Bulletin of the *Transilvania* University of Brasov • Vol. 11 (60) Special Issue No. 1 - 2018
Series I: Engineering Sciences

REVIEW OF RESEARCH ON DYNAMICS AND THERMODYNAMICS OF HIGH-SPEED MOTORIZED SPINDLE

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Abstract: *As a core component of high-speed machine tools, high-speed motorized spindles play a vital role in the performance of high-speed machine tools. On the basis of introducing the characteristics of high-speed motorized spindle, the research contents and research status of motorized-spindle dynamics and thermodynamics are summarized, and the future development trend of high-speed motorized spindle in these two aspects is prospected.*

Key words: *High-speed motorized spindle, dynamics, thermodynamics*

1. Introduction

The high-speed motorized spindle unit is the heart of the CNC machine tool, which directly affects the machining accuracy and processing quality of a machine tool, thus affecting the production efficiency and industrial level of the entire production chain. Therefore, in the situation that modern manufacturing has put forward high-precision, high-speed/ultra-high-speed machining requirements for machine tool processing, research on high-speed motorized spindle units is particularly important. In particular, the in-depth study of the dynamics and thermodynamic characteristics of high-speed motorized spindle units during high-speed machining is a necessary step to improve the rated speed, machining accuracy and machining stability of high-speed motorized spindle units. This paper focuses on the research content and research status of high-speed motorized spindle dynamics and thermodynamics, and looks forward to the future development trend.

2. High-speed Motorized Spindle Features

Today, the overwhelming majority of machine tools are equipped with motorized spindles. Unlike externally driven spindles, the motorized spindles do not require mechanical transmission elements like gears and couplings, but directly drive the cutlery to work. A motor spindle mainly consists of the elements shown in Figure 1.

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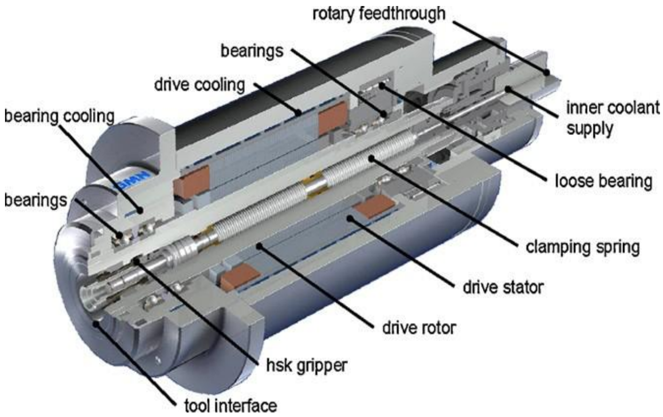

Fig. 1. *Sectional view of a motorized spindle [courtesy: GMN]*

The spindles have at least two sets of mainly ball bearing systems installed at both ends of the spindle. The bearing system is the component with the greatest influence on the lifetime of a spindle, its performance directly affects the performance and lifetime of the motorized spindle. Most commonly the motor is arranged between the two bearing systems and controlled by high frequency pulses.

Due to high ratio of 'power to volume' active cooling is often required, which is generally implemented through water based cooling. The coolant flows through a cooling sleeve around the stator of the motor and often the outer bearing rings.

Today, nearly every spindle is equipped with sensors for monitoring the motor temperature (thermistors or thermo-couples) and the process stability can be attached, but are not common in many industries of the clamping system. In addition, additional sensors are installed to monitor the bearings and drive applications [10-12, 20].

3. Research Content and Current Status of High-speed Motorized Spindle Dynamics

The dynamics of the motorized spindle unit is one of the most important factors in ensuring stable and reliable high-speed operation of the spindle. The main content of the research on the dynamics of high-speed motorized spindle is to establish the dynamics model of the motorized spindle bearing, the spindle dynamics model, the shaft end dynamics model and the spindle integrated dynamics model, and combine the thermodynamics and vibration to analyze the static and dynamic characteristics of the motorized spindle, which achieves the purpose of optimizing the structural design of the motorized spindle and improving the dynamic characteristics of the motorized spindle. In the past several years, the research on the dynamic characteristics of the motorized spindle unit has entered a new research stage.

