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A sensorless approach for tool fracture detection in milling by integrating multi-axial servo information

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ABSTRACT

This paper proposes a sensorless approach for realtime tool fracture detection in milling by means of servo information. Cutting force and torque can be estimated in a wide-frequency range by applying disturbance observer to the ballscrew-driven stages and the spindle controllers. By integrating the estimated information in each axis, a fracture-induced variation in cutting force and torque can be accurately captured with parallel sliding Fourier transform which is an analytical approach of low computation load in time–frequency domain. Validation of the proposed method is presented through milling tests of various milling conditions with several fractured endmills.

1. Introduction

Although numerical controlled machine tools can execute preprogrammed commands accurately, they continue to perform these commands even after the occurrence of unexpected situations, such as tool breakage. Therefore, process monitoring has been investigated by many researchers to ensure machining accuracy, stability, and safety [1,2]. Many studies proposed process monitoring methods based on cutting force measurements with a force sensor because the cutting force changes owing to conditions, such as tool wear, breakage, fracture, and chatter vibration. However, the manufacturing industry usually avoids mounting an additional sensor to the machining space because it leads to frequent maintenance and regulation of the tool-path design. In particular, a force sensor, such as a dynamometer, reduces the machine-tool stiffness, i.e., machining accuracy cannot be ensured. In order to avoid these problems, several studies proposed aberrance detection methods based on motor current measurements, e.g., tool fracture detection in milling [3–5]. However, a small fluctuation in cutting force is difficult to detect with these methods because the current information includes a considerable amount of noise and the high-frequency information is lost because of filtering.

On the other hand, a disturbance observer would be a practical approach to monitor the machining state because it can estimate the cutting force without additional sensors [6]. For example, Kakinuma et al. [7] experimentally showed that the chatter-induced fluctuation in the cutting torque in milling can be detected only from the servo information in a spindle control system. Furthermore, our previous work showed that fracture-induced fluctuations in drilling can also be detected from the servo information of ballscrew-driven stage control systems [8]. These studies indicated that high-frequency changes in the cutting force can also be detected accurately without any additional sensors.

This paper presents a sensorless tool fracture detection method in milling with a disturbance-observer-based cutting force/torque estimation. Tool fracture is an indication of tool breakage because it generally occurs when the cutting force exceeds the acceptable load of the tool. Unlike chatter vibration, a small fracture does not induce a remarkable variation in cutting force. The technique uses a disturbance observer in the spindle and ballscrew-driven stage control systems and the estimated information is analyzed with the sliding discrete Fourier transform (SDFT). This study aims to demonstrate that the proposed observer-based monitoring approach has sufficiently high accuracy to detect small fluctuations due to fractures on the tool edge in milling. The detection accuracy of each axis is experimentally evaluated through side milling and grooving tests to confirm the validity and suitability of the proposed method.

2. Methodology

2.1. Disturbance observer

The cutting force can be regarded as a disturbance that interferes with the precise motion control of the spindle and stage in a machine tool. A disturbance observer is a technique to compensate for the disturbance based on the servo information and can be applied to estimate the disturbances only from the servo information. Therefore, the cutting force could be detectable by the application of a disturbance observer.

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

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

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where K_t is the torque coefficient, I_a^{ref} is the current reference, J is the inertia moment of the spindle shaft, ω is the rotational speed of the spindle shaft, and T_l is the load torque including the cutting torque. The current reference is controlled and the rotational speed is always monitored in the spindle control system; therefore, Eq. (1) indicates that the load torque can be derived when the torque coefficient and the inertia moment are known. However, these parameters change according to the movement of the controlled object and do not agree with the nominal values. Including the error of these parameters, the disturbance torque is generally defined as follows:

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

where the subscript n represents the nominal value and Δ indicates the error of a parameter. However, the change in inertia moment of the spindle during machining is usually negligible. Therefore, assuming that the variation in the torque coefficient is sufficiently small, the load torque can be estimated as follows:

$$T_l \approx \hat{T}_{dis} = \frac{g_{dis}}{s + g_{dis}}(K_{tn}I_a^{ref} - J_n \omega s) \tag{3}$$

where $\hat{T}_{dis}$ is the estimated disturbance torque and g_{dis} is the cutoff frequency of a first-order low-pass filter that is applied to suppress the noise expansion in the differential process. The block diagram of the disturbance observer is provided in Fig. 1.

