DOI: 10.1007/s12541-015-0039-8

A Study on the Thermal Characteristics and Experiments of High-Speed Spindle for Machine Tools

Jian Lee[1], Dong-Hyeon Kim[2], and Choon-Man Lee[2,#]

1 Production Technology Team, HYUNDAI WIA Corp., No. 6, Fenghuang Rd., Fenghuang Town, Zhangjiagang, Jiangsu Province, 215600, China
2 School of Mechanical Engineering, Changwon National University, 20, Changwondaehak-ro, Uichang-gu, Changwon-si, Gyeongsangnam-do, 641-773, South Korea
Corresponding Author / E-mail: cmlee@changwon.ac.kr, TEL: +82-55-213-3622, FAX: +82-55-267-1160

KEYWORDS: High-speed spindle, Finite element analysis, Thermal-structural coupling analysis, Vibration, Natural frequency

Based on the finite element method and thermal analysis, a study on the thermal characteristics and experiments of a 40,000 rpm high-speed spindle for machine tools are carried out. In this study, finite element analysis for the spindle system is carried out to obtain the temperature distribution, temperature rise and thermal deformation of the spindle system as affected by different rotation speeds. And then through vibration test, the relationship between thermal deformation and vibration during rotation of the spindle was tested and analyzed. By comparing the calculated results with experimental results, the accuracy of the model was verified. This provides the basis for design of the high speed spindle system.

Manuscript received: July 31, 2014 / Revised: October 15, 2014 / Accepted: October 22, 2014

NOMENCLATURE

H_f = heat generation of bearing
n = spindle speed
M = amount of bearing friction torques
M_1 = load torque
M_2 = viscous friction torque
d_m = bearing diameter
P_0 = static equivalent radial load
C_0 = basic static load rating
F_a = axial load
F_r = radial load
v_0 = kinematic viscosity of lubricant

1. Introduction

High-speed machining is an advanced 21st century high-tech process capable of providing high efficiency, high precision and high surface quality as basic features. In the automobile, aerospace, die manufacturing and instrumentation industries, it has gained increasingly widespread application while providing significant economic benefits. Now high-speed machining is an important component of contemporary advanced manufacturing.

Thermal control technology has become one of the key technical issues that need to be resolved for further development of high-precision machine tools. During normal operating conditions high-speed spindle machine tools generate heat, from motor, bearing, etc, and that heat is transferred to the machine parts and causes distortions of parts, which affects the machining accuracy. Takabi and Khonsari[1] showed that higher rotational speed, oil viscosity and housing cooling rate led to a larger temperature gradient and thermally-induced preload in the ball bearing. Lin et al.[2] proposed a novel concept of thermal error mode analysis to develop a better understanding of the thermal deformation on a turning center.

Machining accuracy can be affected by thermal deformation through temperature rise. Therefore, the heat source should be analyzed and minimized to reduce temperature in spindle system. The major heat sources are bearings and motor in the spindle system, those are also source of vibration. When rotating speed of the spindle is increased, temperature and vibration are increased by thermal expansion and structural clearance. Temperature distribution, thermal deformation and vibration should be considered for development of a spindle system. Many researches have been carried out on the subject of thermal characteristics of high-speed spindle. However, there are not enough

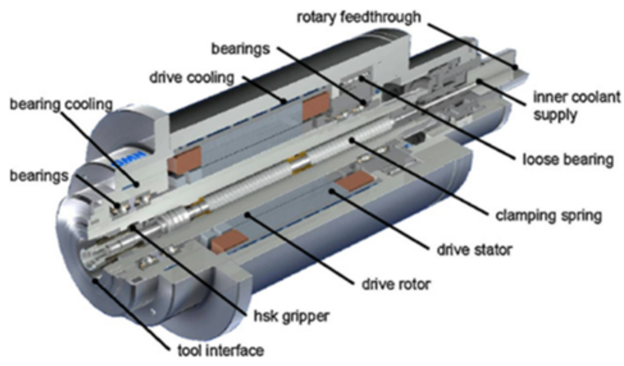

Fig. 1 The schematic of 40,000 rpm high speed spindle

Table 1 Parameters of the test spindle

Parameter	Value
Bearing span (mm)	213.52
Max outer diameter of shaft (mm)	43
Max inner diameter of shaft (mm)	19
Length of shaft (mm)	488

