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Drill fracture detection by integrating disturbance observer and rotational digital filter

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ABSTRACT

Tool fracture detection is important to avoid tool breakage and ensure cutting accuracy. However, conventional tool condition monitoring methods use additional sensors that are expensive, increase the failure rate, and reduce the machine-tool stiffness. This study proposes a novel in-process method to detect tool fracture based on disturbance observer theory. It uses only servo information in a ballscrew-driven stage control system. Furthermore, a rotational digital filter is developed and applied to drilling tests to enhance the detection accuracy. Tool fracture is successfully detected without any external sensors by the proposed method.

Introduction

It is important to monitor the in-process tool condition to improve productivity and ensure cutting accuracy. In particular, countermeasures against tool breakage must be taken to avoid serious damage to a machine tool or a workpiece. However, Teti et al. [1] noted that machine operators are often overwhelmed by the complexity of monitoring systems that need to be suitably applied to a given process. Furthermore, several studies have proposed methods for detecting and predicting tool breakage by using additional sensors such as acceleration sensors and acoustic emission sensors [2–4]; however, these sensors are expensive and increase the failure rate. In particular, introducing dynamometers reduces the machine-tool stiffness. In this light, it is essential to simplify condition monitoring.

Toward this end, indirect methods that measure the armature current of a spindle and estimate the increase in cutting load have been proposed [5–8]. These methods are simple and do not negatively affect the cutting space; however, their estimation accuracy is not high enough to sense a small fluctuation in cutting load, because information about the armature current includes noises and loses high-frequency information. Tool fracture is an important predictor for tool breakage because it often occurs owing to overloading during cutting; however, it is difficult to detect a small fracture on the tool edge, especially during drilling, without external sensors.

A disturbance observer can estimate disturbances in a wide frequency band using only servo information about a control system [9]; furthermore, it does not require any additional sensors and can be integrated easily into a control system. For example, Kakinuma et al. [10] successfully detected chatter vibration in milling by applying a disturbance observer to a spindle motor control system.

In this study, a novel sensor-less drill fracture detection method is proposed by integrating a disturbance observer into ballscrew-driven stages in a machine tool. Furthermore, a novel theory called rotational digital filter (RDF) is proposed to enhance the detection accuracy. RDF serves to distinguish a signal moving in a specific rotation direction on a two-dimensional surface. Because a spindle generally rotates in the clockwise direction, a fracture-induced disturbance force during drilling moves in the same direction. Therefore, RDF may improve the fracture detection accuracy. The proposed method is validated through several drilling tests.

Methodology

Concept of sensor-less tool fracture detection

Under usual cutting conditions in drilling, the resultant cutting force is applied to the tool in the axial direction because the structures of normal drills are axially symmetrical. However, when a fracture occurs on the tool edge, resultant cutting force

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components in non-axial directions are generated because the structure becomes axially asymmetrical. Furthermore, the force components change with the rotational angle of the spindle. In this case, tool fracture can be detected by frequency analysis of the disturbance forces in the *x*- and *y*-axis ballscrew-driven stages, which, in turn, can only be estimated from servo information.

Disturbance observer

A disturbance observer is used to estimate a disturbance in a control system from servo information. In this study, to detect each fracture-induced disturbance force in the *x*- and *y*-directions, disturbance observers are integrated into the control systems of ballscrew-driven stages in a machine tool. A dynamic equation of a single-axis driven stage in a cutting process is represented as follows in the Laplace domain:

$$M_x x s^2 = K_t I_a^{ref} - F_l \tag{1}$$

where M_x [kg] is the mass of movable parts in the *x*-stage including the workpiece; x [m], the position of the stage; K_t [N/A], the thrust force coefficient; I_a^{ref} [A], the current reference; and F_l [N], the load force including cutting force and friction force. Considering the disturbance force, defined as the total force of the load and a fluctuation due to parameter variation, the estimated disturbance force $\hat{F}_{dis}$ is calculated from a nominal plant model as follows.

$$\begin{aligned}\hat{F}_{dis} &= \frac{g_{dis}}{s+g_{dis}}\left\{F_l + (M_x - M_{xn})xs^2 + (K_{tn} - K_t)I_a^{ref}\right\}\\ &= \frac{g_{dis}}{s+g_{dis}}\left(K_{tn}I_a^{ref} - M_{xn}xs^2\right)\end{aligned} \tag{2}$$

where g_{dis} [rad/s] is the cut-off frequency of the disturbance observer; M_{xn} [kg], the nominal mass of the movable parts; and K_{tn} [N/A], the nominal value of the thrust force coefficient.

A first-order low-pass filter is typically used to suppress high-frequency noises expanded by differential processing. Based on Eq. (2), a block diagram of the disturbance observer is shown in Fig. 1.

