A Study on Enhancement of Grinding Accuracy by an Active Tool Control

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An approach to enhance dimensional accuracy of the grinding process has been presented, and grinding of a glass material with a metal-bonded diamond wheel has been studied. In this study, a grinding tool is suspended flexibly and controlled by an electromagnetic actuator. During grinding, profile error of a ground surface is indirectly measured and fed back to a control system. A model of grinding error has been suggested on which the indirect measurement has been based. An optimal PID control is adopted and effectiveness of the in-process feedback control has been verified experimentally.

Key Words : Grinding, In-process, Error Compensation, Robustness, Optimal PID Control

1. Introduction

Precision has been one of the primary goals of today's manufacturing technology. To make machine tool structures more rigid and their motions more accurate may be a passive approach to the precision. A modern approach is to make the tool be active, i.e., servo controlled during machining to compensate the machining error actively in-process (Kegg, 1965, Yazawa et al, 1998 and Higuchi et al, 1998). This approach becomes essential especially for high accuracy that cannot be achieved by the passive one. The most serious difficulty of the in-process control lies on measurement of the machined surfaces because of the uncomfortable environments such as flowing coolant, chips and workpiece movement.

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This study is concerned with the grinding of a glass material with metal-bonded diamond wheel for fabrication of an optical mirror. The grinding is processed to obtain a contour of a mirror surface, and subsequent polishing is processed for extremely fine surface roughness of a mirror surface and some local corrections. The accuracy of grinding is important because the contour of a mirror surface is determined by the process. Contour error in grinding process is caused by various problems such as machine tool vibrations, tool wear, deflection, unquiet feed motions and etc. Even if the tool structure has infinite stiffness, grinding errors come from unquiet rigid body motion such as tool and workpiece feed motion In order to overcome the limitation of the rigid tool and achieve enhancement of grinding accuracy, flexible tool mount and active tool control have been studied in this work.

The grinding tool is suspended flexibly on a headstock of a machining center and its position is controlled by an electromagnetic actuator. A model of the grinding error is derived from consideration of geometry of the grinding process. Based on the model the grinding error is measured indirectly, which overcomes the difficulty of direct measurement. The grinding error is fed back to a controller and an in-process feedback control is applied. Effectiveness of active control of the grinding process has been verified by some experiments.

2. Process and Control System Model

Figure 1 shows a schematic of a grinding process. When the workpiece motion is $b(t)$ normal to the ground surface, the tool displacement is $x(t)$ caused by grinding force, and radial tool wear is $\Delta r(t)$. The grinding error $e(t)$ and instantaneous depth of cut $d(t)$ are defined from the geometrical configuration as

$$e(t)=x(t)+\Delta r(t)-b(t) \tag{1}$$
$$d(t)=w(t)-e(t) \tag{2}$$

where $w(t)$ is a desired depth of cut.

The dynamics of grinding tool is described using the transfer function $G_t(s)$ from an input force $f(t)$ acting on the grinding wheel to an output displacement $x(t)$

$$\frac{X(s)}{F(s)}=G_t(s) \tag{3}$$

where $X(s)$ and $F(s)$ are Laplace transforms of $x(t)$ and $f(t)$, respectively.

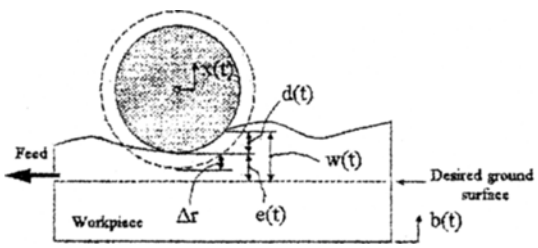

Fig. 1 Schematic of a grinding process

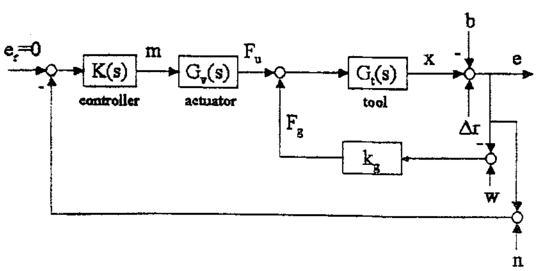

Fig. 2 Block diagram of the grinding control system

It is reasoned that the error $e(t)$ can be vanished by controlling $x(t)$ from Eq. (1). A control system will be developed which generates a control force $f_u(t)$ such that the error $e(t)$ is vanished. Eq. (1) is a basis of indirect measurement of $e(t)$, i.e., the grinding error $e(t)$ is determined by measuring $x(t)$, $\Delta r(t)$ and $b(t)$. The indirect measurement which overcomes the serious difficulties of the direct measurement of $e(t)$ makes the in-process control feasible.