Table 2 Parameters of the ball bearing

Bearing	Front bearing	Rear bearing
Material	Steel	Steel
Inner diameter (mm)	45	40
Outer diameter (mm)	75	68
Width (mm)	16	15
Contact angle (deg.)	15	15

studies considering both of thermal characteristics and vibration simultaneously. The location of the maximum temperature, temperature distribution and the thermal permittivity of the spindle parts with respect to spindle speed are analyzed to reduce temperature increase in this study. Through vibration test, the relationship between thermal deformation and vibration during rotation of the spindle are tested and analyzed, and the methods to reduce the sources of vibration are suggested, also.

In this work, the finite element analysis software ANSYS Workbench is used to obtain the spindle system temperature distribution and thermal deformation at different rotation speeds. And through vibration test, the relationship between thermal deformation and vibration during rotation of the spindle was tested and analyzed. By comparing the calculated with the experimental result, the accuracy of the model is verified. That provides the basis for optimization of the design of the spindle system.

2. Parameters of the Test Spindle

Today, high-speed machining is an important component of contemporary advanced manufacturing. To achieve high-speed rotation, motorized spindles have been developed. This type of spindle is equipped with a built-in motor as an integrated part of the spindle shaft, eliminating the need for conventional power transmission devices such as gears and belts. This design reduces vibrations, achieves high rotation balance, and enables precise control of rotation accelerations and decelerations. However, the high-speed rotation and the built-in motor also introduce large amounts of heat and rotating mass into the system, requiring precisely regulated cooling, lubrication, and balancing.

The schematic of a high-speed spindle is shown in Fig. 1. This spindle has two sets of main ball bearing systems employing an angular-contact ball bearing to support the rotating part of the spindle. The front bearings use NSK 7009C and the rear bearings use NSK 7008C in the spindle system. The assembly form of the bearing is DBB to support the shaft. The bearing system is the component with the greatest influence on the lifetime of a spindle and the motor is arranged between the two bearing systems.

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

Seals at the tool end of the spindle prevent the intrusion of chips and cutting fluid. Often this is done with purge air and a labyrinth seal.

A standardized tool interface such as HSK and SK is placed at the spindle's front end. A clamping system is used for fast automatic tool changes. Ideally, an unclamping unit (drawbar) which can also monitor the clamping force is needed for reliable machining. If cutting fluid has to be transmitted through the tool to the cutter a rotary union becomes a required feature of the clamping system.

The parameters of the test spindle are shown in Table 1 and the parameters of the ball bearing used in the spindle are given in Table 2.

3. Spindle Heat Sources and Boundary Conditions

3.1 Spindle heat sources

Without considering wind age loss in the spindle, which is the viscosity shear friction of the air between the shaft and housing, heat is mainly generated at bearing raceways and balls due to friction, and is influenced by speed, preload and lubricant.[3]

Bearing temperature will rise substantially due to the heat generated by friction losses and rolling resistance. The empirical heat generation in the bearing is given by Ref. 4

$$H_f = 1.047\times10^{-4}\ nM \tag{1}$$

A reasonable estimate of the total friction of a given ball bearing under moderate preload, lubricant and speed conditions is the sum of the load torque and viscous friction torque, so M is,

$$M = M_1 + M_2 \tag{2}$$

where M_1 is the load torque due to all mechanical friction phenomena except for fluid friction, and is the function of applied load. The following equation is given to describe this torque:

$$M_1 = f_1 p_1 d_m \tag{3}$$

in which parameter f_1 is a factor depending on bearing design and relative bearing preload, and p_1 depends on the magnitude and direction of the applied load.

