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In-Process Cutter Runout Compensation Using Repetitive Learning Control

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ABSTRACT

This paper presents the in-process compensation to control cutter runout and to improve the machined surface quality. Cutter runout compensation system consists of the micro-positioning servo system with piezoelectric actuator which is embeded in the sliding table to manipulate radial depth of cut in real-time. Cutting force feedback control was proposed in the angle domain based upon repetitive learning control strategy to eliminate chip load variation in end milling process. Micro-positioning control due to adaptive actuation force response improves the machined surface quality by cutter runout compensation.

Key Words : Cutter Runout, Repetitive Learning Control, Cutting Force Feedback Control, In-Process Compensation

1. Introduction

Milling process is one of the broadly used manufacturing processes for producing parts and products. Despite of its broad use, there are some limitation to improve productivity and machining quality because of a few disturbances.

Especially, as seen in Fig. 1, cutter runout is a common, but undesirable phenomenon in multi-tooth machining such as end milling process. Cutter runout due to non-uniform depth of cut when cutter rotates about an different axis than its axis of geometrical center.

It comes from spindle imperfection such as the offset due to misalignment, thermal deformation or uneven tool wear[1,2], and introduces an accelerated tool wear, amplification of cutting force variation, enlargement of machine tool vibration, and deterioration of surface quality of machined parts (Fig. 2).

This paper presents a methodology to improve surface quality through the real-time compensation of cutter runout effectively. To know the cutter runout mechanism and related cutting force variation, basic experiments were performed. In-process compensation system which is activated with cutting force feedback control algorithm can control the change of chip load with cutter runout phenomenon. Thus, cutting force adaptive control was proposed which is based on repetitive learning control strategy to eliminate chip-load variation due to cutter runout in end milling process.

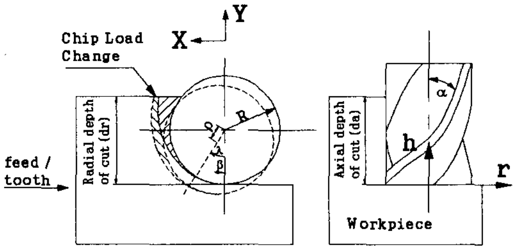

Fig. 1 Schematic diagram of cutter runout and chip load change

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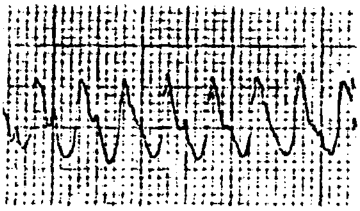
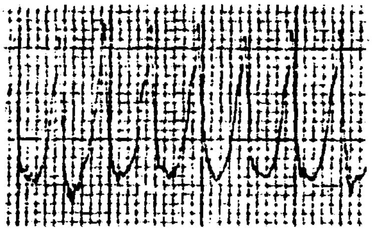


(a) normal cut state



(b) runout cut state

Fig. 2 Comparison of measured surface roughness with respect to runout magnitude ((a) $\rho=2\ \mu m$, (b) $\rho=15\ \mu m$)

2. Compensation System Design

2.1 System Hardware

Cutter runout compensation system consists of tool dynamometer and charge amplifier for cutter runout signal measurements, and micro-positioning servo system and microprocessor for real-time compensation and control, which is installed on vertical CNC milling machine as shown in Fig. 3.

Piezoelectric actuator embedded in low friction sliding table on the X-Y plane (Fig. 4) under the control of microprocessor is activated to manipulate two-axes depth of cut simultaneously in the direction opposite to that of chip load variation.

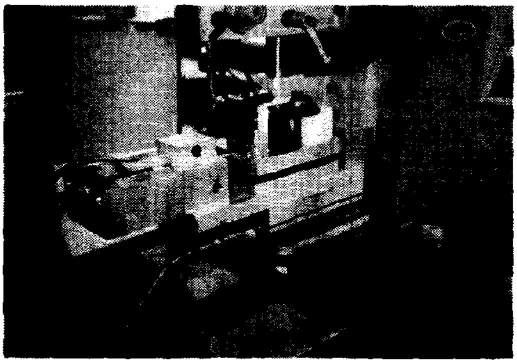


Fig. 3 Photo. of in-process cutter runout compensation system

This position servo control of workpiece with micro-positioning device could suppress the chip load variation and maintain the constant depth of cut.

In this study one-axis manipulation was performed to compensate chip load variation along the radial direction in end milling.