Force $f(t)$ acting on the tool consists of a grinding resistance $f_g(t)$ and a control input $f_u(t)$ as

$$f(t)=f_g(t)+f_u(t) \tag{4}$$

The grinding resistance is assumed as

$$f_g(t)=k_g d(t) \tag{5}$$

where k_g is a coefficient of grinding resistance.

A block diagram in Fig. 2 shows the grinding control system where $G_v(s)$ is a transfer function of an actuator from the controller output to the control input $f_u(t)$.

3. Hardware Construction

A schematic diagram of the hardware built for this study is shown in Fig. 3. A machining center with a grinding tool attached to the headstock has been used. The grinding tool is suspended to the headstock flexibly using a notched hinge. The workpiece motion $b(t)$ and the grinding tool displacement $x(t)$ are measured in-process and fed back to a controller. Position of the grinding tool is controlled by an electromagnetic actuator.

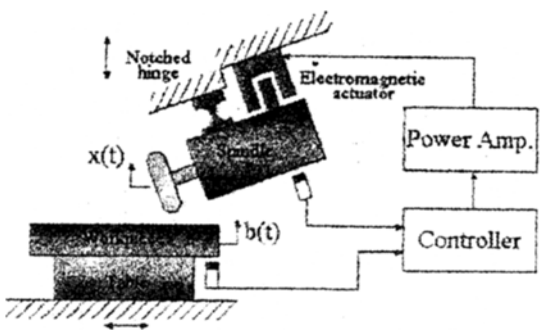

Fig. 3 Construction of a grinding control system

It is hardly possible to measure the tool wear $\Delta r(t)$ in-process because the wheel rotates at high speed and is in contact with the workpiece in coolant flow. Therefore, it seems to be more practical that a mean radius of the grinding wheel is measured intermittently out of the working zone and a mean value of the tool wear Δr is used for a period.

The transfer function $G_t(s)$ of the grinding tool has been found from the result of frequency response test as shown in Fig. 4.

$$G_t(s)=\frac{1/k_t}{\frac{s^2}{\omega_n^2}+\frac{2\zeta s}{\omega_n}+1}$$

where

$$k_t=28.1\mathrm{N/m},\ \zeta=0.021,\ \omega_n=238.7\mathrm{rad/s} \tag{6}$$

As the actuator system composed of a driver and an electromagnetic actuator has been found much faster than the tool dynamics, it is assumed that

$$G_v(s)=1 \tag{7}$$

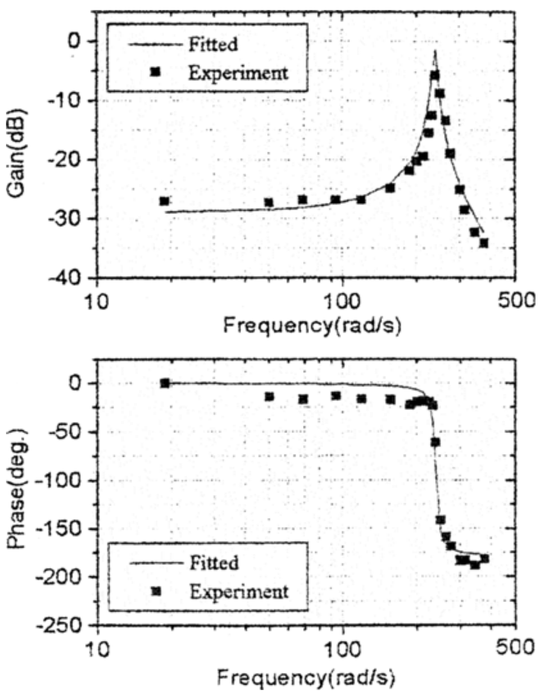

Fig. 4 Frequency response plot of flexible tool structure

The coefficient of grinding resistance is estimated as

$$k_g=2.5\times10^6\mathrm{N/m} \tag{8}$$

4. Controller Design

An optimal PID controller is designed. The following equation is derived from the equations (1)-(6).