For angular contact ball bearings,

Table 3 Values of X_s and Y_s for angular contact ball bearing

Contact angle	15°	20°	25°	30°	35°	40°
X_S	0.5	0.5	0.5	0.5	0.5	0.5
Y_S	0.47	0.42	0.38	0.33	0.29	0.26

Table 4 The base oil viscosity-temperature relationship

Temperature (°C)	Kinematics viscosity (mm²/s)
25	35
40	18
60	10

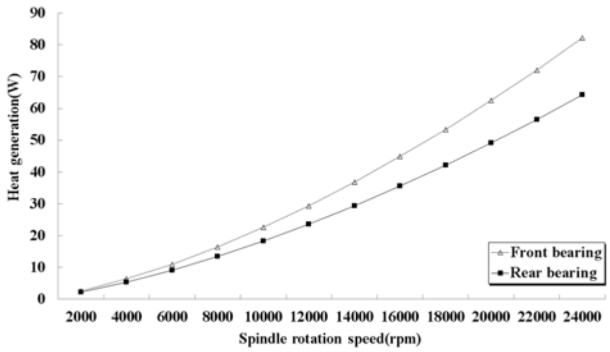

Fig. 2 Heat generation with different rotation speed

$$f_1 = 0.0013\left(\frac{P_0}{C_0}\right)^{0.33} \tag{4}$$

$$p_1 = F_a - 0.1F_r \tag{5}$$

where $P_0=X_sF_r+Y_sF_a$; the values of X_s and Y_s for the single-row angular contact ball bearings with different contact angles are given in Table 3.

M_2 in Eq. (2) is the viscous friction torque, and can be empirically expressed as follows Ref. 4:

$$M_2 = 160\times10^{-7}\ f_0 d_m^3 \quad v_0 n > 2000 \tag{6}$$

$$M_2 = 10^{-7} f_0 (v_0 n)^{2/3} d_m^3 \quad v_0 n \le 2000 \tag{7}$$

where f_0 is a factor that depends on bearing type and lubrication type, and for an angular contact ball bearing f_0=2, v_0 is the kinematics viscosity of lubricant under an operation temperature. Table 4 gives the base oil viscosity-temperature relationship, and the parameters of the bearing are given in Table 2, respectively.

From those equations, the heat generated with different rotation speed can be obtained, shown in Fig. 2. The heat generation increases as the rotation speed increases and the heat generation of the front bearing is bigger than the rear bearing.

3.2 The calculation of heat transfer coefficients

Heat transfer conditions of the main spindle components and heat dissipation boundary conditions include:[5,6]

1. Convection of the air gap around the shaft including mounted components and the housing;
2. Convection of the shaft nose and ambient air;
3. Free convection of ambient air around stationary surfaces (the housing, etc.);
4. Conduction of the initial clearance fit between the outer bearing ring and the housing;
5. Conduction from balls to the inner ring and outer ring;
6. The initial temperatures of bearings and room temperature as measured and given.

The fluids of the test spindle are motor cooling air, cooling water, ambient air and bearing lubrication air. In this work, only the convection between shaft and air is considered.

The calculation of heat transfer coefficient is calculated by Ref. 6

$$\alpha = Nu \times k_{air}/d \frac{W}{m^{2k}} \tag{8}$$

where α is the calculation of heat transfer coefficient, N_u is Nusselt number, k_{air} is the thermal conductivity of the air, d is the diameter of the flow cross-section of the cylinder. Air is highly turbulent, and hence the Nusselt number is given according to Ref. 7

$$Nu = 0.133R_e^{2/3} \times P_r^{1/3} \tag{9}$$

$$R_e < 4.3\times10^5,\ 0.7 < P_r < 670$$

where R_e is the Reynolds number and P_r is the Prandtl number.

Two equations are used for Reynolds number and Prandtl number, respectively:[7]

$$R_e = u_{air} d / v_{air} \tag{10}$$

$$P_r = c_{air} u_{air} d / k_{air} \tag{11}$$

where u_{air} is the mean velocity of the fluid flowing at the shaft surface superimposed by axial and tangent speeds. c_{air} and v_{air} are specific heat and kinematic viscosity, respectively.

A free convection coefficient can be assumed for ambient air around a stationary surface like the spindle housing. The coefficient can be obtained as ∂=9.7 W/(m^{2}k) according to Ref. 5.

From the Eqs. (8)~(11) the convection coefficient of the shaft can be given, in Fig. 3. It shows that the convection coefficient of the shaft increases as the rotational speed increases and the convection coefficient of the outer surface are bigger than the inner surface.

4. Experiment Setup

Experiments were carried out using the 40,000 rpm speed machine tools developed by the present authors.

