# Sensor-Based Inspection of the Formation Accuracy in Ultra-Precision Grinding (UPG) of Aspheric Surface Considering the Chatter Vibration

Yao LEI[1*], Yue BAI[2], and Zhijun XU[2]

[1]*School of Mechanical Engineering and Automation, Fuzhou University, Fuzhou, 350116, China*

[2]*Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, 130022, China*

*Corresponding author: Yao LEI          E-mail: yaolei@fzu.edu.cn

**Abstract:** This paper proposes an experimental approach for monitoring and inspection of the formation accuracy in ultra-precision grinding (UPG) with respect to the chatter vibration. Two factors related to the grinding progress, the grinding speed of grinding wheel and spindle, and the oil pressure of the hydrostatic bearing are taken into account to determining the accuracy. In the meantime, a mathematical model of the radius deviation caused by the micro vibration is also established and applied in the experiments. The results show that the accuracy is sensitive to the vibration and the forming accuracy is much improved with proper processing parameters. It is found that the accuracy of aspheric surface can be less than $4\,\mu m$ when the grinding speed is $1400\,r/min$ and the wheel speed is $100\,r/min$ with the oil pressure being 1.1 MPa.

**Keywords:** Optical aspheric surface; micro-vibrations; ultra-precision grinding; formation accuracy; grinding speed

## 1. Introduction

Ultra-precision grinding (UPG) is often used in the manufacture of components with nanometer ($10^{-9}$ m) level dimensional specifications (1 nm to 500 nm), such as precision molds, miniature lenses, aspheric mirrors, and micro-channels. It is functionally critical to the electro-optical, aerospace, biomedical, and defense industries [1]. The UPG process is observed to be exceedingly sensitive to minute instabilities from extraneous sources, such as machine tool vibrations, and temperature fluctuations [2]. It is noted that an infinitesimal change or drift in process conditions, for instance,

due to vibration from nearby machinery that might be inconsequential in conventional machining, manifest almost immediately on the surface of the work-material in UPG [1, 3]. If such process drifts are not detected in a timely manner, they can render waste several hours of labor, expensive tools, and substrates. Therefore, detection of incipient anomalies is important for quality assurance in a UPG process. From the above excerpt, it is evident that the control of key process output variables (dimensional accuracy and surface integrity of the component) in UPG is a pertinent engineering problem consequential to profitability.

The measured multi-channel vibration and force

sensor signals, although sensitive to variations in surface characteristics, contain significant amount of noises. Consequently, the sensor signal patterns acquired from UPG processes may not be amenable to application of conventional process monitoring approaches. Some research efforts have focused on the mechanisms of material removal in UPG as well as the use of sensors for monitoring and control of the process. For example, Wang *et al.* [4] developed a surface topography simulation model considering the effects of tool geometry, cutting parameters, and the vibration between the cutting tool and the workpiece in UPG operations. Abouelatta *et al.* [5] modeled the effects of process parameters and vibration in both radial and feed direction of machined surface characteristics. Sazedur *et al.* [6] used acoustic emission sensor to predict surface roughness. They determined the surface profile by using a stylus based instrument (TalySurf®), to investigate the frequency spectrum of the surface profile. Particularly, the works of Hayashi *et al.* [7] indicated that accelerometers are best suited for applications where subtle changes, such as surface finish and sub-surface damage have to be monitored. Therefore, there is a compelling need to suggest approaches that can capture evolving process anomalies in manufacturing applications, so that opportune corrective actions can be taken, and yield losses can be minimized.

## 2. Mathematical model

### 2.1 Displacement caused by the vibration

The unbalance of wheel will induce vibration of spindle system, affect grinding efficiency and quality, shorten the life-span of wheel and bearing, make spindle chatter and oscillate, and cause ground waviness and surface roughness in workpiece surface [8, 9]. Displacement caused by the vibration of the grinding wheel and spindle is shown in Fig. 1.