$$\frac{\ddot{e}}{\omega_n^2}+\frac{2\zeta\dot{e}}{\omega_n}+\left(1+\frac{k_g}{k_t}\right)e=\frac{f_u}{k_t}+\left(\frac{k_g}{k_t}\right)w+\frac{\ddot{v}}{\omega_n^2}+2\zeta\frac{\dot{v}}{\omega_n}+v \tag{9}$$

where $v(t)=\Delta r(t)-b(t)$ (10)

An augmented state equation of the system is derived from Eq. (9) to remove steady state error as

$$\begin{pmatrix}\dot{e}_1\\ \dot{e}_2\\ \dot{e}_3\end{pmatrix}=\begin{bmatrix}0 & 1 & 0\\ -\omega_n^2(1+k_g/k_t) & -2\zeta\omega_n & 0\\ 1 & 0 & 0\end{bmatrix}\begin{pmatrix}e_1\\ e_2\\ e_3\end{pmatrix}+\begin{pmatrix}0\\ \omega_n^2/k_t\\ 0\end{pmatrix}f_u+\begin{bmatrix}0 & 0 & 0 & 0\\ \omega_n^2 & 2\zeta\omega_n & 1 & \omega_n^2(k_g/k_t)\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{pmatrix}w_1\\ w_2\\ w_3\\ w_4\end{pmatrix} \tag{11}$$

where $e_1=e$, $e_2=\dot{e}$, $e_3=\int e\mathrm{d}t$, $w_1=v$, $w_2=\dot{v}$, $w_3=\ddot{v}$, $w_4=w$

Transient response as well as the stability is important for the control system. Transient motion of the tool occurs when it starts to contact with a workpiece. It leaves undesirable traces on the ground surface. To achieve both the stability and fast decaying of the transient motion, a cost function is taken to impose a prescribed stability, which is to locate closed-loop poles a units to the left of the imaginary axis (Shahian and Haussaul, 1993)

$$J=\frac{1}{2}\int e^{2at}(\vec{e}^TQ\vec{e}+Rf_u^2)\,dt \tag{12}$$

The Ricatti equation is given by

$$(A+aI)^TP+P(A+aI)+Q-PBR^{-1}B^TP=0 \tag{13}$$

where

$$A=\begin{bmatrix} 0 & 1 & 0 \\ -\omega_n^2(1+k_g/k_t) & -2\zeta\omega_n & 0 \\ 1 & 0 & 0 \end{bmatrix},\ B=\begin{bmatrix} 0 \\ \omega_n^2/k_t \\ 0 \end{bmatrix}$$

The weight matrices and α are taken as

$$Q=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},\ R=10^{-15},\ \alpha=10^3 \tag{14}$$

The optimal control input fu(t) is given by

$$f_u(t)=-[K_p\ K_d\ K_i]e=-R^{-1}B^TPe \tag{15}$$

The PID gains are obtained from the solution of Ricatti equation and listed in Table 1.

Figure 5 shows Bode plot of the open loop transfer function of the designed optimal PID control systems. It is shown that the gain margin is 44.3 dB and phase margin is 65.5° which convinces good relative stability.

Table 1 The optimal PID gains

Gain (Unit)	Value
Proportional, K_p(N/m)	3.18×10^7
Integral, K_i(N/ms)	3.26×10^{11}
Derivative, K_d(Ns/m)	1.79×10^2