In this study, a Spindle Error Analyzer (SEA) is used to measure the deformation of the spindle. The Spindle Error Analyzer is a complete system for spindle metrology that measures and analyses the accuracy of machine tool spindles. The system works by installing a precision Master-Ball target with a maximum roundness error of 50 nm in the tool holder. The spindle motion is measured with non-contact probes mounted in a precision fixture. These readings are analyzed by state-of-the-art algorithms and the results presented in easy to read charts and

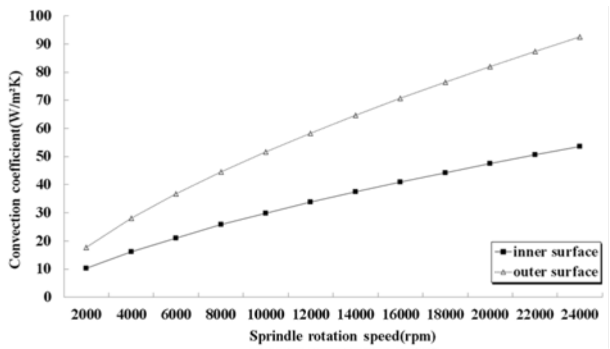

Fig. 3 Convection coefficient of the shaft in spindle

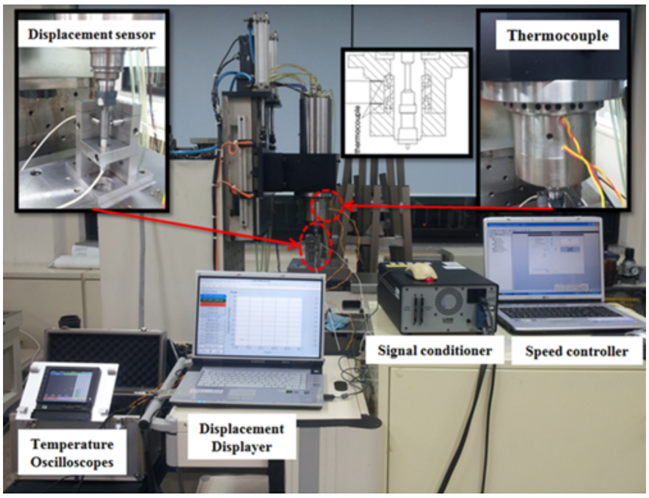

Fig. 4 The experiment setup of the spindle system

graphs.[8]

Fig. 4 shows the experimental setup of the spindle system. The rotation speed of the spindle is detected through a revolution transmitter by the computer. The temperature rise of the front bearings is measured by a thermocouple attached on the outer ring of the spindle system. According to the deformation measured at different rotation speed by the sensors, a control signal is sent to the signal conditioner and the data are displayed in the computer.

5. Experimental Verification

5.1 Thermal analysis of the spindle using ANSYS

Fig. 5 shows the continuous simulation temperature distribution of the spindle after achieving steady state under a certain condition. It can be seen that the maximum temperature 35.49°C is located at the bearing ball because the bearing is the single heat source of this system, and the ball's heat capacity is relatively small. It can also be observed that the temperature drops gradually to housing and shaft. The shaft temperatures are shown to be higher than the housing since a high heat conduction resistance exists between bearing outer rings and the housing. Fig. 5 also shows that the thermal permittivity of the outer ring is greater than that of the inner ring. That can be attributed to the rolling bearing analysis

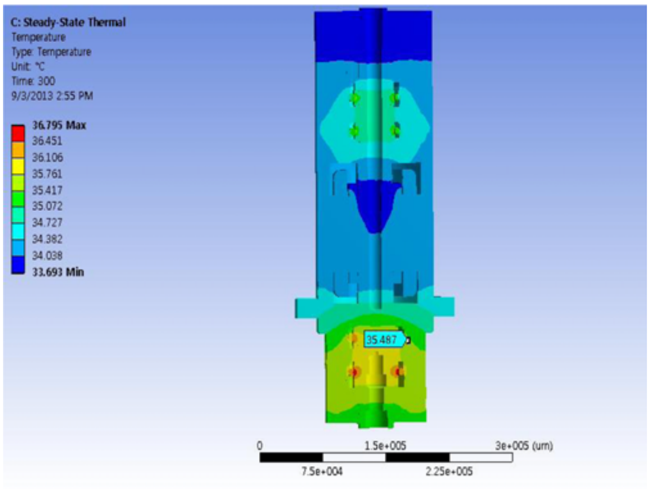

Fig. 5 Temperature distribution of the spindle (speed: 10,000 rpm; preload: 400 N)

