XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

# MONITORING OF MACHINING PROCESSES AND ERROR MOTIONS FOR A HIGH-SPEED AIR TURBINE MICROSPINDLE

Kosuke Uchiyama [1], Hiroshi Murakami [1], Akio Katsuki [2], Takao Sajima [2], Zhu Guangyu [1]

[1] The University of Kitakyushu, Fukuoka, Japan, murakami@kitakyu-u.ac.jp
[2] Kyushu University, Fukuoka, Japan

***Abstract*** – We develop a high-speed air turbine microspindle with a built-in microphone and pressure sensor to detect the breakage and wear of a micro-tool and to detect anomalies in the bearing and other spindle components. The results show that the spindle can detect variations in the microtorque (0.1 N·cm) and the frequency components of the rotation of the balls of the ball bearing. In addition, the effect of the external torque variation on the radial error motions of an air turbine microspindle is investigated. The results show that it is possible to measure the microtorque by measuring the change in the rotational speed of the spindle and that the radial error motions in the X and Y directions increase as the torque increases. In the case of the radial error motion in the X direction, the radial error motion is increased to approximately 0.007 µm per torque variation of 0.001 N·cm.

***Keywords***: High-speed microspindle, Monitoring, Micro-drill, Pressure sensor, Microphone

## 1. INTRODUCTION

In recent years, there has been increasing demand for a method that can precisely machine mechanical microstructures, microelectromechanical systems, micro molds, optical devices, microholes in various nozzles, etc. A microdrill is mainly employed to machine a microhole. However, the breakage of the microdrill creates problems because of the low rigidity of the small-diameter drill. When the drill breaks, the workpiece cannot be used because the broken drill jams the hole of the workpiece. In addition, removal of the broken drill from the hole is time consuming. Many methods have been proposed to detect drill breakage, but they cannot be used for small-diameter drills (a diameter less than 0.1 mm). Therefore, the commercialization of these methods has been unsuccessful so far.

The miniaturization of machine tools and cutting tools in recent years has led to an increased demand for small and high-speed rotation spindles[1, 2)]. In the case of micromachining, a high-speed spindle is employed to attain the required cutting speed. The form accuracy and surface roughness of the workpieces are extremely dependent on the rotational accuracy of the microspindle; hence, the need to evaluate microspindle rotation errors has increased. The rotation errors change when the torque and thrust force loading on the microspindle vary while microdrilling. Therefore, it is very important to investigate microspindle rotation errors while microdrilling. However, it is very difficult to measure the microspindle rotation errors while microdrilling because the various factors leading to rotation errors come into play during machining, e.g., the chucking accuracy, the centrifugal effect of the rotating microdrill, the bite position of the microdrill, and so on. Therefore, it is very difficult to evaluate only the torque variation effect on the spindle, except for the other factors.

In this study, we develop a high-speed air turbine microspindle with a built-in microphone and pressure sensor to detect the breakage and wear of a micro-tool and to detect anomalies in the bearing and other spindle components. The pressure sensor is employed to detect the torque nonuniformity during machining; a frequency analysis of the signals measured by the pressure sensor is used to avoid tool breakage and monitor the wear of the microtool. A microphone is employed to detect the machining state and anomalies in the bearing and other spindle components. The study results show that the high-speed air turbine spindle with a built-in microphone and pressure sensor can detect variations in the microtorque (0.1 N·cm) and the frequency components of the rotation of the balls of the ball bearing by using a frequency analysis of the signals measured by the pressure sensor and microphone.

In addition, the effect of the external torque variation on the radial error motions of an air turbine microspindle is investigated. Two noncontact methods are employed to load the spindle with a torque by using a permanent magnet and an electromagnet. The results show that it is possible to measure the microtorque by measuring the change in the rotational speed of the spindle and that the radial error motions in the X and Y directions increase as the torque increases. In the case of the radial error motion in the X direction, the radial error motion is increased to approximately 0.007 µm per torque variation of 0.001 N·cm.