For the grinding point $k$, the radial displacement $r_x$ and the axial displacement of the wheel $r_y$ in the

UPG process are

$$r_x = b_1 \cos\alpha + a_1 \cos\beta \qquad (1)$$

$$r_y = b_1 \sin\alpha + a_1 \sin\beta \qquad (2)$$

where $\alpha$ is the angle between the axial of the grinding spindle in the $o_1 x_1$ and the radial $ox$, $\beta$ is the angle between the radial of the wheel and the $ox$, $a_1$ is the radial vibration displacement of the wheel, and $b_1$ is the axial vibration displacement of the grinding wheel.
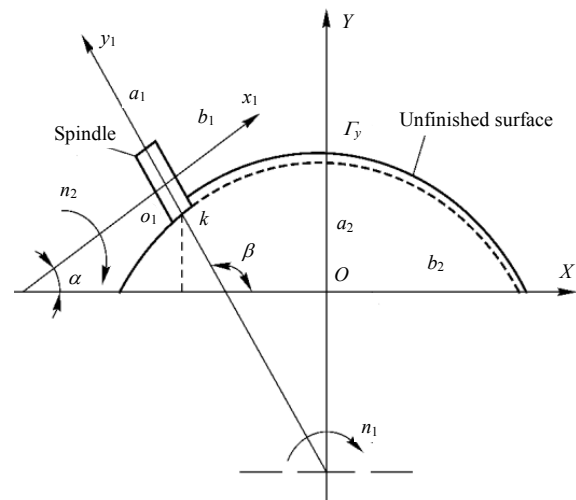


Fig. 1 Displacement caused by the vibration of the grinding wheel and spindle.

The aspheric radius drift $\Delta r_1$ of the aspheric surface caused by the wheel is as follows:

$$\Delta r_1 = \sqrt{r_x^2 + r_y^2} \ . \qquad (3)$$

Similarly, the axial vibration displacement of the grinding spindle is defined as $a_2$, and the radial vibration displacement is defined as $b_2$, so the spherical radius drift caused by the spindle is

$$\Delta r_2 = \sqrt{a_2^2 + b_2^2} \qquad (4)$$

and the syntheses drift $\Delta r$ of the aspheric surface caused by the wheel and the spindle is defined as follows:

$$\Delta r = \Delta r_1 + \Delta r_2 \ . \qquad (5)$$

### 2.2 Machine kinematic effects

A small angular error $\theta$ in the spindle axis is translated into additional periodic displacement, as shown in Fig. 2.
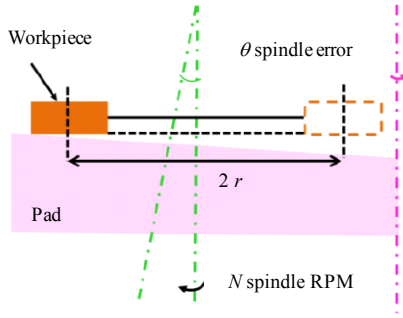
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Fig. 2 Component representing spindle inaccuracy.

The displacement is presented as

$$x_m = 2r \cdot \tan(\theta) \cdot \sin\left(\frac{2\pi N t}{60}\right) \qquad (6)$$

where $r$ is the distance between the center of the wafer and the spindle axis, and $N$ is the spindle speed.

Consequently, the spindle motion introduced from kinematic effects $\ddot{x}_m$ is formulated as follows:

$$\ddot{x}_m + \left(\frac{2\pi}{t}\right) x_m = 0 . \qquad (7)$$

Since the time and length scales over which the effects due to spindle error occur are much larger than those of the asperity-pad induced vibrations, we ignore the effect of small time-scale asperity and pad-induced vibrations on the spindle error-induced displacements.

## 3. Experiments

As shown in Fig. 3, three vibration sensors (model 8728A500 from Kistler) were mounted along three orthogonal directions on the tool holder near the poly crystalline diamond (PCD) cutting tool to measure vibration signals. For experiments with the PCD tool, 36 different process parameters altogether were obtained from varying the spindle speed, wheel speed, and oil pressure, so that we can quantify the effects of factors and interactions among the process parameters and signal features [10]. Sampling rate of 10 kHz was chosen for vibration signals.