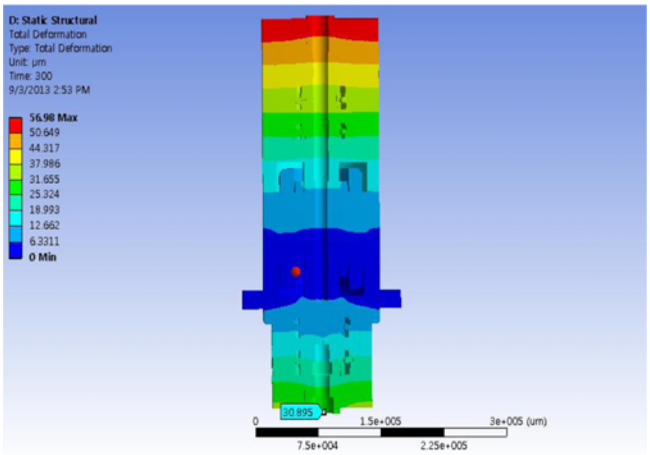

Fig. 6 Thermal deformation of spindle (speed: 10,000 rpm; preload: 400 N)

theory by Harris;[4] a concave surface will conform to contacting bodies, thus reducing the curvature. Conversely, convex surface increase the curvature. Thus, the contact area of the outer ring raceway is larger than that of the inner ring raceway under a fixed axial preload, and subsequently, the thermal permittivity between the ball and the outer ring raceway is larger than that of the ball and the inner ring raceway.

The thermal-structure coupling analysis software ANSYS Workbench is used to obtain the thermal deformation of a spindle system with different speeds. Fig. 6 shows the continuous simulation deformation of the spindle after achieving steady state under a certain condition. The support condition is same as the condition of the test spindle as shown in Fig. 4. It can be seen that the maximum deformation is generated at the end of the spindle. And in this analysis, we should consider the deformation of the shaft nose, because it directly affects the machining accuracy.

5.2 Comparison of experimental results and simulation

To verify the validity of the proposed method in this study,

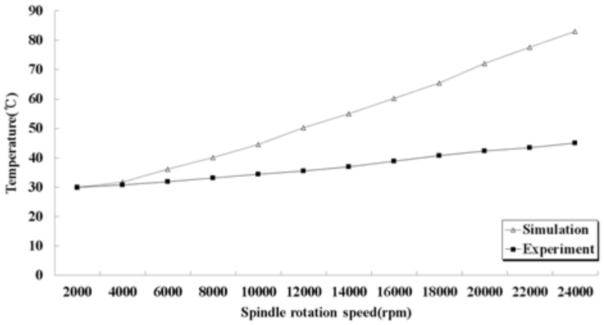

Fig. 7 Temperature distribution with different rotation speed (without convection)

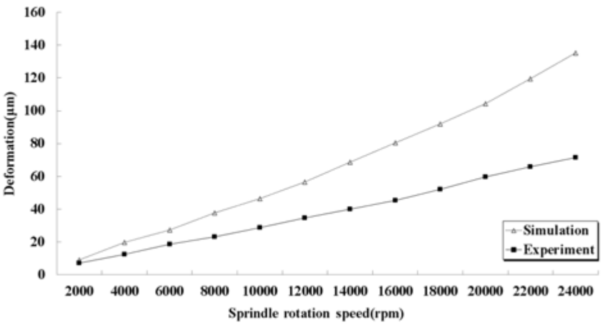

Fig. 8 Thermal deformation of shaft nose with different rotation speed (without convection)

