Enhancement of Sensor-less Tool Fracture Detection Method Applying Rotational Digital Filter

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Abstract

Detection of tool fracture is important to avoid tool breakage and ensure cutting accuracy. Though additional sensors are generally used for monitoring a tool condition, installing them causes high cost and increase of failure rate. In this study, a novel in-process method to detect a tool fracture is proposed on the basis of a disturbance observer theory. It uses only servo information in a ball-screw driven stage and never requires external sensors. Furthermore, a rotational digital filter is invented and applied to drilling tests to improve the detection accuracy. A tool fracture is successfully detected by the proposed method.

Keywords: fracture; in-process monitoring; disturbance observer; digital filter; drill;

1. Introduction

In-process tool monitoring is significant to improve production efficiency and ensure cutting accuracy. Especially countermeasures for tool breakage must be taken to avoid serious damages against a machine tool and a workpiece. Though several studies have proposed the detection and prediction methods for tool breakage by using external sensors such as acceleration sensors and AE sensors until now [1-3], external sensors cause several problems such as high cost, increase of failure rate, reduction of machine-tool stiffness, and so on.

To solve these problems, the indirect detection methods have been proposed by measuring the armature current of the spindle and estimating the increase of cutting load caused by tool breakage [4-6]. Generally tool fracture is one of the important prediction signals for tool breakage because it often happens in an overload cutting condition. However, detection accuracy of the conventional indirect method is not so high to detect a small fracture because information of the armature current includes noise and loses high frequency information.

On the other hand, the disturbance observer can estimate disturbance in the system accurately only from servo information of a spindle [7]. Kakinuma et al. [8] successfully detects chatter vibration in milling tests by applying disturbance observer to the spindle.

In this study, a novel sensor-less tool fracture detection method is proposed. The disturbance observers are applied to ball-screw driven stages in the machine tool to detect infinitesimal vibration caused by cutting with a fractured tool. Moreover, to enhance detection accuracy, a novel digital filtering theory, named “rotational digital filter (RDF)”, is proposed. RDF passes only signal which is moving in an especial rotational direction on two-dimensional surface. Since spindle generally rotates in clock-wise direction, disturbance force applied to the machine-tool stage also moves in the clock-wise direction. Hence, there is a possibility to improve the detection accuracy by utilizing RDF. The validity of the proposed method is verified through drilling tests.
2. Methodology

2.1. Concept of sensor-less tool fracture detection

In a drilling process, cutting force acts in an axial direction, not in the x and y directions, under the usual direction because structures of normal drills are generally axially symmetrical. However, fractured drills are axially asymmetrical, therefore, the cutting force works on workpieces not only in an axial direction but also x and y directions. Applied force in x and y directions changes according to a rotating frequency of the spindle, and the spindle rotates in a clock-wise direction on the x-y plane. Thus, tool fracture is considered to be detected from a frequency analysis of sufficient information of disturbance force in the x and y ballscrew driven stages. In addition, the proposed RDF has a possibility to enhance the detection accuracy. In this study, the RDF is applied to the estimated disturbance force with the disturbance observer.

2.2. Disturbance observer

Disturbance observer is a technique to estimate disturbance in a control system from only servo information. In this study, to detect each disturbance force in x and y directions arising from a tool fracture, disturbance observer is installed in the ballscrew driven stage. A dynamic equation of the single-axis ballscrew driven stage in cutting process is represented as follows:

\[ M_s \ddot{x} + F_l = K_a I_{ref} - F_i \]

where \( M_s \) [kg] is a mass of the movable parts in the stage including workpiece; \( \ddot{x} \) [m/s²], the acceleration of the movable parts; \( K_a \) [N/A], the thrust force coefficient; \( I_{ref} \) [A], the current reference; \( F_l \) [N], the load force such as cutting force and friction force. Taking into account of the disturbance force defined as the total force of the load and fluctuation due to parameter variation, disturbance force \( \hat{F}_{dis} \) is estimated from nominal plant model as shown in Eq.(2).

\[ \hat{F}_{dis} = \frac{g_{dis}}{s + g_{dis}} \left( F_i + (M_s - M_m)\ddot{x} + (K_a - K_m)I_{ref} \right) \]

\[ = \frac{g_{dis}}{s + g_{dis}} \left( K_a I_{ref} - M_m \ddot{x} \right) \]

where \( g_{dis} \) [rad/s] is cut-off frequency of disturbance observer; \( M_m \) [kg], the nominal mass value of the movable parts; \( K_m \) [N/A], the nominal value of the thrust force coefficient.

