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Proposal of ‘accelerative cutting’ for suppression of regenerative chatter

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ABSTRACT

A novel speed variation method, namely ‘accelerative cutting’, is proposed for suppression of regenerative chatter in short-duration plunge cutting, e.g. finishing of sealing, seating, and bearing surfaces. Although the cutting time is short in these processes, the large cutting width often causes chatter. Compared to conventional speed variation methods where moments exist when present and previous cutting speeds do not change and cause the growth of chatter, a unidirectional acceleration is applied resulting in sufficient speed difference throughout the cutting. Since accelerative cutting cannot be realized by conventional NC functions, it is verified through analyses and specially designed cutting experiments.

1. Introduction

Chatter causes limitation in the machining efficiency which is a crucial problem for industrial applications. In particular, there are numerous industrial needs for short-duration plunge cutting, e.g. finishing of sealing, seating, and bearing surfaces. For example, the finishing of the sealing of a hydraulic part is shown in Fig. 1. Although the cutting time is like a few tenths of a second in these particular cutting processes, a large cutting width is necessary which often causes chatter. Especially, chatter caused by the regeneration of the previously cut surface, i.e. regenerative chatter, occurs in practical cutting methods, e.g. turning and milling, and it is the dominant factor among all chatter phenomena.

A variety of researches have been carried out to tackle the regenerative chatter problem. A simple method to increase the efficiency is the selection of the spindle speed and cutting width where regenerative chatter is most unlikely to occur [1]. This method can be applied effectively in the low number lobes, i.e. high spindle speed or cutting speed. Other methods are such as the use of variable pitch/helix cutters [2,3] and the optimization of those [4,5] (for milling), use of vibration absorbers or dampers [6], etc.

Another method for the suppression of chatter is the spindle speed variation (SSV), and many works have been dedicated to reveal its suppression mechanism and to validate its effect both experimentally and analytically. It was first proposed by Takemura et al. [7], and its effectiveness against regenerative chatter was validated experimentally and analytically by means of energy balance. Thereafter, numerous simulation methods in time domain and frequency domain have been proposed, including the semi-discrete time-domain simulation [8], frequency-domain simulations focusing on the eigenvalue [9], etc. [10,11]. For the SSV profiles, sinusoidal, triangular, and random profiles have been proposed, nevertheless all of them having the suppression effect.

However, it is known that SSV has an effect to some level but does not have a significant effect depending on the SSV conditions and vibratory structure [10]. Even worse, it sometimes destabilizes effective conditions in constant speed machining [12]. In the authors’ perspective, this is considered to happen because there are moments when the present and previous cutting speeds are the same which diminishes the effect of SSV. Therefore, it can be observed that there is a limit to the effect of SSV, and correct parameters need to be adapted to realize the suppression effect.

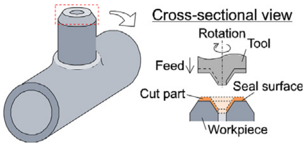

Fig. 1. Schematic of finishing process of sealing of a hydraulic part.

Although conventional methods, for example variable pitch cutters, can be used for the targeted short-duration plunge cutting processes, there is a need of knowing the chatter frequency and other parameters beforehand. In addition, these processes have a short duration, so SSV may cause unstable cutting depending on the SSV parameters because of the aforementioned nature of SSV.

In this research, a novel suppressive cutting method for regenerative chatter, namely ‘accelerative cutting’, is proposed. In this method, the spindle speed is accelerated/decelerated in a unidirectional manner so that the speeds in the present and previous revolutions change at every moment causing suppression throughout the cutting.

In this paper, the limit of SSV is explained first, and accelerative cutting is described focusing on the acceleration rate. Second, a

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time-domain simulation is conducted to reveal its effect against regenerative chatter. Third, since the proposed method cannot be realized by conventional NC functions, specially designed cutting experiments are carried out to validate its effectiveness, and the results are discussed clearly. Last, conclusions follow.

2. Accelerative cutting and its advantage

2.1. Limit of SSV

In SSV, there are moments where the spindle speeds, or cutting speeds, of the present and previous revolutions do not change, hence causing chatter. To confirm this problem, cutting with its experimental setup shown in Fig. 2(a) is conducted with SSV on a turning center (Okuma Corp., Spaceturn LB3000EX). In addition to the spindle speed profile obtained from the spindle motor encoder and vibration acceleration signal obtained from an accelerometer, the acceleration rate r_a, i.e. $r_a = (n_{pres}/n_{prev}) - 1$, of the profile is shown in Fig. 2(b) where n_{pres} and n_{prev} are the speeds in the present and previous revolutions, respectively. n_{prev} is obtained by determining the spindle speed at the position 2π rad, or 1 rotation, before. As observed in the figure, there are moments where r_a is near 0% when the accelerative direction of the spindle changes, which means ordinary constant speed machining is performed, i.e. there is no suppression effect. If r_a is insufficient for suppression and it continues, chatter can grow. In this experiment, the tool is flexible, and plunge cutting of a brass pipe is conducted. It can be observed that chatter grows at moments where r_a is near 0%. In other parts, r_a is sufficient, and thus the chatter diminishes.