## 2. SPINDLE DESIGN AND COMPONENTS

Because the spindle being developed is driven by an air turbine, the rotational speed of the spindle will decrease when the torque is applied to the spindle during machining. Therefore, it is possible to detect the torque variation by monitoring the change in the rotational speed caused by the onset of breakage or wear of the microtool. A pressure sensor is employed to detect the rotational speed of the spindle. Figure 1 shows a photograph of the air turbine microspindle with a built-in microphone and pressure sensor. The pressure sensor is installed to measure the pressure around the turbine

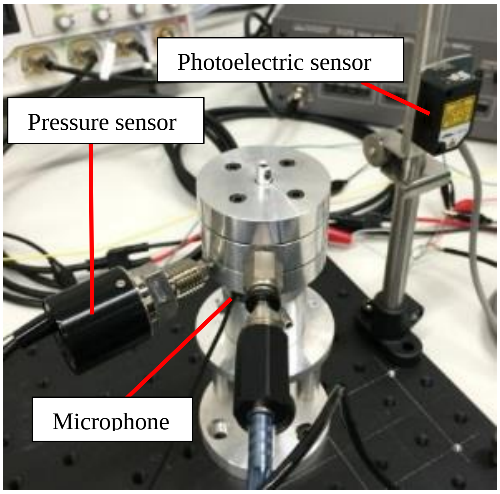


Fig. 1. Photograph of the air turbine spindle.

blade. The signals measured by the pressure sensor include a frequency component representing the product of the rotational speed and the number of turbine blades. Therefore, the rotational speed of the spindle can be calculated by dividing the peak frequency by the number of blades after a frequency analysis of the measured signals. The amplitude of the pressure also varies with the torque variation. As shown in Figure 1, a microphone is additionally installed near the air outlet of the spindle and records the exhaust sound of air. As in the case of the pressure sensor, the sound includes a frequency component representing the product of the rotational speed and the number of turbine blades. Furthermore, the sound includes a frequency component representing the machining state and the anomalies in the bearing and other spindle components. Therefore, the machining state and the anomalies in the bearing and other spindle components can be detected.

## 3. ROTATIONAL SPEED MEASUREMENT AND TORQUE VARIATION DETECTION

Basic experiments were conducted using the method introduced in section 2 to confirm the possibility of detecting the rotational speed variation when a torque is applied to the spindle. For verification of the rotational speed calculated by the above-mentioned method, a photoelectric sensor is installed near the spindle, as shown in Figure 1. Figure 2 shows the results of the frequency analysis of signals measured by the pressure sensor at a rotational speed of 19531 rpm. First, the peak frequency is obtained by the frequency analysis of signals measured by the pressure sensor. Then, the peak frequency is divided by the number of blades; thus, the rotational speed is calculated. It is confirmed that the calculated rotational speed corresponds well with the measured value of the photoelectric sensor (19598 rpm). The measurement error can be reduced by narrowing the frequency interval. Figure 3 shows the results of the frequency analysis of signals measured by the pressure sensor at a rotational speed of 24618 rpm. With an increase in the rotational speed, the pressure amplitude also increases from 0.129 to 0.157, which can be seen by comparing Figures 2 and 3. Therefore, it is confirmed that the amplitude of the pressure around the turbine blade increases with an increase in the rotational speed of the spindle. Figure 4 shows the results of the frequency analysis of signals measured by the microphone at a rotational speed of 24618 rpm. Figure 5 shows the results of the frequency analysis of the recorded exhaust sound of air using the microphone when the spindle is not rotated. By comparing Figures 4 and 5, it is confirmed that most of the frequency components around the peak frequency represent the exhaust sound of air. Figure 6 shows the results of the frequency analysis after the frequency components of the exhaust sound (Figure 5) are removed from Figure 4. Figure 6 shows another peak frequency at 11047 Hz. This frequency matches the frequency component of the rotation of the balls of the ball bearing. Therefore, it is considered that the condition of the ball bearing can be monitored by measuring the variation in this peak frequency.

Next, a verification experiment was conducted to detect variations in the microtorque. Figure 7 shows the experimental apparatus for loading the spindle with a torque using the leaf spring. The tip of the leaf spring contacts the spindle while the spindle is rotated. Figure 8 shows the measurement results of the rotational speed of the spindle using the measured signals of the pressure sensor when a microtorque (0.1 N·cm) is applied to the spindle. The maximum torque is 0.4 N·cm when a 40-µm-diameter microdrill is used to machine stainless steel[3]. From Figure 8, it is confirmed that the high-speed air turbine microspindle with a built-in microphone and pressure sensor can detect variations in the microtorque using a frequency analysis of signals measured by the pressure sensor.