Although the disturbance observer can be directly installed in a spindle control system owing to its simple dynamic equation, both the ballscrew rotation and stage movement must be considered simultaneously to apply the disturbance observer to a ballscrew-driven stage. During milling, the dynamic equation of a ballscrew in the x-axis can be described as follows:

$$K_{tx}I_a^{ref} = J_x \theta_x s^2 + \tau_{fric} + \tau_{reac} \tag{4}$$

where K_{tx} is the torque coefficient of the servo motor in the ballscrew, J_x is the inertia of the ballscrew, θ_x is the rotational angle of the ballscrew, τ_{fric} is the friction torque, and τ_{reac} is the reaction torque from the stage. Moreover, the dynamic equation of the stage can be written as follows:

$$F_{reac} = M_x x s^2 + F_{fric} + F_{cut} \tag{5}$$

where F_{reac} is the reaction force from the stage, M_x is the mass of the stage, x is the position of the stage, F_{fric} is the friction force, and F_{cut} is the cutting force. The reaction torque and force have the following linear relation:

$$\tau_{reac} = \frac{l}{2\pi}F_{reac} \tag{6}$$

where l is the lead of the ballscrew. Assuming that the coupling stiffness is sufficiently high, the rotational angle of the ballscrew and the position of the stage also have a linear relation:

$$x = \frac{l}{2\pi}\theta_x \tag{7}$$

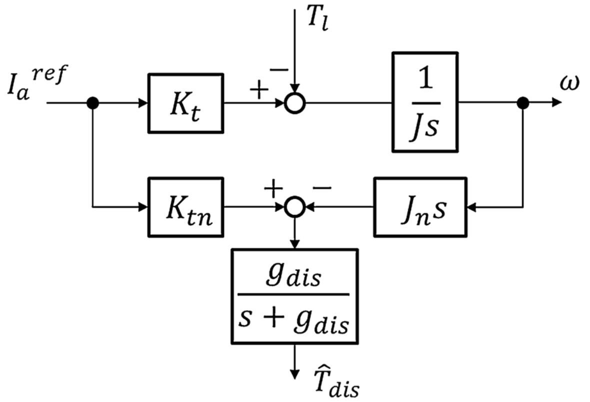

Fig. 1. Block diagram of disturbance observer for spindle.

By substituting Eqs. (4), (6), and (7) in Eq. (5) and nominalizing the parameters, the cutting force can be derived as follows:

$$\hat{F}_{cut} = \frac{g_{dis}}{s + g_{dis}} \cdot \frac{2\pi}{l}\{K_{tx}I_a^{ref} - J_{xa}\theta_x s^2 - \tau_a\}$$
$$\text{where } J_{xa} = J_x + M_x\left(\frac{l}{2\pi}\right)^2 \text{ and } \tau_a = \tau_{fric} + \frac{l}{2\pi}F_{fric} \tag{8}$$

Eq. (8) indicates that the cutting force in the x- and y-axis can also be estimated from the current reference and the rotational angle of the ballscrew. Although an accurate friction model must be employed to estimate the cutting force separately, the friction force hardly affects the frequency analysis result because it is almost constant during milling. Therefore, the estimated disturbance torque and force are directly analyzed in this study without friction compensation.

2.2. Concept of fracture detection in milling

The estimated disturbance information generally includes a high-frequency noise due to quantization error. In order to evaluate the cutting force separately from the noise component, frequency analysis is a practical approach.

In milling, the tool edges repeatedly contact the workpiece in the regular manner at the tooth-passing frequency when the process is stable and no tool fracture occurs. In this case, the frequency components of the cutting force are theoretically only harmonics of the tooth-passing frequency. On the other hand, the contact condition between the tool edge and the workpiece changes when a fracture occurs; thus, the cutting force does not fluctuate in a regular manner at the tool-passing frequency but at the spindle rotational frequency. In this case, the frequency components of the cutting force are not only harmonics of the tool-passing frequency but also those of the spindle rotational frequency. Therefore, in this study, the unbalance component is defined as the total value of power spectrum densities of the harmonics of the spindle rotational frequency excluding the tooth-passing frequency to evaluate the unbalance of the cutting force among the teeth. By comparing the total cutting force/torque component, which is defined as the total value of the power spectrum densities of the harmonics of the spindle rotation frequency, the fracture-induced variation in the cutting force can be detected. This procedure can be performed by using SDFT analysis [9], which is defined as follows:

$$S[n+1] = S[n]e^{j2\pi k} + x[n+N] - x[n] \tag{9}$$

where $S[n]$ is the discrete Fourier transform from $x[n]$ to $x[n+N-1]$, $x[n]$ is the analyzed signal, and k is the frequency. The SDFT is an efficient method to monitor the power spectrum of a special frequency component because it involves only one complex multiplication and two complex additions.

By performing the SDFT for the harmonics of the spindle rotational frequency in the estimated disturbance information and summing the power spectra, as shown in Fig. 2, the fracture-induced variation in the cutting force can be determined with a small number of computations. This algorithm can be applied to the estimated cutting torque and force in each axis. Therefore, the reliability and the repeatability of the detection should be investigated based on the analysis results of the estimated cutting force/torque in each axis.

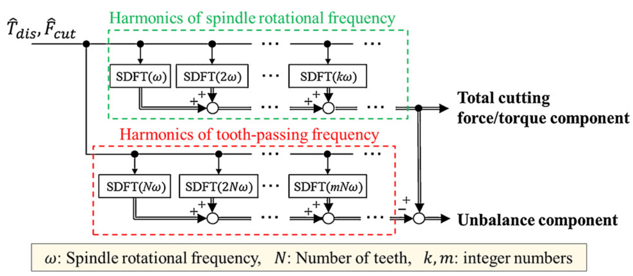

Fig. 2. Diagram of parallel SDFT algorithm for fracture detection.

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