Development of an in-process form error measurement system for surface grinding

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Abstract
An in-process form error measurement device is developed to deal with vibration and coolant which are the two key problems in precision machining. The device is based on a single laser sensor design together with a data processing technique. A damping technique and a moving average technique are proposed. The damping technique accelerated vibration attenuation up to 21 times compared to the natural attenuation. The moving average technique reduced errors caused by vibration more than 10 times and there is no distortion to the form profile results. For a workpiece sample, the measurement result under coolant condition is only 2.5% larger compared with the one under no coolant condition. For a certified Wyko test sample, the overall system measurement error can be as low as 0.3μm. The measurement repeatability error can be as low as 2.2%.

Keywords: In-process form error measurement, vibration, coolant, single sensor design, damping, moving average technique, machining, grinding

1. Introduction
In-process measurement of surface form error in a machining process can usually be used for feedback for process control. In our study to model a surface grinding process, in-process form error measurement was found to be very critical to modeling accuracy enhancement. Without in-process form error measurement, the workpiece has to be removed to measure offline in laboratory. This would lead a significant positioning error as the workpiece has to be mounted again.

A key problem for in-process form measurement is vibration. For this problem, a number of techniques have been proposed to reduce the vibration effects. One required sophisticated optical settings [1-4]. Sivakumar et al [1] proposed an instantaneous phase shifting interferometry method in vibrating environment. Gao et al [2] proposed an optical system based on a dual beam interferometric technique so that the effect of vibration can be isolated. A lateral shearing interferometer system based on use of birefringence plate was developed [3-4]. Another technique required double sensors to subtract the vibration signal [5-6]. Veggel et al [7] proposed a special mechanical design for mounting of beam splitters for sufficient alignment stability. It can be seen that the existing techniques [1-7] are complex and costly.

Another key problem for in-process form measurement is coolant. For this problem, Gao [6] proposed a water beam technique to deal with the problem. Gao et al [8] also proposed an air beam technique to solve the problem.

To address the above problems in a single device for grinding research and for industrial use, a new single laser sensor design together with a data processing technique for in-process form error measurement is proposed. The proposed design is based on the use of air beam [8] and is simple and costs less. The device is based on use of a triangulation laser digital range sensor.
2. Measurement setup

Developed system. The developed in-process form error optical measurement system is mainly made up of a triangular laser sensor Cyber Optics DRS300 to detect the workpiece surface form profile (Fig. 1). The applicator is to limit the coolant thickness and to redirect the coolant flow. The air piece is to allow forming of an air beam. The air beam applied to a moving workpiece will make a clean zone for measurement [8]. The measured profile height \( y \) from sensor and position signal \( x \) from a linear scale are both collected by a control PC to deliver a surface form profile \( y(x) \).

![Fig. 1. Setup for in-process form error measurement.](image1)

![Fig. 2. Stability test.](image2)

3. Vibration reduction

Working principle. Vibration is a key problem. The device was found to take a long time to be stable affecting measurement results as only air offers resistance when subject to a disturbance. A damping technique is proposed to use to solve this problem. To explain the working principle, the model of free damped vibration [10] (Fig. 2)

\[
m \ddot{y} + \gamma \dot{y} + k y = 0,
\]

where \( m \) is the mass, \( k \) is the stiffness coefficient, and \( \gamma \) is the system drag coefficient, is studied. If \( 2\beta=\gamma/m \) and \( \omega_0^2=k/m \), when \( \beta<\omega_0 \), we have

\[
y = Ae^{-\beta t} \cos(\omega_0 t + \varphi),
\]

where \( \omega=(\omega_0^2-\beta^2)^{1/2} \), \( \varphi=\tan^{-1}\left(-\left(v_0+\beta y_0\right)/\omega_0^2\right) \), \( A=(y_0^2+(v_0+\beta y_0)^2/\omega_0^2)^{1/2} \), \( y_0 \) is the initial position, and \( v_0 \) is the initial speed.

Damping technique. From Eq. (2), we increase \( \beta \) through fixing the device (Fig. 1) to the grinding machine to accelerate the vibration amplitude attenuation. To verify the analysis and to test the proposed technique, experimental tests (Fig. 2) were conducted (Fig. 3). The proposed technique is found effective. In particular, in the \( y \) direction, the attenuation (Fig. 3(d)) can be approximately 21 times faster compared to the one without the damping (Fig. 3(c)). The proposed technique can improve measurement accuracy and efficiency.

Effects of vibrations. The vibration in the \( x \) and \( z \) directions increase sampling position error which will indirectly affect the accuracy of profile height \( y \) (Fig. 1). For the measured workpiece, the error is 0.016\( \mu \)m and 0.01\( \mu \)m, respectively. The vibration in the \( y \) direction can directly change the profile height measurement value \( y(x) \) (Fig. 1-2). A vibration amplitude value of 1.5\( \mu \)m brings a form profile \( PV \) error of 3.0\( \mu \)m.