In the research of Shuyun Jiang, considering the effects of drawbar on the dynamic behavior of the milling motorized spindle-bearing system, a double-rotor model of spindle-drawbar-bearing assembly has been established by utilizing the whole transfer matrix method (WTMM) and a nonlinear rolling bearing dynamic model including the centrifugal force and gyroscopic effects. The critical speeds and the dynamic stiffness of the spindle have been systematically studied. The effects of bearing axial preload, bearing specifications, bearing span and the inner diameter of motor rotor on the dynamic characteristics of the spindle were analyzed, and the spindle was designed by using the optimum selecting method [22]. Songtao Xi presented a dynamic modeling approach of machine tool spindle bearing system supported by both angular contact ball bearing and floating displacement bearing with the consideration of bearing defect. The dynamic model of angular contact ball bearing and floating displacement bearing were developed by discrete element method based on the geometrical relationship between different bearing components and Hertz contact theory. The spindle shaft was modeled by finite element method with Timoshenko beam theory [24].

Ching Yuan Lin developed a finite element model integrated with the modeling of linear components with the implementation of contact stiffness at the rolling interface [5]. Yunsong Li designed a dynamical model of high speed motorized spindles in free state and work state. An excitation-measurement test in the free state was designed to analyze the cross spectral density and auto spectral density of input and output signals. Then the frequency response function of system and coherence function of input and output signals which were used to analyze the inherent characteristics of the double-rotor model could be obtained [13-14, 26, 27]. Junfeng Liu presented a comprehensive model for the motorized spindles in machine tools. The proposed model consisted of a thermo-mechanical dynamic model and a milling stability model. The thermo-mechanical dynamic model was established based on finite element method with the consideration of the transfer function at cutting point, which was coupled with the milling stability model [17]. Chi-Wei Lin firstly developed a design flow chart to represent the overall spindle design problems to improve the dynamic performance of the spindle [6].To investigate the dynamic stiffness of the rotating spindle, Atsushi Matsubara applied a non-contact loading method [1]. Juan Xu built the dynamic model of the motorized spindle system, and then derived a mathematical solution of the vibration response caused by unbalance. A finite element model of the motorized spindle system was constructed based on the structural characteristics of it. The dynamic response characteristics caused by unbalance were simulated, which revealed the vibration transmission characteristics of spindle system and the regularity of variation under the effect of different types of unbalance [16].

4. Research Content and Current Status of Thermodynamics of High-speed Motorized Spindle

The motor heating and bearing friction heating in the motorized spindle are unavoidable. The study on the thermodynamics of the motorized spindle is mainly to establish the temperature field model from the aspects of heat source analysis, thermal error compensation and thermal growth control, so as to reduce temperature rise, reduce thermal deformation and improve machining accuracy.

Jin-Huang Huang presented an inverse method for estimating time-varying heat sources in a high speed spindle under various working conditions. The method was established by developing a numerical code combining the mechanical ANSYS parametric design language and the conjugate gradient method. The proposed method featured a high efficiency solution to direct and inverse problems. It required a small number of iterations for the computational algorithm, while provided excellent accuracy in temperature and heat source estimations. Computational time was also taken into account through choosing the best form of conjugation coefficient as well as mesh size [15].

Conventional model-based prediction (MBP) methods for spindle thermal errors have three serious contradictions: those between un-modeled dynamics and robustness, between model precision and model complexity, and between partial linearization and overall complexity. To avoid these contradictions, Sitong Xiang applied a new data-driven prediction (DDP) approach to the dynamic linearization modeling for spindle thermal errors. In this model, the current thermal errors were predicted by history temperature data without the information of physical mechanisms. Four points along the spindle front bearing circle (left, right, front and back sides) were selected, whose temperatures were recorded in real time via thermocouples, and the average values were calculated. Then the temperature gradients of these four points were selected as the input to predict the axial and radial offsets and the tilt angle errors. The hysteresis phenomenon between temperature and deformation was determined via thermal characteristic tests, and the time interval for data input was identified [23].

Combining the finite element model and the conjugate gradient method, Van-The Than presented an inverse method to estimate time-varying heat sources in a high speed spindle based on experimental temperatures of housing surface. An experimental setup and process to measure temperatures for inversely predicting heat generation sources in high speed spindle and validating inverse results were developed [29].

