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Evaluation of sensor-less identification method for stable spindle rotation against chatter with milling simulation analysis

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Abstract

Although chatter stability analysis is necessary to enhance cutting accuracy and efficiency, a reliable prediction is difficult to achieve because of the analysis error of frequency response function. Therefore, the investigation proposes an experiment-based identification method for stable spindle rotations in milling by gradually changing the spindle rotation and capturing chatter frequency shift from servo information. In order to evaluate the identification accuracy, this paper presents theoretical approaches to analyze time-dependent variation in chatter and the expected identification error of proposed method by using a time-domain simulator and a frequency-domain model considering amplitude ratio between inner and outer modulations of the chip.

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Keywords: Observer; Monitoring; Chatter.

1. Introduction

Chatter must be avoided in milling because it deteriorates machining accuracy and leads to tool breakage. Therefore, many researchers have focused on mechanism of chatter and proposed various stability prediction methods by constructing precise milling models [1,2]. However, the prediction results often do not agree with real process because the stability analyses require frequency response function of the tool system generally, which are technically difficult to identify with high accuracy and vary according to the spindle rotation due to heat generation in bearings and so on [3].

In order to enhance the reliability, some process-based analysis methods also have been proposed until now. For example, some researches proposed chatter stability analysis by ramping up the spindle rotation during chatter and monitoring the amplitude and frequency of chatter [4,5]. This method can identify the stable cutting condition accurately; however, measurement devices such as dynamometers are needed, which requires high cost, frequent maintenance and expert skills to correctly use them. Furthermore, the identification error is hardly discussed from theoretical viewpoint, though the experimental investigation sufficiently has been performed. Because chatter mechanism is generally explained in frequency domain, the time-dependent variation in chatter cannot be dealt with in conventional milling models.

In order to improve the practicability, this paper proposes a sensor-less approach for process-based analysis on chatter stability in milling on the basis of disturbance observer theory. Changing the spindle rotation gradually and capturing the chatter frequency shifts by analyzing the servo information, the stable spindle rotation against chatter is identified without additional sensors. Furthermore, to discuss the identification error of the proposed method, the time-dependent variation in chatter is analyzed with a time-domain milling simulator and a frequency-domain milling model including the amplitude ratio between inner and outer modulations of the chip. The adequacy of the proposed method is confirmed by comparing the experimental results and the theoretical analyses.

2. Theory of chatter stability analysis

2.1. Concept of experiment-based chatter stability analysis

In order to avoid chatter, the critical depth of cut should be identified accurately. That is the reason why the relation

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between the critical depth of cut and spindle rotation is mainly focused on in chatter stability analysis. In contrast, the chatter frequency information does not gather attention, though it generally can be also obtained in the procedures of chatter stability analysis. The chatter frequency also has a unique characteristic related to the chatter stability.

As an example, Fig. 1 shows the variations of critical depth of cut and chatter frequency along with spindle rotation [1], where the modal parameters and cutting conditions are given as Tables 1 and 2. The critical depth of cut locally gets large at some spindle rotation regions, which are so-called stability pockets and necessary to be identified to enhance the cutting efficiency. The chatter frequency gradually gets higher with higher spindle rotation and drastically shifts lower at the stable spindle rotations, defined as spindle rotations at which the critical depth of cut becomes locally largest. Based on this characteristic, the stable spindle rotation against chatter can be captured by gradually changing the spindle rotation and monitoring the chatter frequency variation. In this case, the chatter frequency would gradually change and drastically shifts at spindle rotations which are stable against chatter.

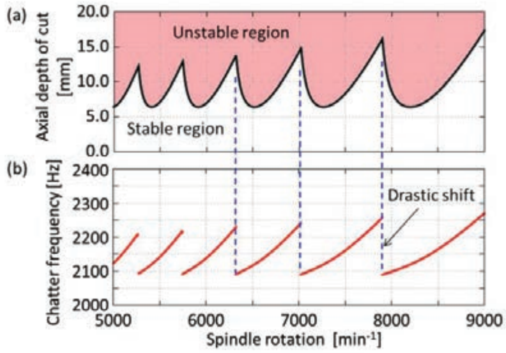

Fig. 1. Relations between spindle rotation and (a) critical depth of cut; (b) chatter frequency.

Table 1. Modal parameters of tool system.

Parameters (same parameters are given in both X and Y directions)	
Natural frequency Hz	2082
Damping ratio	0.0178
Mass kg	0.048

Table 2. Cutting conditions.

Parameters	
Number of tooth	2
Immersion angle deg	-25.8～0.0
Helix angle deg	30
Type of cut	Down milling
Tangential cutting coefficient MPa	1500
Radial cutting coefficient MPa	450

2.2. Disturbance observer

To capture the chatter frequency variation without additional sensors, disturbance observer is applied to a spindle control system in this study. Disturbance observer is a technique to estimate a disturbance in a control system by integrating the servo information [6]. It is applicable to monitor the cutting torque, which is defined as load torque due to cutting force. Therefore, a chatter-induced fluctuation in the cutting torque also can be captured.

A dynamic equation of a spindle motor in Laplace domain can be described as follows:

$$K_t I_a^{ref} = J\omega s + T_l \quad (1)$$

where K_t [Nm/A] is the torque coefficient, I_a^{ref} [A] is the current reference, J [kg·m^2] is the inertia moment of the spindle shaft, ω [rad/s] is the rotational speed, and T_l [Nm] is the external torque including the cutting torque.

Generally, disturbance torque is defined as total torque of load torque and error due to parameter variation as

$$T_{dis} = (J - J_n)\omega s - (K_t - K_{tn})I_a^{ref} + T_l \quad (2)$$

where the subscribe n represents the nominal value. In case of milling process, the error is negligibly small compared with cutting torque because the inertia moment hardly changes and the influence of torque coefficient variation is also small. Assuming $K_t \approx K_{tn}$ and $J \approx J_n$, the following equation is derived by combining Eqs. 1 and 2.

$$T_l \approx T_{dis} = K_{tn} I_a^{ref} - J_n \omega s \quad (3)$$

Thus, the external torque can be estimated approximately from the current reference and the rotational speed of the spindle shaft by using the nominal values of torque coefficient and inertia moment. Although the external load includes not only cutting torque but also other components like friction, the required disturbance torque is directly analyzed in this study because the chatter-induced fluctuation in cutting torque is sufficiently large to capture without compensating the other components. In practical usage, a first-order low-pass filter is generally installed to the disturbance observer in order to suppress the high-frequency noise expanded in the differential process as Fig. 2.

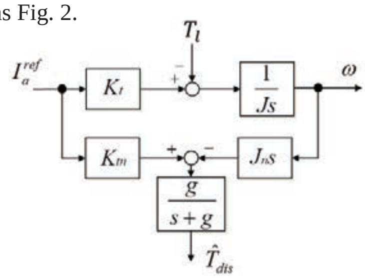

Fig. 2. Block diagram of disturbance observer.

3. Milling test

3.1. Experimental setup

In order to investigate the proposed identification method for stable spindle rotations, side milling tests are conducted with a 3-axis machining center as shown in Fig. 3. The test is conducted on a square-shaped workpiece having 15 mm height. By changing the override rate of the spindle rotation during chatter, the chatter frequency shift is captured by analyzing the estimated disturbance torque with short-time Fourier transform. To avoid a sudden change in cutting torque, feed per tooth is kept by changing the feed rate at the same rate with the spindle rotation. The details of cutting condition