The design and fabrication of a temperature diagnosis system for the intelligent rotating spindle of industry 4.0

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ABSTRACT
Nearly all machinery depends on high-speed rotation to convert kinetic energy into output power. However, high-speed rotation generates heat which needs to be removed to prevent operational anomaly. Prolonged overheating will result in decreased accuracy and reliability of the machine and may even cause serious damage. It is therefore valuable to monitor the heat generation in each and every part of a rotating shaft while it is operating. Internal sensors can be installed to determine temperature distribution and measures can be taken to remove heat from places which reach high temperature to prolong the life of the shaft and its precision. However, to measure temperatures in a high-speed rotating body, it is necessary to provide a means of transferring the signal from the sensors to the measuring device because leads cannot be used. This paper describes a temperature measuring device that uses a slip ring to transfer temperature sensor signals from a rotating spindle to the measuring instruments. Successful measurement of the internal temperatures of a rotating component is very useful. In event of a temperature anomaly, an alarm can be given which allows action to be taken to avert both damage to the machine itself and the output of defective production.

1. Introduction
Modern production has become very dependent on the accuracy and reliability of machine tools and other manufacturing equipment. The rotating spindles and shafts of these machines may generate enormous amounts of heat and prolonged operation can result in overheating that may cause serious damage to the system. To understand the buildup of temperature in a rotating metal shaft, it is necessary to measure and analyze the distribution of heat over every part of the shaft. After this has been done, steps can be taken to dissipate heat from the hottest parts of the metal to both extend machine service life and improve workpiece precision.

Chang [1] demonstrated the elasticity coefficient of disk springs experimentally using limited element analysis on spring deformation affected by centrifugal force. He further studied temperature rise affecting tool pulling force exerted by the disk springs during the process. Li [2] discussed the precision of rotation, dynamic flexibility and the system damping ratio of shafts held by a pneumatic bearing affected by different air-pressures, surrounding temperature, and rotation speed. Hsiao [3] suggested that thermal deformation in a shaft results mainly from the thermal expansion and shrinking effect of heat sources in the bearings and motor. However, cooling and/or isolating the heat source cannot effectively improve errors that result from temperature rise in the shaft. Software compensation is required to solve this problem. Hung [4] pointed out that machining precision is significantly affected by axial play in a shaft which occurs during rotation. The axial play caused by the magnitude of the centrifugal force and a heat source is especially significant. This leads to a discussion of the impact on shaft axial error caused by the magnitude of centrifugal force and heat source, which is the subject of this study. Wang [5] developed a real-time motor monitoring system using the C# object-oriented programming language, for controlling high-speed motors. The system monitors motor operation including temperature, rpm, voltage and current, and vibration. Chuang [6] suggested a spindle testing system for precision milling machines, including the design and configuration of a test mechanism, a data acquisition system and HMI, etc. The tests were mainly focused on the precision of angular degree and reproducibility.
Encoders were used for precision comparison of angular degrees of the spindle. Liu [7] established a method for measuring dynamic error in rotating shafts. He used a Double Ball Bar in combination with spindle circular path verification, to measure spindle circular path error in a 5-axis machine tool using reference coordinates. Wang and Yau [8] numerically investigated the nonlinear dynamic characteristics of a rigid rotor supported by ultra short gas bearing (USGB) system. They showed the pressure distribution of the USGB system and therefore provided a useful guideline for the bearing system. Wang et al. [9] numerically simulated and examine the nonlinear dynamic behaviors including chaotic, subharmonic, and quasi-periodic motions of a rigid rotor supported by floating ring gas bearing (FRGB) system over representative ranges of the rotor mass and bearing number. Their results summarized the variations in the dynamic behavior of the FRGB system as increasing the rotor mass and bearing number. Tseng et al. [10] observed the behavior of turbulent Taylor flow in a co-axial rotating cylinder with and without ribs using smoke flow field imaging technique. He simulated a temperature distribution field using numeral calculation. Jeng et al. [11] studied the heat transfer characteristics of a rotating cylinder with a lateral impinging air jet. He found that all the factors (impact distance, jet flow, nozzle width, and rotation speed) were active and affected heat transfer. Jeng et al. [12] studied the heat transfer characteristics of a rotating Al-foam cylinder using a confined/unconfined impinging jet. The results suggested that the empirical formula of Nusselt number (Nu) can be used as reference for relevant cooling design. Jeng et al. [13] also observed interaction between the Taylor flow and an impinging jet in an annulus within co-axial rotating cylinders, noting that the impinging jet prevented Taylor flow. Lin [14] provided a temperature measuring device in rotating cylinders using a thermostat embedded in the superficial layer of a cylinder and a transmission unit installed inside a resin end cover, together with two receivers capable of verifying their reception status and selecting temperature information from the one in good condition. Temperature from the selected unit was displayed on the control unit. The transmission unit included an antenna, a transmitter and battery, and two receiving antennas inside the cooling cylinder. Yada et al. [15] invented a mixer temperature detector using thermocouples. The sensing tip of the thermocouple installed in the mixer (for blending high-viscosity materials) measures temperature in real time, the physical load on the sensing tip from the mixture flow is minimized as much as possible. Chen [16] proposed a temperature conversion and adjustment device for spindles that included a liquid container for the transmission medium; a booster pump to deliver the pressurized liquid from a container; a heater for the transmission medium coming from the pump; a spindle driven by the liquid; and a main warm-up pipeline connected to the liquid container. There was also a boosting pump, to provide a path for the medium to flow sequentially through the container, from the pump, to the heater and spindle and back to the container to give continuous circulation. This allowed the heated medium to pass through and pre-warm the spindle. A temperature sensor was located in the main heating pipeline to measure the temperature of the medium passing through the pipeline. This significantly reduced spindle warm-up time and enhanced work efficiency. Moroi et al. [17] invented a temperature measuring device for a treatment container with a heater and turntable carrying a substrate. The temperature measuring device faced the radius of the turntable and recorded the temperature at many different places as the turntable rotated. In this way the total area could be sensed. Acting on temperature sensing information a movement control stopped the turntable while the chamber was heated. After a pre-set time, the turntable began to rotate again and radial scanning was repeated. After temperature readings had been obtained for multiple areas around the turntable, temperature mapping was carried out which displayed the temperature distribution around the turntable.

