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Research on Variable Preload Device for Spindle Bearing by Piezoelectric Actuators

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ABSTRACT

The bearing preload has significant influence on dynamic performance of motorized spindle. The dynamic performance and the life of bearing can be significant improve if the bearing preload can change according to the different conditions. The main purpose of this paper is to calculate the minimum bearing preload to prevent gyroscopic rotation and study the natural frequency and mode analysis of spindle vibration. Perform the experiments of variable bearing preload device based on piezoelectric actuators. Research the mechanical characteristic of piezoelectric actuators. Providing theory for improving the performance of the motorized spindle by controlling the bearing preload .

INTRODUCTION

High performance motorized spindle is the key technology of high speed CN machine tool and ultrahigh speed CN machine tool[1]. High speed machine tool spindle bearing preload as key technology of high speed motorized spindle. Spindle need to improve the stiffness by increase bearing preload when the motorized spindle is under heavy load, high torque working condition. It needs to decrease the preload in the contrary condition. So variable preload technology has been deeply and widely explored and studied enhance the performance of machine tool.

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Many researches have been carried out about variable preload in different working conditions. Harris used the Hertz contact theory to calculate a more comprehensive model of static analysis model of ball bearing[2]. Antoine use raceway control theory to achieve static and dynamic calculation of bearing contact angle[3]. Young Kug Hwang and Choon Man Lee controlled bearing preload by electromagnet to complete variable preload under different working conditions [4]. Yuchuan Ma from Chongqing University used multilayer piezoelectric ceramic to complete variable preload [5]. The technical needs to protect environment and response fast with the development of society.

This paper calculated minimum preload avoid gyroscopic rotation in different rotational speed, calculated effect of different preload on natural frequency, mode analysis of spindle vibration. Design experiment analysis mechanical characteristic of piezoelectric actuator. Design the variable preload system driven by multilayer piezoelectric actuators, provide fundamental theory to automatic adjustment preload.

THEORETIC ANALYSIS ABOUT THE INFLUENCE OF BEARING PRELOAD ON THE MOTORIZED SPINDLE

Angular contact ball bearings are widely used in motorized spindle systems because they have many excellent characteristics [6]. This paper has studied on Angular contact ball bearing 7009C which is used for the grinding spindle.

Calculation of Minimum Preload Avoid Bearing Ball Gyroscopic

Gyroscopic sliding motion of bearing balls occur when gyroscopic torque increased, and it will cause the friction heat of angular contact ball bearing rapid increase[7].So the calculation of the minimum preload avoid bearing ball gyroscopic has an important influence on the performance of high speed spindle.

The minimum preload at different speeds are calculated by the method of quasi-static analysis in this paper.Formula1 is the relationship between contact angle α after preload and original contact angle α0 is [8]

$$\left(\frac{\cos\alpha_0}{\cos\alpha}-1\right)\cdot(\sin\alpha)^{\frac{2}{3}}=\frac{c}{2f_m-1}\left(\frac{F_a}{Z\cdot D_W^2}\right)^{\frac{2}{3}} \tag{1}$$

Where, c is coefficients of contact deformation, f_m is average radius curvature of outer and inner ring, DW is diameter of bearing balls, Z is number of bearing balls.

Assuming the motion of bearing balls are steady state and only have rigid displacement under external load. The minimum friction torque MF should not less than gyroscopic torque can avoid gyroscopic rotation Mg, is shown as formula 2.

$$M_F=0.5D_W(F_i+F_e)\geq M_g \tag{2}$$

Where, Fi and Fe is tractive force of bearing balls with inner and outer ring raceway.

The minimum preload can be solved based on the calculated that the minimum preload increases with the increase of the rotation speed of motorized spindle. The preload of the bearing design should not less than it.

Theoretic Analysis of Inherent Frequency Calculation and Simulation

This paper use VB6.0 compile program to calculate the contact angle, the axial and radial stiffness under different preload. As is shown in table I the stiffness is increased with the increase of preload and it is the important data for simulation of motorized spindle.