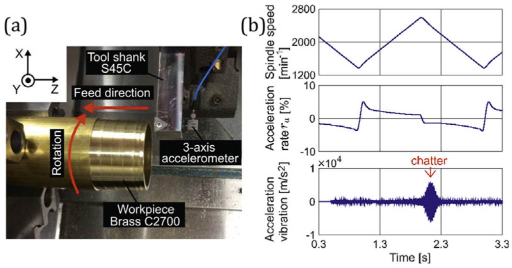

Fig. 2. (a) Experimental setup for SSV experiment and (b) spindle speed profile, acceleration rate r_a, and vibration acceleration signal.

2.2. Proposal of accelerative cutting and its advantage

From the above results, it is observed that sections where the accelerative direction changes limit conventional SSV. Therefore, a novel method named 'accelerative cutting' is proposed where there are no such sections. In this method, the spindle speed is continuously accelerated/decelerated in a unidirectional manner resulting in sufficient speed difference between the present and previous revolutions. In addition, the spindle speed is controlled to keep r_a constant, and hence chatter is suppressed in the whole cutting process. Since short-duration plunge cutting, e.g. cutting time of few tenths of a second, is targeted, only a small number of revolutions are needed. Hence, the speed range is within a few ten percent of the beginning speed. Therefore, the spindle is able to keep its speed within its limitation, and also built-up edges in low speeds and tool wear in high speeds will not be a problem.

Accelerative cutting cannot be realized by conventional NC functions since the cutting has to end while the spindle is still accelerating. Fig. 3 shows the ideal machine tool motion for accelerative cutting. The spindle speed is accelerated so that r_a is constant, i.e. +2% in this case, and the cutting ends, meaning that the feed ends, when the spindle is still accelerating. By doing so, chatter cannot grow throughout the cutting as long as r_a is sufficient. Note that the acceleration/deceleration profile does not always have to be commanded to keep r_a constant, but the minimum rate throughout the cutting has to be larger than the critical rate for the suppression of chatter.

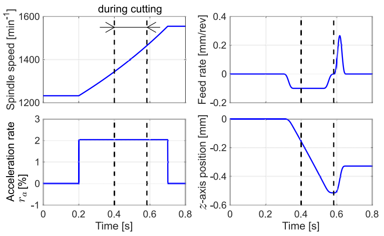

Fig. 3. Ideal machine tool motion for accelerative cutting.

3. Time-domain simulation of accelerative cutting

3.1. Time-domain simulation model

To verify the effectiveness of accelerative cutting and show evidence of the critical rate, time-domain simulations are conducted. A single-degree-of-freedom (SDOF) vibratory system is assumed, which is a simplified form of the actual system in Fig. 1, but here the tool is flexible instead of the workpiece. The schematic illustration of the SDOF model is shown in Fig. 4.

It is well known that the vibration in the previous revolution affects the present cutting. Hence, the uncut chip thickness $h(t)$ can be formulated as follows.

$$h(t) = h_0 + z(\theta(t) - 2\pi) - z(t) \tag{1}$$

Here, h_0 is the static depth of cut, $\theta(t)$ is the angular position, and z is the displacement in the depth of cut direction. In order to obtain $\theta(t)$, the spindle speed is first expressed as a function of θ: $n(\theta) = n_0(1 + r_a)^{\theta/(2\pi)}$, where r_a is constant as in Fig. 3 and n_0 is the initial speed. As $d\theta/dt = 2\pi n/60$, the differential equation $d\theta/dt = 2\pi n_0(1 + r_a)^{\theta/(2\pi)}/60$ is obtained and solved as follows: $\theta(t) = -2\pi \ln(1 - n_0 t \ln(1 + r_a)/60)/\ln(1 + r_a)$, and $n(t) = n_0/(1 - n_0 t \ln(1 + r_a)/60)$.

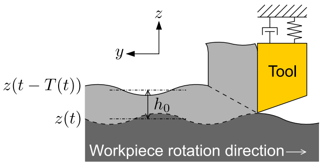

Fig. 4. Schematic of SDOF model.

The cutting force $F_z(t)$ fluctuates according to the uncut chip thickness as follows.

$$F_z(t) = K_t b h(t) \tag{2}$$

K_t is the specific cutting force in the thrust, i.e. depth of cut, direction, and b is the total cutting width. The tool's equation of motion is expressed by using modal parameters, and the governing equation of the SDOF system can be expressed as follows.

$$m z(t) + c\dot{z}(t) + kz(t) = K_t b\{h_0 + z(\theta(t) - 2\pi) - z(t)\} \tag{3}$$

Here, m, c, and k are the modal mass, damping coefficient, and stiffness, respectively. In the simulation, the initial increase in the depth of cut is the only inputted source of displacement which can grow to chatter. Note that this depth of cut increases gradually in the beginning of cutting due to the nature of the turning process. The solution is approximated by the 4th order Runge–Kutta method. $\theta(t)$ and $z(t)$ are memorized at each calculation step, and they are utilized afterwards as the previous displacement $z(\theta(t) - 2\pi)$. The utilized parameters are shown in Table 1.

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