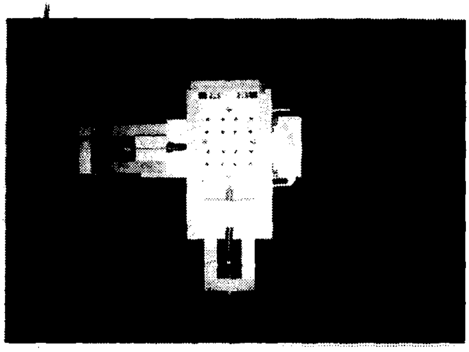


Fig. 4 Micro-positioning device with embedded piezoelectric actuator

For sampling and controlling of cutting system in the angle domain rotary encoder is attatched to the spindle as the external triggering device. The cutting force due to cutter runout is sampled and controlled with equivalent period of regardless of the spindle rotating frequency.

Through the previous study the band-pass filtered signal of cutting force component at a frequency near spindle rotating frequency reflects periodic chip load change due to the engagement and disengagement of individual cutter tooth with the workpiece.

2.2 Control Algorithm

To achieve appropriate compensation of depth of cut, micro-positioning device was controlled by using repetitive learning control algorithm. The repetitive learning control in Fig. 5 is frequently used in control applications. In this study, the objective of the control is to achieve as follows,

$$e_{ss} = \lim_{\theta \to \infty} e(\theta) = 0 \qquad (1)$$

where, $y_d(\theta) = 0$ for all θ.

The use of the repetitive controller was motivated by the fact that the cutting force variation induced by cutter runout is basically periodic with a period given to be 100 samples.

The repetitive control utilizes the internal model principle[3] in the internally modeling the non-asymptotically stable part of the plant dynamics. This is accomplished by incorporating in the controller a time delay that has a period identical to the time period of the error. This type of controller is rather suited for the control of machining processes in which the rotation of either the workpiece of the tool often induces disturbances of periodic nature.

The transfer function of a digital repetitive learning controller as,

$$\frac{u(\theta)}{e(\theta)} = \frac{1}{(1-q^{-N})}\frac{P_c(q^{-1})}{Q_c(q^{-1})} \qquad (2)$$

where, $\frac{1}{(1-q^{-N})}$ presents the asymptotic stability of the control system, N is the number of samples per one period of spindle revolution, 100, in this study, $e(\theta)$ is the difference between the reference signal and the measured cutting force, $u(\theta)$ is controlling voltage command to the actuator.

For a known open loop plant dynamics a controller of pole-zero cancellation type can be formulated as,

$$P_c(q^{-1)} = K_r^{-N+1}\cdot P_p(q^{-1}) \qquad (3)$$

$$Q_c(q^{-1}) = q^{-1}\cdot Q_p(q^{-1}) \qquad (4)$$

where, K_r designates the learning gain which is the steady state gain of the feed forward loop incorporating the dynamics cancellation between the controller and the machining process.

$P_p(q^{-1})$ and $q^{-1}\cdot Q_p(q^{-1})$ are the denominator and numerator polynomials for the open loop plant transfer function as seen by the learning controller,

$$\frac{f(\theta)}{e(\theta)} = \frac{q^{-1}P_p(q^{-1})}{Q_p(q^{-1})} \qquad (5)$$

where, $f(\theta)$ is the cutting force.

The characteristic equation for the closed loop system, defined with respect to the force reference input and the force measurement output, can be shown to be,

$$Q_p(q^{-1})\cdot P_p(q^{-1})[(1-q^{-N})+K_r\cdot q^{-N}]=0 \qquad (6)$$

$$0 < K_r < 2 \qquad (7)$$

The learning gain is selected to satisfy K_r gain because that the asymptotic stability of the closed loop system under learning control will be guaranteed.

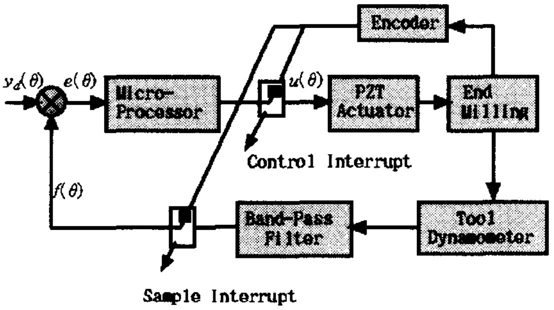


Fig. 5 Block diagram of cutting force feedback control system

To know the feasibility of cutter runout compensation system and its control algorithm, cutting experiments were performed.