Assuming that the fluctuating force due to parameter variation is much smaller than the cutting force, the estimated disturbance force becomes equal to the load force applied to the control system. The load force can then be estimated by using the servo information and the parameters of the nominal model as follows:

$$\hat{F}_{dis} \approx \hat{F}_l = \frac{g_{dis}}{s+g_{dis}}\left(K_{tn}I_a^{ref} - M_{xn}xs^2\right) \tag{3}$$

However, the estimated load force cannot be directly used for monitoring the cutting force because it includes both the cutting and the friction forces. To obtain information about the cutting force, friction force must be eliminated from the estimated load force.

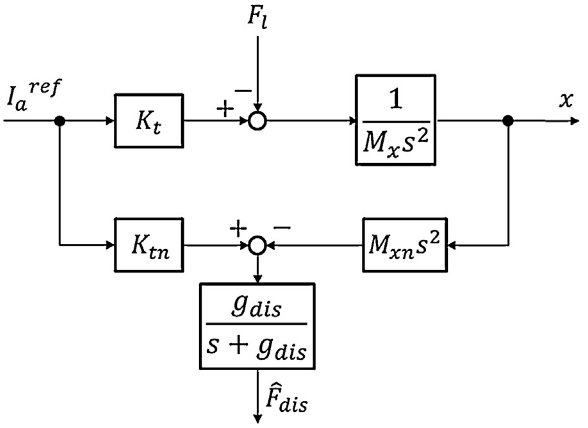

Fig. 1. Block diagram of disturbance observer.

Model to estimate load force

To compensate the friction force, nominal models of *x*- and *y*-axis ballscrew-driven stages are employed in this study. During cutting, the dynamic equation of a ballscrew in the x-axis stage can be described as follows:

$$K_{tx}I_a^{ref} = J_x\ddot{\theta}_x + D_x\ddot{\theta}_x + C_x sgn(\ddot{\theta}_x) + \tau_{reac} \tag{4}$$

where K_{tx} [N m/A] is the torque coefficient of the servo motor in the ballscrew; J_x [kg m^2], the inertia of the ballscrew; θ_x [rad], the rotational angle of the ballscrew; D_x [N m/(rad/s)], the damping coefficient of the ballscrew; C_x [N m], the Coulomb friction in the ballscrew; and τ_{reac} [N m], the reaction torque from the stage. Assuming that the coupling stiffness is sufficiently high, the rotation angle of the ballscrew and the stage position show a linear relation.

$$x = \frac{l}{2\pi}\theta_x \tag{5}$$

where x [m] is the position of the stage and l [m/rev], the lead of the ballscrew. In addition, the reaction torque from the stage is translated to the reaction force F_{reac} [N], as shown in Eq. (6).

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

Because this reaction force is applied to the stage, the dynamic equation of the stage is described as follows:

$$F_{reac} = M_x\ddot{x} + F_{cut} + (D\dot{x} + Csgn)(\dot{x})) \tag{7}$$

where F_{cut} [N] is the cutting force; D [N/(m/s)], the damping coefficient of the stage; and C [N], the Coulomb friction in the stage.

Thus, Eq. (8) can be obtained by substituting Eqs. (5)–(7) into Eq. (4) as follows:

$$\begin{aligned}&\frac{2\pi}{l}K_{tx}I_a^{ref} = M_{ax}\ddot{x} + F_{cut} + (D_{ax}\dot{x} + C_a sgn(\dot{x}))\\ &\text{where } M_{ax} = M_x + J_x\left(\frac{2\pi}{l}\right)^2,\ D_{ax} = D + D_x\left(\frac{2\pi}{l}\right)^2,\\ &C_{ax} = C + C_x\left(\frac{2\pi}{l}\right)^2\end{aligned} \tag{8}$$

By using the nominal parameters and the low-pass filter, the cutting force can be estimated in the Laplace domain as follows:

$$\begin{aligned}&\hat{F}_{cut} = \frac{g_{dis}}{s+g_{dis}}\left\{\hat{F}_l - (D_{axn}\hat{v} + C_{axn}sgn(\hat{v}))\right\}\\ &\text{where } \hat{F}_l = \frac{2\pi}{l}K_{txn}I_a^{ref} - M_{axn}xs^2, \hat{v} = \frac{g_{LPF}}{s+g_{LPF}}sx\end{aligned} \tag{9}$$

$\hat{v}$ [m/s] is the estimated velocity of the stage by pseudo-differential operation, g_{LPF} [rad/s] is the angular cut-off frequency of low-pass filter in pseudo-differential operation, and each parameter is the nominal one of Eq. (8). In other words, Eq. (9) can be regarded as a nominal model of Eq. (8).

A first-order low-pass filter is generally used in the differential process to suppress expanded high-frequency noises. In this study, it was used to determine the stage velocity. However, low-pass filters cause a time delay in the signal and a time lag between the input force and the inertia force in the disturbance observer. To compensate for the time delay, a same-order low-pass filter is loaded at the input side. Fig. 2 shows a block diagram of the proposed cutting force estimation algorithm integrated into the *x*-axis ballscrew-driven stage.