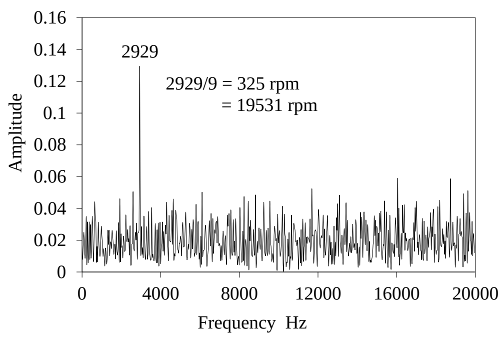


Fig. 2. Results of the frequency analysis of signals measured by the pressure sensor at a rotational speed of 19531 rpm.

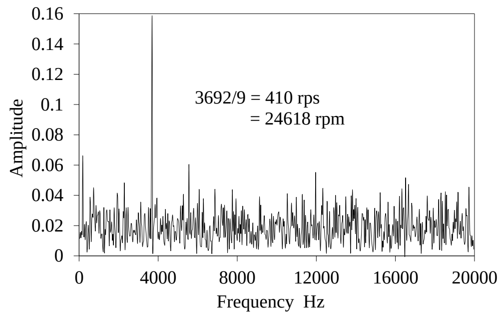


Fig. 3. Results of the frequency analysis of signals measured by the pressure sensor at a rotational speed of 24618 rpm.

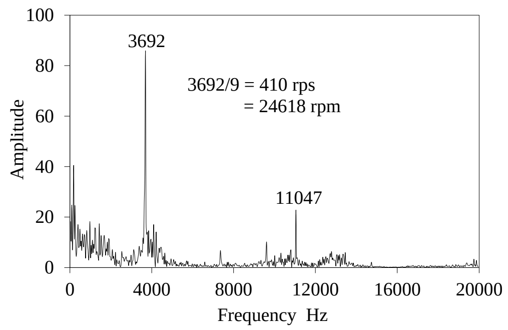


Fig. 4. Results of the frequency analysis of signals measured by the microphone at a rotational speed of 24618 rpm.

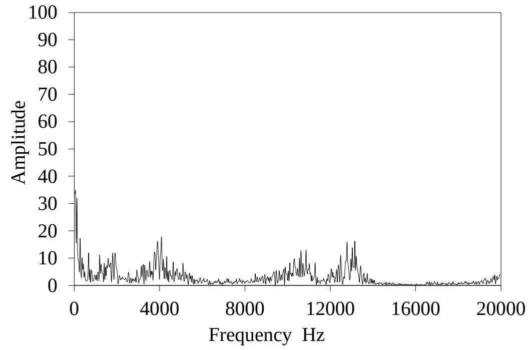


Fig. 5. Results of the frequency analysis of the recorded exhaust sound of air using the microphone when the spindle is not rotated.

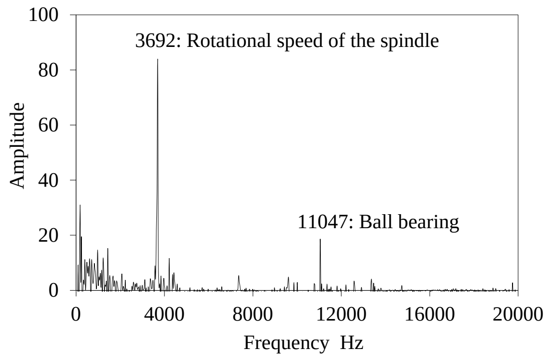


Fig. 6. Results of the frequency analysis after the frequency components of the exhaust sound (Figure 5) are removed from Figure4.

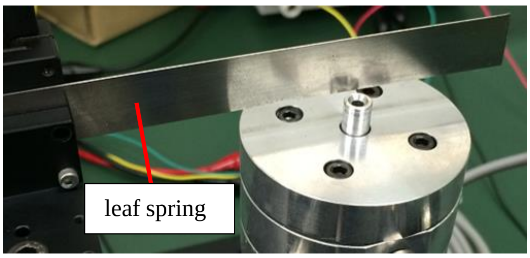


Fig. 7. Experimental apparatus for loading the spindle with a torque using the leaf spring.

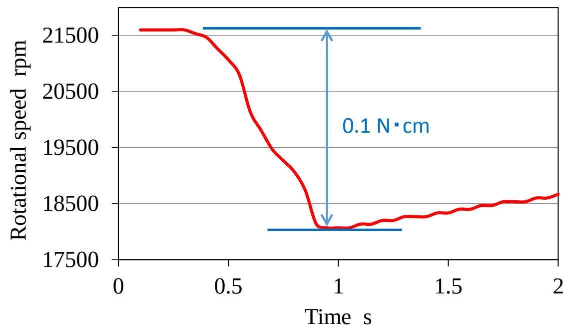


Fig. 8. Measurement results of the rotational speed of the spindle using signals measured by the pressure sensor when a microtorque (0.1 N·cm) is applied to the spindle.

