As one of the following influential studies, M.A.Alfares, A.A.Elsharkawy built a five degrees of freedom model to study the effects of axial preloading of angular contact bearings on the vibration of the spindle. The analysis proved the key role of preloading, and provided access to calculate the optimum initial axial preloading in order to obtain high accuracy for surface finish [5]. J.P.Jing, G. Meng built the nonlinear dynamic model of the rotor-bearing system, proposed three kinds of nonlinear oil-film force models to denote the oil-film forces by retaining certain terms of Taylor series expansion of the oil-film force, indicating that the linear oil-film coefficients can be identified from these models [6,7]. A. Chasalevris improved both the accuracy and evaluation time of the pressure distributions in bearings on the basis of exact analytical solutions, and the exact analytical solution was proposed to be applied in rotordynamic algorithms [8]. F. Murer, F. Bogard and L. Rasolofondraile did a lot of work to develop a set of experimental equipment that equipped with capacitive probes able to measure strains and displacements of different components with high sensitivity [9–12]. M. Ricci introduced an iterative computational procedure which calculates internal normal ball loads in statically loaded single-row, angular contact ball bearings [13]. F. Barnaby established a relation between modal damping and the rolling contact fatigue damage of the thrust ball bearing, and found that damping varies depending on the component's damage state [14]. S.E.Deng focused on the impact of lubricant traction coefficient on cage's dynamic characteristics in high-speed angular contact bearing, and the stability of cage under various working conditions were assessed by the slip ratio of cage [15–17]. J. Jedrzejewski, W. Kwasny presented the model of moving sleeve and spindle tip displacements in angular contact ball bearing system, proving that the axial forces were related to centrifugal forces, gyroscopic forces, contact deformations and contact angles [18]. A. Ashtekar and F. Sadeghi developed and applied A 3D explicit finite element model of the cage and combined with an existing discrete element dynamic bearing model with six degrees of freedom, the results demonstrated that the magnitude of ball-cage impacts and the ball sliding reduced in the presence of a flexible cage [19]. S. Jiang and S. Zheng conducted sensitivity analysis of the structure parameters, and the results showed that the processing condition, the shaft shoulder, the dimension of motor, and the bearing arrangement were sensitive to the spindle dynamic behavior [20]. P.G.Nikolakopoulos and C.A.Papadopoulos developed an analytical model is in order to find the relationship among the friction force, the misalignment angles, and wear depth, and created friction functions dependent on misalignment and wear of the bearing [21]. Q.K.Han, F.L.Chu proposed a three-dimensional nonlinear dynamic model to predict the skidding behavior of angular contact ball bearings under combined load condition. The results indicated that radial load leads to the fluctuations in the slipping velocity of the ball contacting with inner/outer races, especially for the ball in load-decreasing regions [22]. T.A.Stolaski, R. Gawarkiewicz, and K. Tesch tested three bearings of different geometry and recorded their dynamic performance using fast response data acquisition system [23]. B.H.Rho and K.W.Kim adopted a cavitation algorithm to predict the cavitation regions in a fluid film, and then investigated the acoustical properties through frequency analysis [24]. However, the result was without the consideration of the effect of rotation speed. S. Bouaziz, T. Fakhfakh investigated the effect of elastic deformation of bearing liner on the acoustic behavior of oil lubricated journal bearings through an analysis of pressure fluctuation calculated from the Reynolds equation governing the flow in the clearance space of the journal bearing, proving that the sound pressure level of the bearing is markedly influenced by the flexibility of the bearing liner, the viscosity of lubricant and the load applied to journal [25]. The study only aimed at the amplitude of the noise, and did not go into the frequency domain for further analysis.

As are displayed above, the theoretical studies on the performance of the bearing mainly concentrated in the nonlinear dynamic response of the elements, and refused to go a step further to get the acoustic response. The present research on the acoustical performance is mainly conducted through experimental methods. As the bearing is working under relatively high speed, it is hard to find the precise locations of the acoustic sources if the bearing is considered as a whole. Furthermore, the characteristics of acoustic sources are affected by the working parameters, which will bring about nonlinear and unstable factors. In this paper, the bearing is decomposed into several sub sources, and the calculation on the bearing noise is conducted on the basis of sub-source decomposition method. The sub-source decomposition method makes separate calculation according to the vibration response on the source components respectively, and the boundary conditions can be rectified with the change of working conditions, thus avoiding the nonlinear and unstable factors. The overall radiation noise is obtained through the superimposed calculation of the acoustic fields, and the result is analyzed and validated through experimental methods afterwards.

2. Theoretical derivation of the sub-source decomposition method

In this paper, the outer ring is fixed to simulate the actual working condition, the inner ring rotates under stable rotation speed, the cage and the balls are guided by the inner ring. Assuming that the mass centers of the components coincidence with the geometrical centers, the dynamic model of the bearing can be described by the coordinate systems shown in Fig. 1.