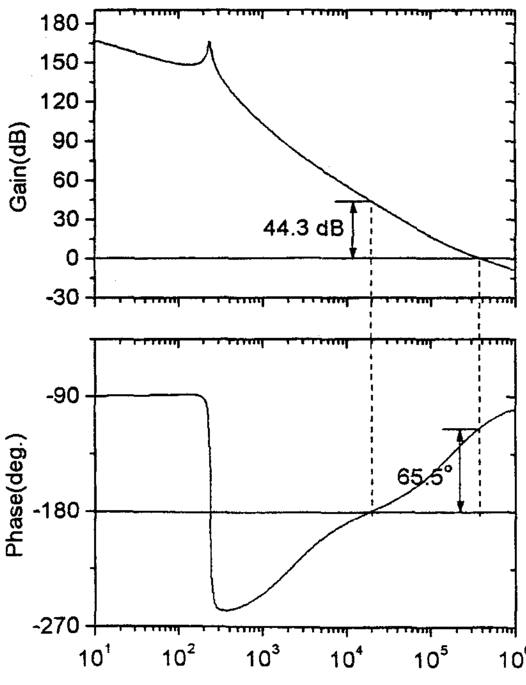

Fig. 5 Open-loop Bode plot with PID controller

Figure 6 shows the numerical solution of the grinding error $e(t)$ and the corresponding control force $f_u(t)$ with the desired depth of cut $w(t)$ is set as a step function of $1\mu m$ magnitude. It shows that the control system has good transient response characteristics and the magnitude of $f_u(t)$ is acceptable.

Performance of disturbance rejection of the control system is shown in Fig. 7. It is shown that effects of the workpiece motion $b(t)$ and the surface wave $w(t)$ on the grinding error are much attenuated by the control, whereas the effects of measurement noise $n(t)$ cannot be attenuated. It is noted that the gain of $e(t)/b(t)$ would be 0dB for all frequencies with a rigid tool suspension. The grinding wheel contacting the workpiece has a rather large radius (the radius is 7.5mm in this study). Thus high frequency components of $e(t)$ are much attenuated by the large tool radius without any control, e.g., geometrical analysis shows that relative motion between tool and workpiece with $100\mu m$ amplitude and 1 kHz leaves cusps of only $0.116\mu m$ height

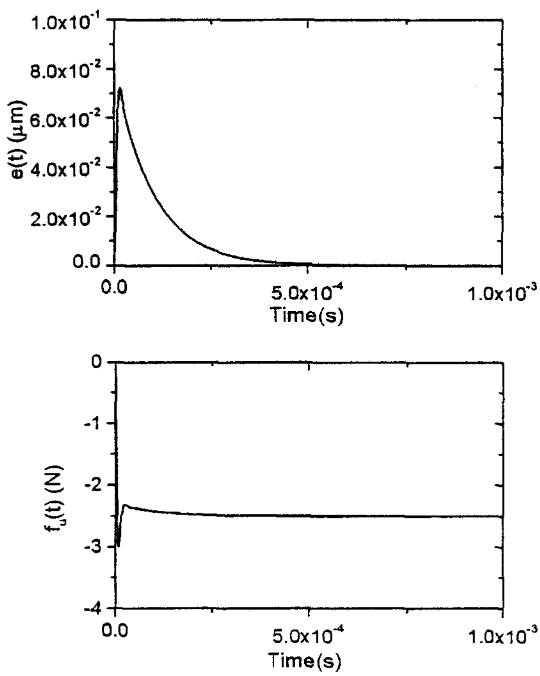

Fig. 6 Step responses of $e(t)$ and $f_u(t)$ to $w(t)=1\mu m$

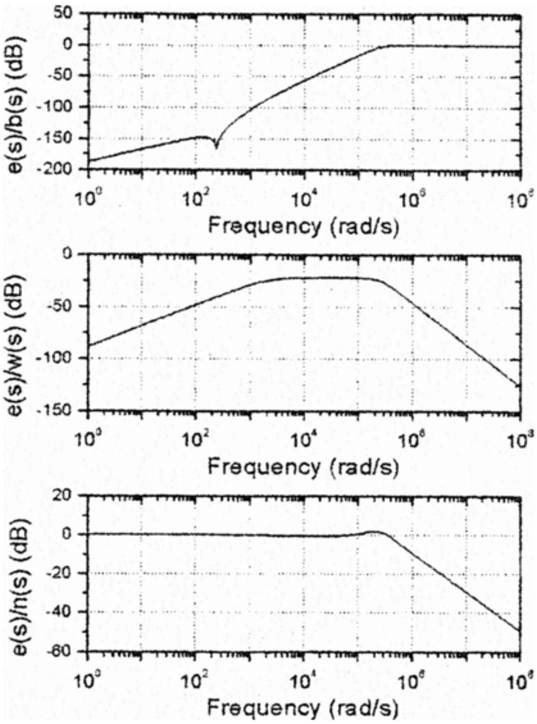

Fig. 7 Disturbance attenuation

when the grinding wheel is fed at 5m/min. It implies that disturbance attenuation by the control at low frequencies is more of interest.