The vibration characteristics of natural frequency and vibration type of structures or components are calculated by the modal analysis method[9]. The inherent frequency of the system is reflected by solution the homogeneous equation of the free vibration. The characteristic of the forced vibration of the spindle is reflected by solution the inhomogeneous equation under the force input. The equivalent model is based on the relationship between preload and bearing stiffness.

As shown in Fig. 1 is first order inherent frequency of the spindle is increased with the increase of the bearing preload. As is shown in Fig. 2, the front and rear part

radial displacement is reduced with the preload increase. The middle part radial displacement is increased with preload increase. This is theoretical reference for improving the critical speed of spindle by controlling the preload of bearing.

TABLE I. STIFFNESS OF BEARING AND DEFORMATION OF SPINDLE UNDER DIFFERENT PRELOAD.

Preload F_p/N	50	100	150	200	250	300	350	400
Contact Angle	22.68	25.40	27.30	28.80	30.00	31.06	32.00	32.83
Axial Stiffness	69188	104110	133251	159181	182433	204280	224843	244187
Radial Stiffness	58147	98800	132658	162245	189351	213876	236517	257806

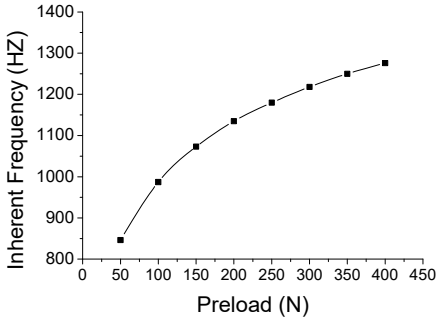

Figure 1. Relationship of preload and natural frequency of the spindle.

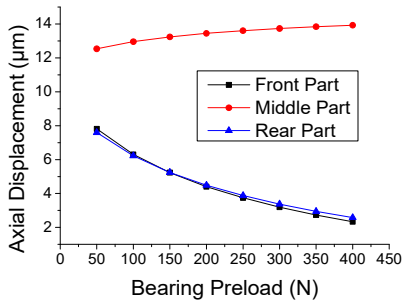

Figure 2. The displacement of spindle under different preload.

Figure 3. The experiment platform.

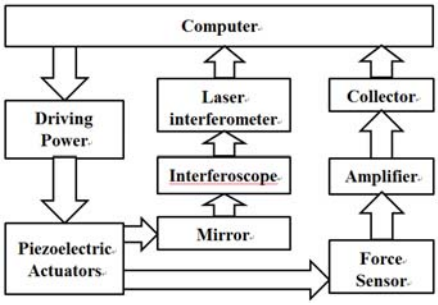

Figure 4. Connection schematic diagram of experimental equipment.

RESEARCH PROJECT OF VARIABLE PRELOAD DEVICE

The variable preload device is designed on the high Speed Motorized Spindle for grinding which use cylindrical type piezoelectric PSt15/4/7 VS9. This equipment used three uniform distribution piezoelectric actuators to achieve uniform stress and sufficient preload force. The piezoelectric actuators are driven by power of HVA-150.A1 and package by threaded connection sleeve and shield.

The Research on The Mechanical Characteristic of Piezoelectric Actuator

The main purpose of this experiment is to research the relationship between the input voltage of the piezoelectric ceramic actuator and the external load on the output force. The input voltage select from 0 to 150 V and the external load select from 0 to 150 N. The experimental platform is shown in Fig. 3 and the connection principle diagram is shown in Fig. 4. The experimental design is carried out by using L25 orthogonal table to five levels of input voltage and external load make the experimental parameters can be analyzed comprehensive.