The accelerometer was capable of measuring vibration between ± 3 g and had a maximum sampling rate of 1600 Hz for each axis at 3.3 V direct current (DC) power input. Data transmission took place wirelessly. The sensors conveyed data to an XBee® radio transmitter (IEEE 802.15.4 Protocol RF module) supplied by Digi International. The transmitter wirelessly communicated with a coupled receiver. The receiver was powered by universal serial bus (USB) attachment that connected to a laptop. The power input was regulated to minimize voltage fluctuations and subsequently directed to both the transmitter and sensor. Power regulation was critical for amicable performance of the sensor-transmitter-receiver schema, since excessive variations in input potential can cause spurious fluctuations in sensor data.
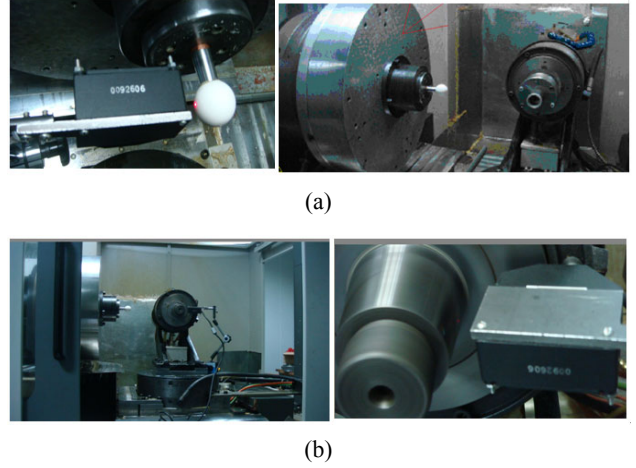


(a)



(b)

Fig. 3 Experimental setup: (a) spindle displacement measurement and (b) wheel displacement measurement.

In this work, we used the data gathered from the vibration sensors in axial and radial directions (in the *X-Y* plane with respect to the rotating spindle) because the applied down force constrained the movement of the workpiece in the vertical direction. Therefore, the observed magnitude of the vibration sensor response in the vertical direction was diminished.

These tests were in accordance with a full factorial design of experiment for a total of four treatment conditions, with oil pressure, wheel speed, and spindle speed as main factors varied from 1 MPa – 1.4 MPa, 50 r/min – 140 r/min, and 900 r/min – 1600 r/min, respectively. Vibration sensor data in the axial and radial direction were gathered for 3 min test runs, approximately 120 000

data points (for each interval, for each sensor direction). From this data set, the first and last 30 seconds of data were quarantined in order to eliminate presence of transient elements in the signal. Thus, about 80 000 data points were used for this analysis. We presented the results from the axial and radial directions vibration sensor.

## 4. Results and discussions

Full factorial design of experimental tests is conducted under different oil pressure and spindle speed conditions for both axial and radial cases. As noted in Section 2, detection of surface variation can be vital for minimizing scrap rate and rework in an industrial UPG process. The displacement of the spindle is shown in Fig. 4.
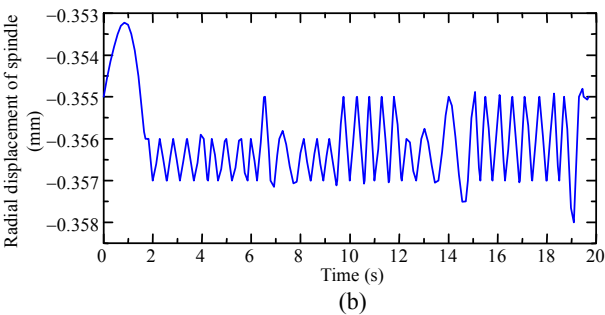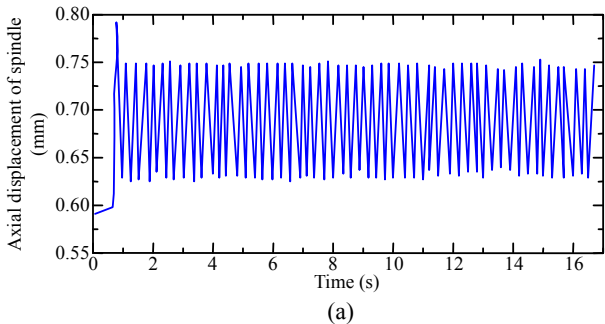
(a)

(b)

Fig. 4 Displacement of the spindle: (a) axial displacement (90 r/min, 1.1 MPa) and (b) radial displacement (50 r/min, 0.8 MPa).