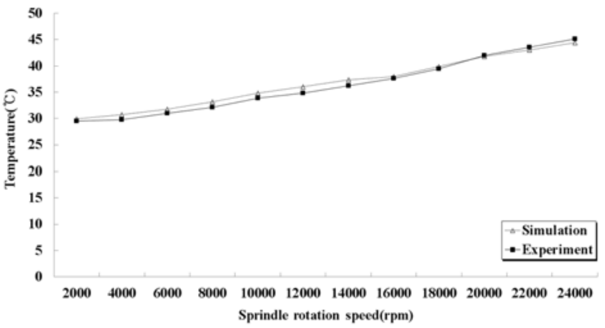

Fig. 9 Temperature distribution with different rotation speed (with convection)

experiments were carried out to detect the temperature using thermocouples. Considered without convection, the temperature rises are measured according to different rotation speeds, as shown in Fig. 7. Comparing the temperature distributions obtained in the experiment and analysis, it is shown that there is quite a big difference between them. The thermal deformations according to different rotation speeds were measured as shown in Fig. 8. The deformation of the spindle nose is detected by eddy current sensor. Comparing the thermal deformation between the experiment and analysis, it is shown that as rotation speed increases, the error between simulation results and experimental measurement also increases.

Considered with convection, the temperature rises according to different rotation speeds are measured as shown in Fig. 9. Comparing the temperature distributions by the experiment and analysis, it is shown that there is good agreement between them, i.e., the error is below 10%. In particular, the temperature rise increases as the rotation speed increases. So it can be concluded that the simulation modeling is reliable, and can be used to provide basic data for optimizing the design of the spindle system.

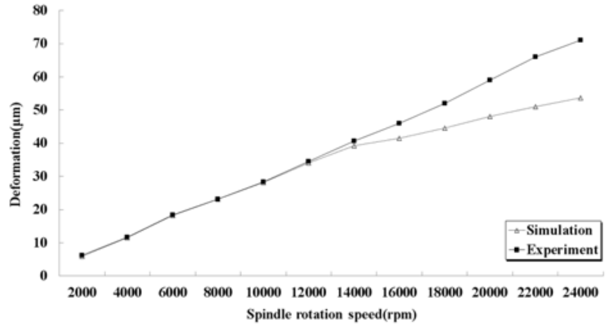

Fig. 10 Thermal deformation of shaft nose with different rotation speed (with convection)

Considered with convection, the thermal deformations according to different rotation speeds are measured as shown in Fig. 10. Comparing the thermal deformation between the experiment and analysis, it is shown that at the low speed range, the simulation results and experimental measurement almost agreed, but at a high speed range, the error is obvious. The error between simulation results and experimental measurements could have resulted from the following.[9]

1. In the experiment, the experimental process is complex. The sensitivity of the sensor is high, so a slight vibration generates errors easily, and since the draw bar in the shaft shakes up and down as the vibration increases, it might increase the errors of measurement results.

2. In the FEM analysis, the actual situation was idealized and simplified, so from the model to the parameter setting, some errors may have resulted.

To verify the effect of vibration on the deformation of the spindle nose, a vibration test was used.

6. Vibration Test

6.1 Natural frequency

When the maximum speed of high-speed machine tools is over a critical speed, a resonance could be observed. This will reduce the life of the spindle. The critical speed can be expressed as follows:[10]

$$n = 60 \times f \tag{12}$$

where the n is speed, f is frequency. Because the speed of the spindle is 40,000 rpm, it can be determined that the resonance frequency is about 667 Hz.

FEA software ARMD is used to obtain the natural frequency of the spindle, as shown in Fig. 11. Usually to be safe, the natural frequency is at least 1.3 times as large as the resonance frequency, so the natural frequency must be more than 867 Hz. Table 5 shows that the 1st~6th