This experiment measure displacement and force under different load, get actual relationship of output force and output voltage with preload. As is shown in Fig.5thattrend of output displacement curves increased with increase of input voltage. Mechanical characteristic is optimal under external load of 50N. Use four order polynomial between output force, input voltage and applied load which shown in formula3 is obtained by regression analysis and effective range are $15V \leq U \leq 150V$, $10N \leq F \leq 150N$ .Goodness of-fit-R2 of fitting formulas is 0.9992. Significance test of fitting formula is tested by using residual sum of squares and Explained Sum of Squares. By the way it is significant with F test under the significance level $\alpha=0.01$ and it can be concluded that the fitting effect of formula is well.

$$F_{output}=-47.829+1.7266U+28.6556F+0.0054U^2-7.1895F^2-6.25\times10^{-6}U^3+0.75589F^3 +1.67\times10^{-7}U^4-0.0284F^4 \quad (3)$$

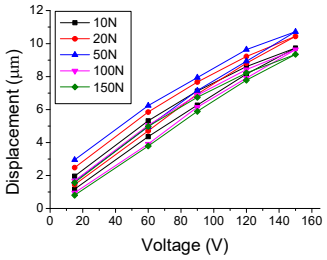

Figure 5. Curves of voltage and displacement.

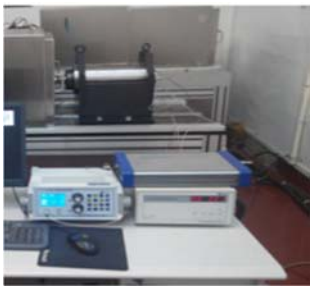

Figure 6. Experiment platform of variable preload device.

Experimental Analysis of Variable Preload Device by Piezoelectric Actuators

As is shown in Fig. 6 this experiment is based on the dynamic analysis of the multi-physical coupled model of high speed motorized spindle [10]. This experiment adjusting the output voltage by driving power to control the output force of piezoelectric actuators, use strain gauge measure the preload applied to the bearing. The preload are under the condition of 150N,300N and 450N, and test the vibration and temperature rise from 1000r/min to 5000r/min, did once signal sampling rotation speed rise every 500r/min. In order to make detected information to be comparable and reliable, vibration amplitude is selected when spindle work vibration around 100HZ, the temperature of spindle must achieve a relatively stable temperature before experiment. The curves of experimental results are shown in Fig.7 and Fig. 8.

This experiment has proved the feasibility of piezoelectric actuators in variable preload device and verified the calculation. The vibration and the temperature of motorized spindle are increased with constant bearing preload. The vibration is reduced and the temperature is increased with the increasing bearing preload at the same speed. The theoretical basis is provided for the research of preload automatic control technology on motorized spindle.

CONCLUSION

This paper calculated the minimum preload is increased with the increase of the rotation speed of motorized spindle. The inherent frequency of bearing, the middle part displacement is increased with the increase of preload. The front and rear part displacement is reduced with the stiffness increase. Regression analysis the four

order polynomial between the output force, the input voltage and the applied load. Design and experiment of the variable bearing preload by piezoelectric actuators .

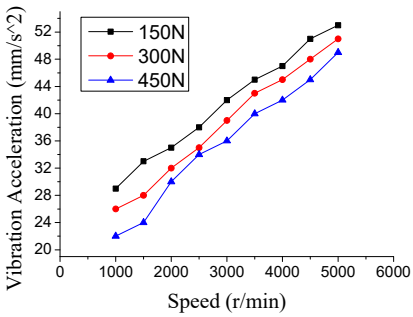

Figure 7. The relation curve of preload, spindle speed and spindle vibration.

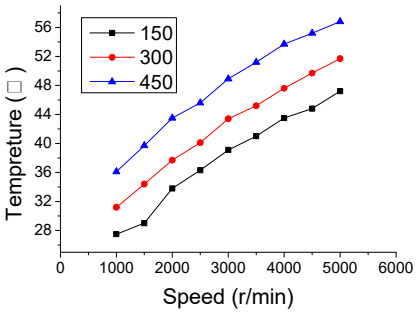

Figure 8. The relation curve of preload, spindle speed and bearing temperature.

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