For the axial displacement, the deviation of the value is slightly higher due to the roughness of the measuring surface. However, it is clear that as the speed increases, the radial displacement of the spindle gradually decreases. Considering that the hydraulic pressure may not be stable enough, the effect of the hydraulic pressure on the measurement of the spindle is limited.

Figure 5 shows the displacement of the wheel

when the speed is 800 r/min where the oil pressure is 0.8 MPa.
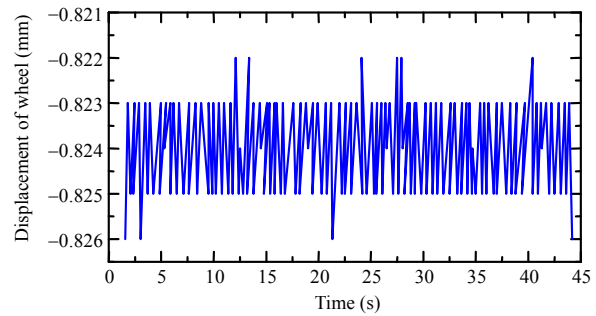
Fig. 5 Displacement of the wheel (800 r/min, 0.8 MPa)

It is interesting to note that the effect of speed on the displacement of the wheel is relatively constant around 0.824 mm. Since the hydraulic pressure has no obvious effect on the displacement of the grinding wheel spindle, which is possibly due to the small range of hydraulic variation. Consequently, the hydraulic oil pressure with 0.8 MPa is recommended with a good consistence for both the spindle and the wheel.

Figures 6 and 7 summarize the overall results for detecting changes in the surface characteristics during UPG using vibration signals.
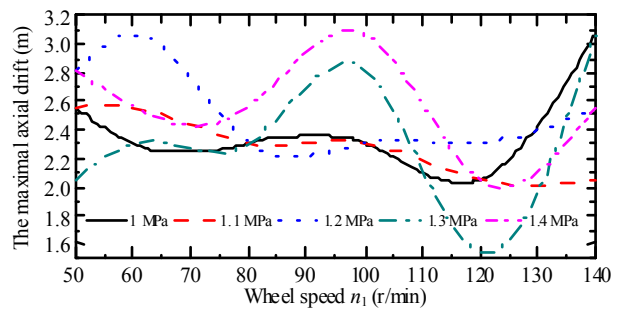
(a)
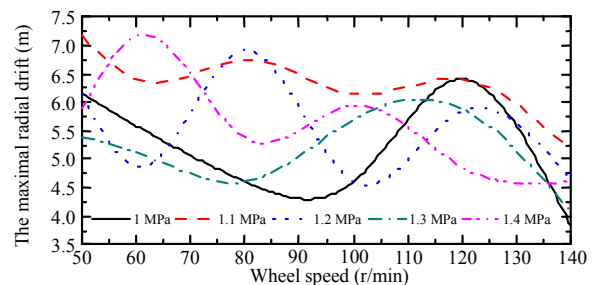
(b)

Fig. 6 Displacement of the wheel: (a) the maximal axial displacement of the wheel and (b) the maximal radial displacement of the wheel.

As shown in Fig. 6, it can be seen that the signals bear information sensitive to machined surface characteristics. This examination of the signals indicates that the measured signals are sensitive to variation in the material removed under different surface characteristics. The max displacement of the wheel is on the radial direction with $7.2\,\mu m$.