## 4. EFFECT OF EXTERNAL TORQUE VARIATION ON RADIAL ERROR MOTIONS

In order to investigate the effect of the external torque variation on the radial error motions of an air turbine microspindle and the resolution of the torque measurement, two noncontact methods are employed to load the spindle with a torque by using a permanent magnet and an electromagnet.

Figure 9 shows the experimental apparatus for loading the spindle with a microtorque using the permanent magnet. Two permanent magnets are installed on the disk, which is chucked with the high-speed air turbine microspindle. The rotation errors of the spindle are measured by using two capacitance displacement meters, which are orthogonally installed in the X and Y directions. The disk connected to piano wire is installed above the spindle. A mirror is glued together with the piano wire close to the disk. The piano wire far from the disk is fixed to an immobile jig.

When the spindle with two permanent magnets rotates, an eddy current is generated on the disk connected with the piano wire. The eddy current brake generates a torque on the disk connected with the piano wire. Then, the piano wire is twisted by the torque generated by the eddy current. The angle of torsion of the piano wire is measured by an autocollimator. The autocollimator measures the tilting angle of the mirror attached to the piano wire close to the disk. The torque applied to the spindle is calculated using the angle of torsion of the piano wire. The torque can be varied by changing the air gap between the permanent magnet and the disk connected with the piano wire.

Figure 10 shows the changes in the rotational speed and torque when the air gap between the permanent magnet and the disk was changed in 2-mm steps. It is confirmed that the rotational speed decreases, but the torque increases as the air gap is narrow. Therefore, it is confirmed that it is possible to measure the microtorque by measuring the change in the rotational speed of the spindle. Moreover, from the above-mentioned result, any torque could be added to the spindle using a permanent magnet by changing the air gap.

Figure 11 shows the change in the radial error motion of the spindle in the X and Y directions and the torque when the air gap between the permanent magnet and the disk was changed in 2-mm steps. As the torque increases, the radial error motions in the X and Y directions increase. In the case of the radial error motion in the X direction, it increases to approximately 0.007 μm per torque variation of 0.001 N·cm.

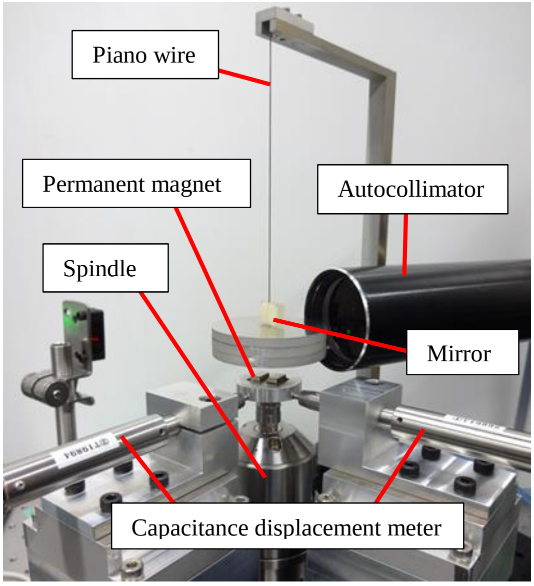


Fig.9. Experimental apparatus for loading the spindle with a microtorque using a permanent magnet.

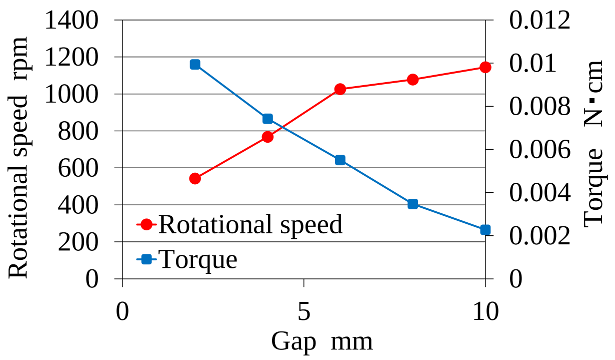


Figure 10. Measurement results of the rotational speed and torque of the spindle when a microtorque is applied to the spindle using a permanent magnet.