Spindle dynamics is a key issue in machining. Thermo-mechanical models of spindle need to be developed to understand and predict the complex behavior of spindles at high speed. Accurate bearing stiffness model is required, since it is a boundary condition of the shaft. Besides, bearings also play an important role in heat generation in the spindle. Bearing models rely on kinematics hypotheses at the ball-race contacts. Clément Rabréau studied the influence of these kinematics hypotheses on bearing heat generation. Simulations of bearing dynamics were performed and contact force and torque at ball-race contacts were compared. Behavior of the bearing models with different kinematic models was studied using a coupled thermo-mechanical model of a specialized test bed. Loss torque and temperatures simulated were compared and validated by experiments [8]. Ke Yan proposed a novel wireless temperature sensor and non-intrusive temperature measurement method for bearing monitoring, based on spectrum parameter analysis of CdTe quantum dots films [18]. Considering the six-DOF-balls, five-DOF-inner ring and three-DOF-cage, the quasi- dynamic model of ball bearing were promoted by Ke Yan. The motions and heat generation obtained via the model were then input to a precise numerical model for cage thermal analysis. The oil–air flow pattern inside bearing cavity, the influence of cage parameters such as the pockets shape, methods of guiding, clearance, on bearing cage heat dissipation performance were all investigated. The results indicated that, at ultra high rotation speed, suitable cage parameters were significant to air–oil flow and thermal dissipation inside bearing cavity [19]. Kuo Liu studied the spindle's radial thermal drift error (RTDE) on a vertical machining center. RTDEs in X-direction and Y-direction of a vertical machining center were tested and the main direction of RTDE was determined as Y-direction. RTDEs in Y-direction and temperatures in key points of spindle were tested using different rotating speeds. RTDE models under different postures were established and the compensation strategy was presented. Thereafter, the influence of geometric parameters on the prediction of results was obtained using advanced first order second moment method. The compensation effects were verified using both simulation and experiment. The results indicated that high accuracy and strong robustness could be achieved with the proposed model, even if the rotating speed of spindle randomly changed, or the spindle was disturbed by the cooling system [21, 28]. Van-The Than presented a unified method to predict nonlinear thermal characteristics of a high-speed spindle bearing subjected to a preload. Based on a quasi-static model and finite different method, the change of thermal contact resistance, bearing parameters, and heat source with temperature per second was completely analyzed using a new algorithm. The bearing parameters and lubricant viscosity affected by time-varying temperature were updated in each time step. As a result, the thermal effects on contact angles, contact forces, the preload, and stiffness of the bearing were found. Moreover, the analysis results showed that the estimated preload and bearing stiffness nonlinearly varied with the increase in temperature and the present method took much less computational effort than the finite element method [30, 31].

In order to avoid the degeneration of high-speed spindle's machining accuracy in actual machining caused by the uneven distribution of temperature field at the design stage, Chi Ma proposed a three-dimensional (3D) finite element analysis (FEA) model, which considered the combined influence of thermal contact resistance (TCR) and bearing stiffness on the accuracy of simulation results, to conduct transient thermal-structure interactive analysis of motorized spindles [3, 4].

Based on quasi-static analysis, Xiaohu Li analyzed and calculated the bearing friction heat , and the effect of tilting bearing outer ring on bearing’s contact angle, contact force and friction heat was investigated [25]. Ching-Feng Chang proposed a direct displacement measuring system, which was a great improvement compared with other inaccurate readings using a traditional thermo-coupler, to accurately monitor and compensate the thermal growth associated with motorized high speed spindles [7]. Dexing Zheng firstly established an integrated comprehensive thermal grid model for the front bearing of high-speed spindle and its surroundings to forecast the bearing temperature. Next Euler's method was employed to solve the equations by Matlab and the node temperature was calculated. Finally, the bearing temperature rise was tested and the comparative analysis was made with the numerical results [9]. A. Zahedi, M.R. Movahhedy presented an effort to develop a comprehensive model of high speed spindles that included viable models for the mechanical and thermal behavior of its major components, i.e., bearings, shaft and housing. Bearings were modeled as two-node elements with five displacements and a thermal load component at each node. Mutual interaction between the thermal and structural behavior of both spindle shaft/housing and bearings was characterized through thermal expansion and the rate of heat generation/transfer. Components were combined to form a finite element model for the thermo-mechanical analysis of spindle-bearing systems [2].

5. Summary and Outlook

From the perspective of future engineering technology's demand for continuously improving dynamic and thermal characteristics of high-speed motorized spindle, the author thinks that the study on dynamic and thermal characteristics of motorized spindle still has the following problems:

- less attention is paid to the nonlinear friction characteristics between the moving parts of the spindle system;
- the study on the influence of the dynamic characteristics of the spindle system, such as structure, gap, friction, thermal generation and thermal deformation, etc. is still isolated;
- the damping and stiffness coefficients of the combined surfaces of the spindle system, such as the cutter, the spindle bearing and the spindle sleeve, as well as the non-linear variations of them in the cutting process of the machine tool also need to be accurately identified.

Acknowledgements

This article is supported by Shenyang science and technology program project F16-096-1-00, National Natural Science Fund 51675353 and The innovation team project about the Ministry of Education IRT-15R45.

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