In Fig. 6 cutting force variation due to cutter runout effect and control signal to compensate cutter runout

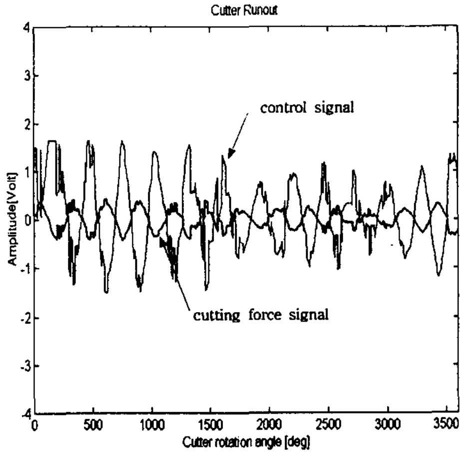


Fig. 6 Variation of cutting force & control signal under cutter runout state (fr=300 mm/min, dr=1.0 mm)

effect. Cutting force under runout condition shows large fluctuation and repetitive periodic variation due to non uniform depth of cut because of cutter rotation about an different axis than its axis of geometric center.

Cutting force was sampled and controlled according to spindle rotation angles. The compensation signal was generated opposite to chip load change due to cutter runout magnitude.

3. Experimental Results

To know the feasibility of cutter runout compensation system and its control algorithm, a few experiments were performed under experimental conditions which is described in Table 1.

Table 1 Experimental cutting conditions

Cutting Variables	Cutting Conditions
Cutting tool	ϕ10 mm, 4-flute, 30° helix angle
Workpiece material	UHMW Polyethylene
Axial depth of cut (da)	14.0 mm
Radial depth of cut (dr)	1.0 mm
Feed rate (fr)	150, 300 mm/min
Feed direction	down cut
Spindle speed (n)	300 - 600rpm
Cutter runout magnitude(ρ)	16μm

Typical cutting force variation in the radial direction of end milling are shown in Figs. 7 and 8 under normal cutting state and cutter runout state, respectively. As shown in Fig. 8, cutting force with cutter runout presents large fluctuation due to non-uniform depth of cut when cutter rotates about a different axis than its axis of geometrical center.

Through the frequency response analysis, 5Hz spectrum peak as the cutter rotating frequency(fn) shows the existence of cutter runout which is compared with normal cutting state. From these first experiments filtered cutting force signal at the spindle rotating frequency strongly indicates cutter runout effects and is useful to compensate chip load change.

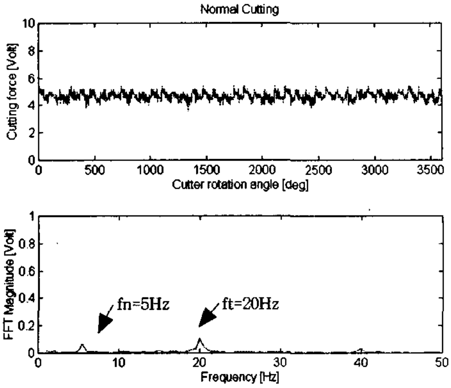


Fig. 7 Variation of cutting force and frequency response under normal cutting state (fr=150 mm/min, n=300 rpm)

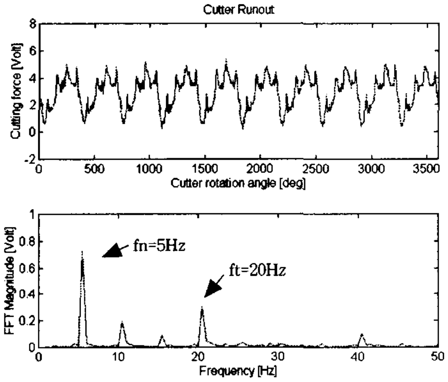
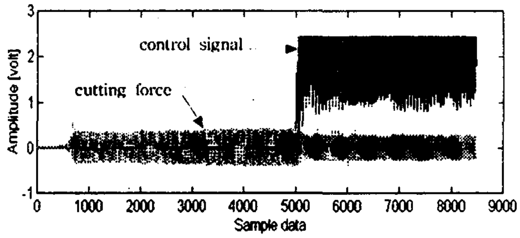
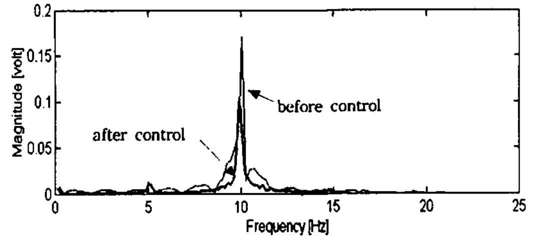


Fig. 8 Variation of cutting force and frequency response under cutter runout state (fr=150 mm/min, n=300 rpm)

The results of cutter runout compensation via repetitive learning control under normal cutting state and cutter runout state are shown in Fig. 9 and Fig. 10.