Some of the above references dealt with the retrieval of temperature data from inside a spindle, others suggest that temperature variations in a spindle will affect precision. It is clear that the monitoring of the internal temperature of a spindle will provide advanced notice of possible spindle failure and/or a deterioration of precision that will affect product quality. This study was undertaken with these last perceptions in mind. Temperature sensors were located at different places inside a rotating shaft to monitor heat distribution while the shaft rotated at different speeds. A slip ring arrangement was used to connect the leads from the sensors inside the rotating shaft to an external data recorder. In the event of a temperature anomaly, a real-time warning signal can also be triggered so that action may be taken to prevent damage to the machinery, or a lack of precision results in defective products. Knowledge of the temperature distribution can also be a guide to design or procedural changes that will increase the working life of a rotating shaft and also increase processing precision.

2. Design and fabrication of a temperature diagnosis system

Figure 1 shows the equipment devised and built for the real time measurement of the internal temperature of a rotating shaft. The setup includes an air source, a pipeline, a circulating oil cooler, a shaft testing section, an inverter,
the signal slip rings and thermocouples, a data acquisition system, an IR imaging device, a PC and image retrieval system. For the experiments, a precision spindle made by Spintech Precision Machinery Co Ltd (Model M3, 23400 rpm, 230 V, 18 A) was used. This spindle is cooled by built-in oil circulation. The oil circulator used for cooling the spindle was a Model EOC-60 (5000/6000 BTU/Hr) made by Taiwan Spinflow Co Ltd. The air supply was provided by a Dolomann (1 HP, 100 L/min, 8 kg/cm²) air compressor with a 25-L air tank. When the spindle is activated, internal pins are pushed out so that they will not be damaged in the operation. A slip ring arrangement was used to connect the leads of the thermocouples inside the spindle, see Figure 2. The output of the thermocouples was connected to the terminals of the external data recorder via the slip rings. A Yokogawa MX100 was used for data retrieval and the signals were then fed to a PC for real-time recording and observation. The inverter used to drive and adjust the rotation speed of the spindle was a Chong Da Model VFD-075V23A (7.5 kW/10 HP). The fixed output current was 33 A and maximum variable output was 41 A. The rated output capacity was 12.5 kVA. The IR imaging device (see Figure 1) was used to record surface temperature distribution on the spindle housing. An additional test point was provided on the surface for calibration of the radiation ratio of the IR imaging system.