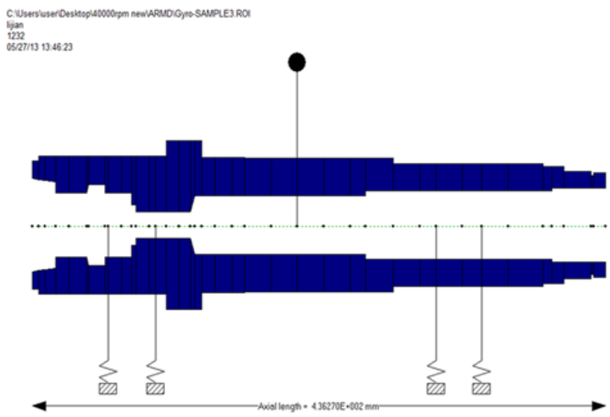

Fig. 11 Rotor-bearing-shaft FE Model using ARMD

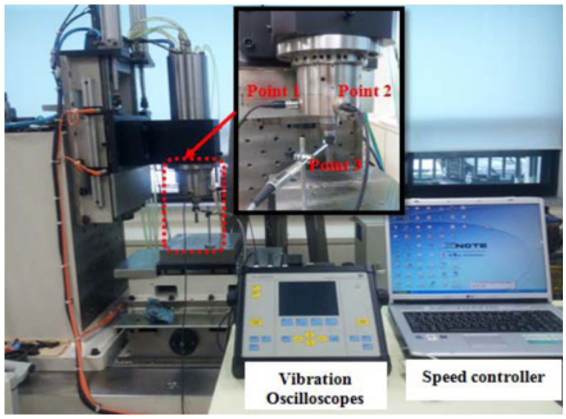

Fig. 12 The experiment setup of the spindle system for vibration test

Table 5 Natural frequency of spindle

Mode	Natural frequency (Hz)
1st	1543.8
2nd	2403.3
3rd	2403.3
4th	4106.6
5th	4106.6
6th	5589.9

natural frequencies are all more than 867 Hz, so the resonance will not be generated.

6.2 Vibration test

In this test, Field Balancing Instrument was used to measure the vibration velocity of the spindle as shown in Fig. 12. The system works by three sensors with a detection limit of 0.1 mm/s and the measurement range is 0.1~200 mm. It can work at a speed of 60~180,000 rpm and the display range is 0.001~100,000. The rotation speed of the spindle is measured through a revolution transmitter by point 3. The vibration velocities of the X-axis and the Y-axis are measured by point 1 and point 2. In this work, to detect the vibration at different spindle rotation speeds with sensors, a signal was sent to oscilloscopes and the data displayed.

Table 6 shows that the vibration increases drastically above 12,000 rpm and the draw bar in the shaft shakes up and down as the vibration increase.

The vibration behavior of a machine tool can be improved by a reduction of the intensity of the sources of vibration, by enhancement of the effective static stiffness and damping for the modes of vibration which result in relative deformations between tool and workpiece, and by appropriate choice of cutting processes, tool design, and workpiece design. Abatement of the sources is important mainly for forced vibrations. Stiffness and damping are important for both forced and self-excited (chatter) vibrations. Both parameters, especially stiffness, are critical for the accuracy of machine tools, stiffness by reducing structural deformations from the cutting forces, and damping by accelerating the decay of transient vibrations. In addition, the application of vibration dampers and absorbers is an effective technique for solving machine-vibration problems. Such devices should be considered as a functional part of a machine, not as an add-on to solve specific problems.

Table 6 Vibration velocity at different rotation speed

Rotation speed (rpm)	Point 1 (mm/s)	Point 2 (mm/s)
2000	0.057	0.016
4000	0.031	0.026
6000	0.055	0.085
8000	0.298	0.096
10000	0.721	0.178
12000	1.574	0.294
14000	1.597	0.369
16000	1.183	0.367
18000	0.972	0.232
20000	0.941	0.480
22000	0.950	0.838
24000	1.006	1.928

6.3 Improvement methods of spindle thermal characteristics

It has been shown that heat generation strongly affects the characteristics of the spindle system. By improving the lubrication of the spindle system, the temperature rise can be reduced and then, the thermal characteristic of the spindle can be improved. To reduce the thermal deformation of the spindle, one should reduce the power of the heat source in the spindle system, reduce the temperature rise, and reduce the thermal deformation of the spindle system.[11,12]

There are two methods to reduce the heat generation of the overall spindle system. The major heat sources are the bearing and driving motor in the spindle system. First, a low power loss motor should be used for the driving motor, such as a permanent magnet spindle motor. Also, the driving motor should be located in the proper position in order to reduce its influence on heat generation in the spindle system. Secondly, ceramic ball bearings should be used to replace steel bearings. Also, proper preload of the bearing should be used. In addition, using an advanced means of lubrication can reduce the friction and heat generation of the bearing.

7. Conclusions

In this work, the finite element analysis software ANSYS Workbench was used to obtain the spindle system temperature distribution and thermal deformation for different rotation speeds. By comparing the calculated results with experiment results, the influential factors and the accuracy of the analysis method were analyzed. It was thus shown the proposed method can be applied to deeply understand the characteristics of spindle design and to obtain basic data for optimizing the design of the spindle system. The research results can be summarized as follows.