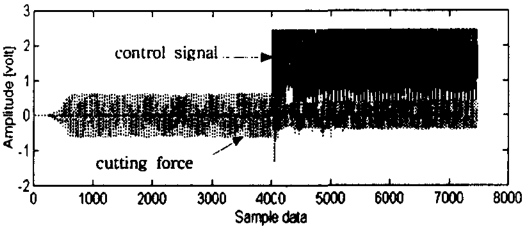


(a) cutting force & control signal

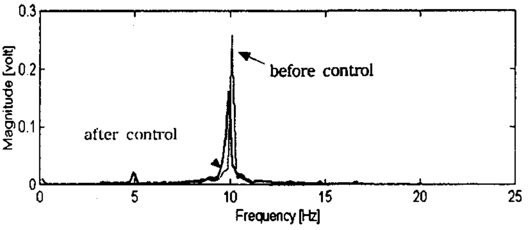


(b) frequency response of cutting force

Fig. 9 Variation of cutting force and frequency response under normal cutting state (fr=300 mm/min, n=600 rpm)



(a) cutting force & control signal



(b) frequency response of cutting force

Fig. 10 Variation of cutting force and frequency response under cutter runout cut state (fr=300 mm/min, n=600 rpm)

Cutting force amplitude under cutter runout state changes according to cutter runout magnitude. After repetitive controlling cutting force amplitude decreases effectively. Cutting force amplitude change due to cutter runout magnitude can be controlled by precision control of depth of cut effectively.

Generally at the normal cut state about 2 μm cutter runout exists because of imperfection of tool holder manufacturing or assembly quality. This in-process compensation system can be compensated the cutter runout under normal cut state through rejection or minimize of chip load change.

Form the above experimental results it is possible to control chip load change due to cutter runout using dynamic cutting force component at spindle rotating frequency, In-process compensation system which is developed in this study performed micro-positioning servo control of workpiece to obtain constant depth of cut and minimum cutting force variation.

The variation of dynamic cutting force change during machining process could be reflected to surface roughness, tool life and machine tool stability. Surface roughness in multi-tooth machining is complicated kinematic and dynamic relationships between dynamic cutting force variation and trajectories of cutting tool.

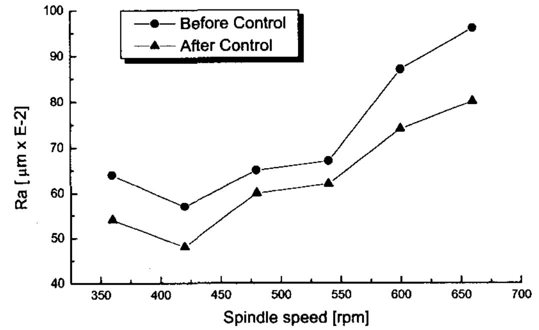


Fig. 11 Comparison of the center line average surface roughness height under before/after cutter runout compensation

The measured surface roughness results of machined parts are shown in Fig. 11. The comparison of center line average value of surface roughness R_a results under before and after compensation state shows improvement of surface roughness by repetitive learning control.

4. Conclusions

The achievable productivity and part surface quality in machining processes are often limited by the capability of the machine tool to cope with disturbances. Cutter runout issues of the cutting tool is one of such example of disturbances frequently experienced on the shop floors.

In this study, a chip load servo control methodology to compensate for cutter runout thereby improving the machined surface finish in end milling process has been discussed. The force servo involved the measurement of cutting force variation in the radial direction due to cutter runout, and the angle domain piezoelectric actuation of the workpiece relative to the cutter so as to maintain a cutting force free of spindle rotating frequency component.

As a result that the cutter runout compensation system, which used by repetitive learning controller, improved the surface finish of machined part by an order of about 20% in the sense of center line average roughness. It also leads to an improved part surface finish which is critical to the quality and productivity of machining process.

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