Figure 3 is an operation schematic of the temperature sensors and diagnostic system. It has two main functional components: (1) a real-time temperature recording and diagnosis section, and (2) a temperature anomaly alarm. The recording and diagnosis system uses thermocouples connected to the slip rings to retrieve and transmit the microvolt signals to the data recorder. The voltages are converted to temperature readings and recorded by the PC in real time to give a history of the internal temperatures prevailing during spindle operation. These files can be used for long-term monitoring of spindle operating temperatures, as well as for troubleshooting spindle faults. The temperature anomaly alarm will detect abnormally high-temperature and can activate an alarm. If the temperature exceeds a pre-set value, the buzzer is activated and a warning light will flash. This will alert the operator who can stop work and check the most recent batch of products for conformance with precision requirements.

3. Results and discussion

Figures 4–6 show the spindle temperature history at 3000, 6000, and 9000 rpm, respectively. This work used the
can avoid thermocouples to be damaged during rotation. The rotational-speed limit of the present slip ring is 10000 rpm. Therefore, the rotational speeds of 3000, 6000, and 9000 rpm were selected as typical test conditions. It can be seen that after the spindle has started to rotate, the temperature at different test points rises and becomes stable, when thermal equilibrium has been reached, after 45 min. The circulating cooling oil keeps the temperature steady. A higher RPM results in the generation of more frictional heat and the equilibrium temperature reached is higher. Table 1 shows the steady-state temperature measurements of the spindle at different speeds. At 3000 rpm, a temperature rise of 5.6 °C is seen at the test point inside the spindle. This increases at 9000 rpm and a temperature rise of 18.5 °C is seen. Test results demonstrate that the temperature sensor and diagnosis system is effective. Real-time history files of temperatures inside the rotating spindle can be recorded. These files can be used for long-term temperature monitoring of rotating spindles, and as a database for troubleshooting.

Figure 4. Spindle temperature rise at 3000 rpm.

Figure 5. Spindle temperature rise at 6000 rpm.

Figure 6. Spindle temperature rise at 9000 rpm.

Table 1. Spindle internal steady-state temperature measurements.

| Speed (rpm) | Inner Temp No. 1 [°C] | Inner Temp No. 2 [°C] | Inner Temp No. 3 [°C] | Inner Temp No. 4 [°C] | Inner Temp No. 5 [°C] | Outer wall Temp [°C] | Room Temp [°C] |
|-------------|------------------------|------------------------|------------------------|------------------------|------------------------|---------------------|---------------|
| 3000        | 34.8                   | 34.7                   | 34.3                   | 34.6                   | 34.3                   | 33.3                | 29.2          |
| 6000        | 44.8                   | 43.5                   | 42.5                   | 42.7                   | 41.9                   | 40.5                | 29.0          |
| 9000        | 46.2                   | 44.6                   | 43.9                   | 45.0                   | 44.1                   | 37.7                | 29.5          |
Real-time temperature recording and diagnosis, and (2) a Temperature Anomaly Alarm. Experimental results show this system is capable of the real-time retrieval of temperature history inside a rotating spindle and the detection of high-temperature points. The data provided can be used to improve the internal design of spindles with respect to heat dissipation. These improvements in design can increase spindle lifespan and also reduce the risk of precision defects in the product.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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4. Conclusions

The Spindle Temperature Sensing and Diagnosis System described in this study has two functions: (1) exceeds a pre-set value. The buzzer will sound and a light will flash in the event of an abnormal temperature rise. The protection of the spindle against damage from overheating is important both for the harm it might cause to the machine and the defective products that might result.
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