In order to suppress a high frequency noise expanded by differential processing, a first order low-pass filter is applied for estimation of disturbance force. Based on the Eq. (2), a block diagram of the disturbance observer is represented as Fig.1. To assume a variation of the mass in a cutting process is sufficiently small for the mass of movable parts, nominal mass is given as constant value.

When the parameter variation is sufficiently small, disturbance force becomes equivalent to the load force. In this case, load force can be estimated by using servo information and parameters of the nominal model.

\[ \hat{F}_{dis} \approx \hat{F}_i = \frac{g_{dis}}{s + g_{dis}} (K_m I_{ref} - M_m \ddot{x}) \]

Generally, friction force must be compensated to estimate cutting force by using the disturbance observer. In this study, cutting force is assumed to be dominant, and enough large to detect its dynamic change due to tool fracture. Hence, there is a possibility that tool fracture can be detected from the estimated load without friction compensation.

2.3. Rotational digital filter

In order to enhance the sensitivity to detect tool fracture with disturbance observer, rotational digital filter is proposed and designed.

A spindle generally rotates in a clock-wise direction on an x-y plane in drilling. From this viewpoint, we propose a novel digital filter which passes only signals moving in a clock-wise direction at a certain rotational speed on a two-dimensional surface.

When a signal moves in a clock-wise circular orbit on an x-y plane, x-component phase lag against y component becomes \( \pi/2 \) radians as follows:

\[
\begin{align*}
X &= A \sin \omega t \\
Y &= A \sin \left( \omega t + \frac{\pi}{2} \right)
\end{align*}
\]

where \( X \) and \( Y \) are the x and y components of the signal; \( \omega \) [rad/s], the rotational speed; \( A \), the radius of the circular orbit. Therefore the signal moving in the clock-wise circular orbit can be amplified by accumulating the x component and the y component with \( \pi/2 \) radians delay. Based on coordinate transformation, it is possible to set an appropriate virtual axis for each sampling data to amplify the clock-wise
rotational signal. Since rotational angle for one sampling time can be acquired theoretically at the constant rotational speed, each x and y component value of a present signal on a virtual coordinate axis at k-th sampling period before can be described in discrete space as follows:

$$
\begin{bmatrix}
X_k \\
Y_k
\end{bmatrix} =
\begin{bmatrix}
\cos \omega_k T_f \\
\sin \omega_k T_f
\end{bmatrix}
\begin{bmatrix}
X_{k-1} \\
Y_{k-1}
\end{bmatrix}
$$

(5)

where $X_k$ and $Y_k$ are the k-th previous sampling data; $X_{k-1}$ and $Y_{k-1}$, each component of a present signal data; $F_f$ [Hz], the sampling frequency.

On the other hand, the virtual coordinate axes can be set with rotational matrixes for an integral multiple of the rotational angle at one sampling time. The present signal data on the appropriate virtual coordinate axis defined by n-th rotational angle is represented as Eq. (6).

$$
\begin{bmatrix}
X_{n\omega} \\
Y_{n\omega}
\end{bmatrix} =
\begin{bmatrix}
\cos \frac{\omega n}{F_f} \\
\sin \frac{\omega n}{F_f}
\end{bmatrix}
\begin{bmatrix}
X_{n-1} \\
Y_{n-1}
\end{bmatrix}
$$

(6)

where $X_{n\omega}$ and $Y_{n\omega}$ are the transferred components of the present signal. According to Eq. (5) and Eq. (6), following Eq. (7) is satisfied only if the input signal rotates in the clock-wise direction at the constant rotational speed $\omega$.

$$
\begin{bmatrix}
X_{n\omega} \\
Y_{n\omega}
\end{bmatrix} =
\begin{bmatrix}
X_n \\
Y_n
\end{bmatrix}
$$

(7)