Moving average technique. To further reduce the effect of vibration (Eq. (1)-Eq. (2) and Fig. 1-3), a moving average technique is proposed. Tests show that sinusoidal harmonic motion is involved in the vibration steady stage (Fig. 3). The vibration effect in the \( y \) direction can be reduced if sampled data of a number of integral cycles are averaged over a distance \( \Delta x_a \) to deliver a single point of form profile \( y(x) \) (Fig. 4). \( \Delta x_a \) is also the sampling interval for \( y(x) \) (Fig. 6). A 40Hz vibration frequency will have 25 sampled data in one vibration cycle under a sampling frequency of 1000Hz. The number of cycles for averaging \( n_{ca} \) was studied (Fig. 5).
Fig. 3. Sensor position vibration with and without the proposed damping.

Fig. 4. Moving average model.

Fig. 5. Effects of $n_{ca}$. 

$$y_i = \left(\sum_{i=1}^{n_i} y_{n_i}\right) / n_i \quad \text{(profile height in } x_i)$$

$\Delta x_a$ - difference in position on workpiece

PV (μm) of vibration profile $y(x_{ca}, \Delta t)$ by the laser sensor (Fig. 1) at a particular point $(x_{ca}, \Delta t)$ indicates the error of vibration $e_{ca}$ (μm).

Test sample without coolant Workpiece with coolant
Error study. Because the workpiece moved during an average process, an extra error $e_d$ from workpiece profile due to $x$ position deviation is introduced (Fig. 6) and $e_d=0.5y_{pv}\Delta x_d/x_w$. In Fig. 6, $n_{ca}$ is the number of cycles for averaging, $t_v$ is the vibration cycle time, $t_v=0.025s$ for 40Hz vibration, $v_w$ is the grinding table velocity, and $v_w=0.5mm/s$. Based on the Wyko optical profiler results for the measured workpiece, $y_{pv}=6\mu m$ and $x_w=1.5mm$ (Fig. 6). $e_d$ is proportional to $n_{ca}$. The vibration error $e_v$ in the $y$ direction decreases with $n_{ca}$ (Fig. 5). For the two factors, the total error $e$ indicates that $n_{ca}=4$ is a good choice (Fig. 7). In this case, the error is reduced by more than 10 times (Fig. 5), $\Delta x_d=0.05mm$ (Fig. 7), which is far smaller than the form profile period of $3mm$, since by the Wyko optical profiler, the spatial frequency of the measured workpiece is $0.33/mm$. Therefore, the surface form profile $y(x)$ will not be distorted.

**Fig. 6.** Error due to $v_w$.

**Fig. 7.** Results of two error factors.

Measurement error of the system. The vibration error reduced by the moving average technique was assessed (Fig. 8). The original surface form profile (Fig. 8(c)) measured by the Wyko optical profiler has a nominal step height $10.02\pm0.085\mu m$. After applying the proposed moving average technique (Fig. 4), the PV value of the surface form profile is $10.38\mu m$ which has an error of approximately $0.3\mu m$ (Fig. 8(b)). If without using the proposed technique, the error is $2.08\mu m$ approximately. The error reduction is approximately 7 times as $e_d$ was also involved (Fig. 6-7).

**Fig. 8.** Results of a Wyko precision test sample.
4. Coolant problem study and performance assessment

**Coolant problem study.** To assess the coolant effect of the proposed device (Fig. 1), a workpiece sample was measured by the developed in-process form error sensor (Fig. 9). It can be seen that result of $PV=5.27\mu m$ with coolant is only 2.5% larger than the one without coolant (Fig. 9). The result shows that the air beam approach [8] works very well in coolant removal to deliver a clean zone for optical measurement. Since the measurement starting point on the workpiece surface cannot totally be the same, the shapes of two measured profiles will be slightly different.

**Performance assessment.** To assess the performance of the proposed device, the $PV$ values of surface form profiles at four $z$ positions (Fig. 1) were obtained. Each surface form profile in one $z$ position was measured twice to give 2 results (Table 1). It can be seen that the measurement repeatability error can be as low as 2.2%.

![Table 1. Repeatability test of the surface form profile in-process measurement (Fig. 1(a)).](image)

<table>
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<th></th>
<th>For $y(x, z_1)$</th>
<th>For $y(x, z_2)$</th>
<th>For $y(x, z_3)$</th>
<th>For $y(x, z_4)$</th>
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<tr>
<td>Measurement 1 $PV_1$ ($\mu m$)</td>
<td>11.10</td>
<td>11.57</td>
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<td>Measurement 2 $PV_2$ ($\mu m$)</td>
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<td>12.14</td>
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<td>0.25</td>
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<td>0.41</td>
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<td>Relative error $\Delta PV/PV_1$ (%)</td>
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<td>3.5%</td>
<td>4.2%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Relative error $\Delta PV/PV_2$ (%)</td>
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<td>3.4%</td>
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</table>

5. Conclusion

For the proposed in-process form error measurement system to solve two key problems, the damping design can accelerate vibration attenuation up to 21 times. The moving average technique can reduce vibration errors more than 10 times and there will be no distortion to the form profile results. For the workpiece sample, the measurement result under coolant condition is only 2.5% larger compared with the one under no coolant condition. For a certified Wyko test sample, the overall system measurement error can be as low as 0.3$\mu m$. The measurement repeatability error can be as low as 2.2%.

6. Acknowledgement

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References