Observation of the displacement shown in Fig. 6 also reveals that during polishing, the radial amplitude [Fig. 6(b)] is almost twice as high at the axial direction for the same condition [Fig. 6(a)]. Additionally, for the same test condition i.e., as the speed increases the magnitude of the displacement increases in the range of $50\% - 85\%$. However, this apparent variation can lead to ambiguous results with different oil pressures. A more complete test to ascertain the effect of vibration, which quantifies the variations of the spindle in the axial and radial directions, is presented in Fig. 7.
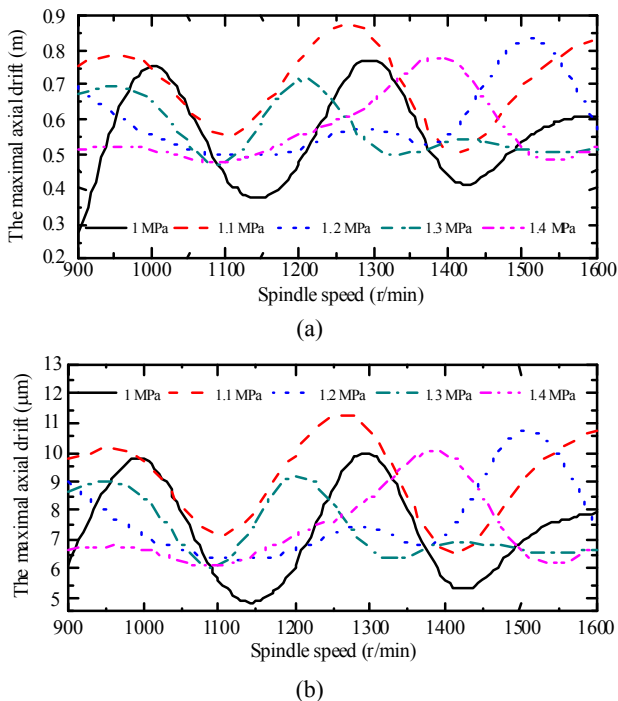


(a)



(b)

Fig. 7 Displacement of the spindle (a) the maximal axial displacement of the spindle and (b) the maximal radial displacement of the spindle.

As shown in Fig. 7, it can be noted that the signal peaks appear to be aligned with the spindle speed of 1300 r/min, and the signal appears to be modulated

at a wavelength of $11\,\mu m$. While there is a noticeable change in the signal characteristics with surface variations, the use of time domain vibration signals may not lead to early stage surface detection. In UPG, earlier detection of defects even by a few milliseconds can significantly avert excessive rework.

A comparison of vibration signals with different oil pressures between 1.2 MPa and 1.3 MPa maintains identical. As spindle speed increases, for both the axial and radial directions, we notice that the radial displacement is much higher than the axial displacement with the identical test conditions. Additionally, both axial and radial displacements share the same trend as the spindle speed increases, which is not significantly affected by the change in the spindle speed. Furthermore, the magnitude of radial direction is almost double during UPG in comparison with axial direction. Additionally, the increased oil pressure from 1 MPa to 1.4 MPa leads to an increase of $50\% - 75\%$ in magnitude of displacement in the both direction.

## 5. Conclusions

This study presents an experimental approach based on the sensor validation for real-time monitoring of displacement considering the chatter vibration in the UPG process. Specific conclusions are summarized in the following:

(1) A mathematical model of an aspheric surface based on the principle of grinding process is validated to confirm the formatting accuracy;

(2) Vibration caused by replacement of wheel and spindle vibration induced by workpiece is dominant factors affecting the process accuracy;

(3) Through optimizing the selection of the proper processing parameter (wheel speed is 100 r/min, the oil pressure is 1.1 MPa, and the grinding speed is 1400 r/min), workpiece surface accuracy can be improved effectively, and the surface waviness can be decreased.

Above all, the present approach can lead to a

reliable monitoring system for detecting incipient surface characteristic variations in the UPG process. Future investigations will attempt to combine information from other signals, as well as use longer-range predictions to improve the reliability and timeliness of incipient surface variation detection.

## Acknowledgment

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