1. This work gives the theoretic and mathematical models of temperature field and thermal-structural coupling analysis needed to study the thermal characteristics of the spindle system.

2. It was seen that the maximum temperature is located at the bearing ball and the temperature drops gradually to housing and shaft. The shaft temperatures were shown to be higher than the housing since a high heat conduction resistance exists between bearing outer rings and the housing. It was also shown that the thermal permittivity of the outer ring is greater than that of the inner ring. It also could be seen that the thermal deformation of the spindle nose increases with the increase of rotation speed.

3. Comparing the temperature distributions and the thermal deformation obtained by experiment and analysis for the case without convection, it was shown that there is quite a big difference between them. By considering convection, the results show good agreement, i.e. the error is below 10%. In particular, the temperature rise increases as the rotation speed increases. So it can be concluded that the simulation modeling is reliable.

4. Vibration increased drastically above 12,000 rpm and the draw bar in the shaft shook up and down as the vibration increased, so errors in the compared measurement of the thermal deformation between the experiment and analysis at speeds above 12,000 rpm rotation also increased.

The design of the spindle system plays an important part in the machine tools development. Thermal control technology is one of the key technical issues to be solved urgently. Based on this study, basic data for the thermally controlled design of spindle systems are provided, and methods for improving the thermal characteristics of the spindle system are proposed.

ACKNOWLEDGEMENT

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (No. 2013 053632).

REFERENCES

1. Takabi, J. and Khonsari, M., "Experimental Testing and Thermal Analysis of Ball Bearings," Tribology International, Vol. 60, pp. 93-103, 2013.
2. Lin, C. W., Tu, J. F., and Kamman, J., "An Integrated Thermo-Mechanical-Dynamic Model to Characterize Motorized Machine Tool Spindles during Very High Speed Rotation," International Journal of Machine Tools and Manufacture, Vol. 43, No. 10, pp. 1035-1050, 2003.
3. Jiang, S. and Mao, H., "Investigation of Variable Optimum Preload for a Machine Tool Spindle," International Journal of Machine Tools and Manufacture, Vol. 50, No. 1, pp. 19-28, 2010.
4. Harris, T., "Rolling Bearing Analysis," John Wiley and Sons, pp. 153-206, 1991.
5. Bossmanns, B. and Tu, J. F., "A Thermal Model for High Speed Motorized Spindles," International Journal of Machine Tools and Manufacture, Vol. 39, No. 9, pp. 1345-1366, 1999.
6. Li, H. and Shin, Y. C., "Integrated Dynamic Thermo-Mechanical Modeling of High Speed Spindles, Part 1: Model Development," Journal of Manufacturing Science and Engineering, Vol. 126, No. 1, pp. 148-158, 2004.
7. Kreith, F., Roberts, L. G., Sullivan, J. A., and Sinha, S. N., "Convection Heat Transfer and Flow Phenomena of Rotating Spheres," International Journal of Heat and Mass Transfer, Vol. 6, No. 10, pp. 881-895, 1963.
8. Yang, J. G., "Error Synthetic Compensation Technique and Application for NC Machine Tools," Ph.D. Thesis, Department of Mechanical Manufacturing and Automation, Shanghai Jiao Tong University, 1998.
9. Yang, J., Yuan, J., and Ni, J., "Thermal Error Mode Analysis and Robust Modeling for Error Compensation on a CNC Turning Center," International Journal of Machine Tools and Manufacture, Vol. 39, No. 9, pp. 1367-1381, 1999.
10. Wang, W. R., and Chang, C. N., "Dynamic Analysis and Design of a Machine Tool Spindle-Bearing System," Journal of Vibration and Acoustics, Vol. 116, No. 3, pp. 280-285, 1994.
11. Jeng, Y. R. and Gao, C., "Investigation of the Ball-Bearing Temperature Rise Under an Oil-Air Lubrication System," Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 215, No. 2, pp. 139-148, 2001.
12. Park, S. J., Kim, D. H., and Lee, C. M., "A Study Determining the Optimal Machining Conditions for a 40,000 rpm Ultra High Speed Spindle System," Precision Engineering, Vol. 36, No. 3, pp. 451-457, 2012.