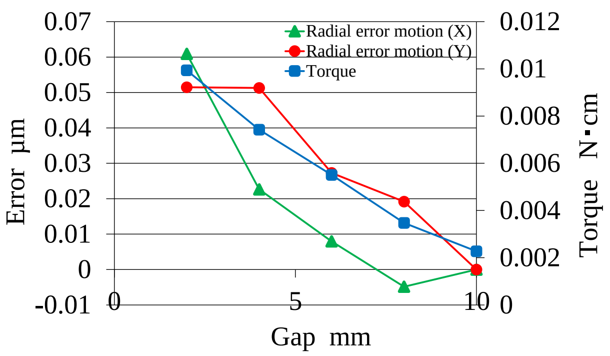


Figure 11. Measurement results of the radial error motion of the spindle and the torque when a microtorque is applied to the spindle using a permanent magnet.

## 5. CONCLUSIONS

In this study, we develop a high-speed air turbine microspindle with a built-in microphone and pressure sensor to detect the breakage and wear of a microtool and to detect anomalies in the bearing and other spindle components. In addition, the effect of the external torque variation on the radial error motions of an air turbine microspindle is investigated.

The results show that the high-speed air turbine microspindle with a built-in microphone and pressure sensor can detect variations in the microtorque (0.1 N·cm) and the frequency components of the rotation of the balls of the ball bearing using a frequency analysis of the signals measured by the pressure sensor and microphone. Furthermore, it is possible to measure the microtorque by measuring the change in the rotational speed of the spindle, and the radial error motions in the X and Y directions increase as the torque increases. In the case of the radial error motion in the X direction, it increases to approximately 0.007 μm per torque variation of 0.001 N·cm.

## 6. FUTURE PLAN

It is impossible to load the spindle with a short-term torque variation in order to evaluate the feasibility of the detection of the breakage and wear of a micro-tool when a permanent magnet is employed (Figure 9). Therefore, other noncontact methods are developed to load the spindle with a short-term torque variation by using an electromagnet.

Figure 12 shows the other experimental apparatus for loading the spindle with a microtorque using an electromagnet. In the future, a verification experiment will be conducted using this experimental apparatus.

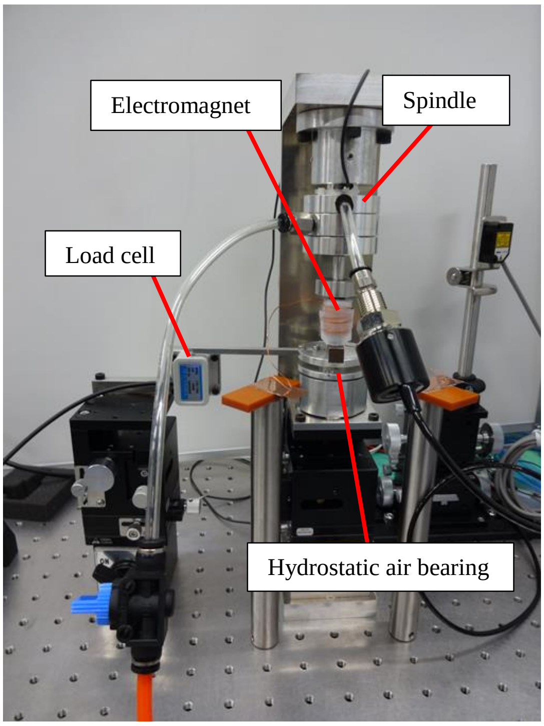


Figure 12. Experimental apparatus for loading the spindle with a microtorque using an electromagnet.

## ACKNOWLEDGMENTS

This study was partly supported by a research grant from the Mitsui Foundation for the advancement of tool and die technology and by JKA and its promotion funds from KEIRIN RACE.

## REFERENCES

[1] Axinte DA, Abdul Shukor S, Bozdana AT 2010 An analysis of the functional capability of an in-house developed miniature 4-axis machine tool International Journal of Machine Tools & Manufacture. 50 191

[2] Dornfeld D, Min S, Takeuchi Y 2006 Recent advances in mechanical micromachining CIRP Annals – Manufacturing Technology. 55 2 667

[3] Ono M, Sugawara A and Yano H 1992 Study on Micro Drill Machining (1st report) – On the Measurement of Cutting Force – Journal of the Japan Society for Precision Engineering. 58 8 79