5. Experiments

The control system was implemented on a machining center as shown in Fig. 5, and the grinding conditions are listed in Table 2.

While the workpiece is being fed and ground, it is programmed to move up and down sinusoidally with $10\mu m$ peak-to-peak amplitude. As illustrated in Fig. 8, the workpiece motion, $b(t)$, and the tool displacement, $x(t)$, are measured by gap sensors mounted on a headstock and fed back to a controller which is implemented by a DSP board. It calculates the grinding error, $e(t)$, according to to the equation (1) and gives command to the electromagnetic actuator. In this experiments, tool wear $\Delta r(t)$ is neglected because of the short grinding period of about 20 seconds.

Figure 9 shows some signals flowing in the

Table 2 Grinding conditions of experiments

Process	Surface grinding
Wheel	Metal bonded diamond wheel
Mesh (#)	400
Wheel speed (m/s)	20
Feed rate (mm/min)	200
Coolant	dry

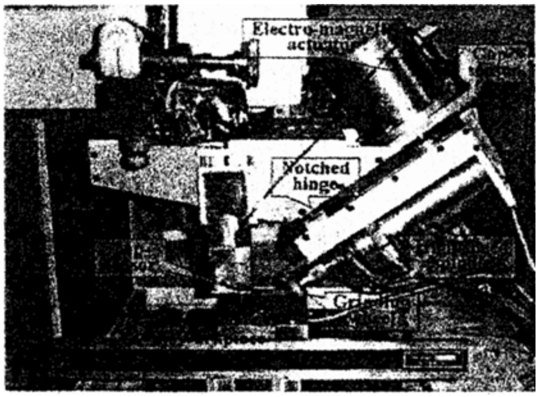

Fig. 8 Photograph of an experimental setup

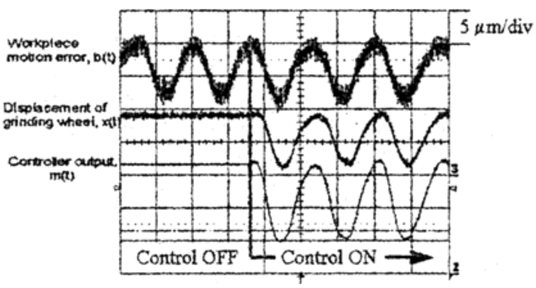

Fig. 9 Signals in the control system

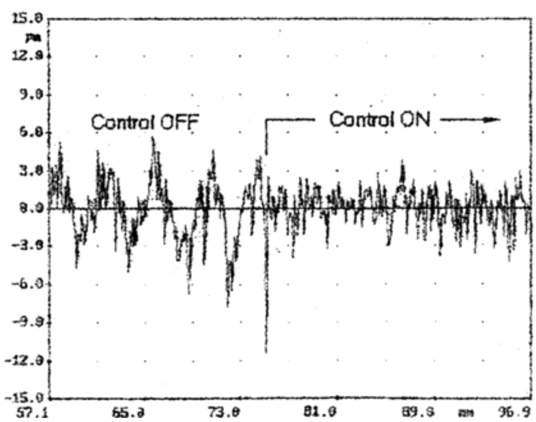

Fig. 10 Profile of a ground surface

control system, and it shows that the intended control system works well.

As a result, the ground surface was scanned in longitudinal direction using the surface roughness tester as shown in Fig. 10. In the figure, high frequency component corresponds to the surface roughness while the low frequency component does to the surface waviness which is attributed to the workpiece motion. It is clearly shown that the waviness of ground surface is much attenuated by the control such that the waviness is reduced approximately to 20% by control.

6. Conclusion

An in-process feedback control of a grinding process has been studied to improve the grinding accuracy. The grinding tool is suspended flexibly and controlled by an electromagnetic actuator. A grinding process model has been suggested which provides a basis for the indirect measurement of the grinding error. The indirect measurement circumvents the difficulty of the direct measurement so that the in-process control becomes feasible. An optimal PID controller is designed to achieve both the prescribed stability and the fast decaying of the transient response. The control system has been implemented and verified by the experiments, which shows that the proposed approach works successfully.

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