Taking into account of inverse matrix, Eq. (6) can be transformed as follows:

$$
\begin{bmatrix}
X_n \\
Y_n
\end{bmatrix} =
\begin{bmatrix}
\cos \frac{\omega n}{F_f} \\
\sin \frac{\omega n}{F_f}
\end{bmatrix}
\begin{bmatrix}
X_{n\omega} \\
Y_{n\omega}
\end{bmatrix}
$$

(8)

Every sampling signal satisfies Eq. (8), therefore, the clock-wise rotational signal is amplified by giving n-th sampling time delay to the n-th previous signal and summing up them. The proposed rotational digital filter read out their average as its passed signals as follows:

$$
\begin{bmatrix}
X_{out} \\
Y_{out}
\end{bmatrix} =
\frac{1}{N+1} \sum_{n=0}^{N} \begin{bmatrix}
\cos \frac{\omega n}{F_f} \\
\sin \frac{\omega n}{F_f}
\end{bmatrix}
\begin{bmatrix}
X_n \\
Y_n
\end{bmatrix}
$$

(9)

Finally, to suppress spectrum leakage, a window function $\psi$ of Kaiser is installed to the Eq. (9) as follows:

$$
\begin{bmatrix}
X_{out} \\
Y_{out}
\end{bmatrix} =
\frac{1}{N+1} \sum_{n=0}^{N} \begin{bmatrix}
\cos \frac{\omega n}{F_f} \\
\sin \frac{\omega n}{F_f}
\end{bmatrix}
\begin{bmatrix}
\cos \frac{\omega n}{F_f} \\
\sin \frac{\omega n}{F_f}
\end{bmatrix}
\begin{bmatrix}
X_n \\
Y_n
\end{bmatrix}
$$

(10)

As a result, rotational digital filter outputs only signals which depend on an especial rotational direction and speed on the x-y plane so that it is possible to enhance the sensitivity of the tool fracture detection. Furthermore, outputs obtained through the RDF are regarded as radial and tangential components in rotary coordinates at $\omega$ (spindle coordinates) as shown in Fig. 2.

![Fig. 2. Relation between X-Y coordinates and rotary coordinates at $\omega$](image)

In this study, to evaluate the cutting force arising in x and y directions quantitatively, geometric mean of x-component and y-component outputs of the RDF is calculated and utilized as a spectrum density. The performance of the RDF is evaluated by comparing with short-time Fourier transform of single frequency component (SFT).

3. Simulation

To confirm the effect of the rotational digital filter (RDF), a time-domain simulation was carried out. In this simulation, x and y inputs signals are represented as Eq. (11).

$$
\begin{bmatrix}
X \\
Y
\end{bmatrix} =
\begin{bmatrix}
\sin 2\pi f t \\
\sin(2\pi f t + \theta)
\end{bmatrix}
$$

(11)

where $f$ [Hz] is frequency of input signals; $\theta$ [rad], phase difference between x and y components. To compare the characteristics equally, the order of both the RDF and SFT are set to 500.

Influence of the frequency and phase difference on both frequency analysis methods is investigated. As shown in Fig. 3 (a), RDF has a passband around 150 Hz and $\pi/2$ phase difference between x and y components. However, counter-clock-wise signal is cut off even if frequency of the signal is 150 Hz. Fig. 3 (b) shows the average spectrum density of x and y components required with SFT separately. Its frequency passband is constant regardless of phase.
difference between x and y components. Thus, the counter-clock-wise cut-off effect cannot be realized in case of SFT. The unique function of RDF which can cut phase difference would be useful to improve the accuracy of tool fracture detection because rotation of spindle is generally clock wise. That makes it possible to reduce the influence of the other disturbance such as current noise.

4. Experiment

4.1. Experimental setup

In this study, several drilling tests of aluminum alloys (A2017) were performed to evaluate the validity of the proposed method and the effect of the RDF. Carbide drill with diameter of 6mm was used in the experiment and three types of fractured drills which have different corner edge fracture are prepared. All tests were conducted with a three-axis vertical machining center (TC-S2C, Brother Industries, Ltd.). The other cutting control system of the x and y-axis ballscrew driven stage and RDF was applied to the estimated disturbance force. Cutting conditions and the control system specification of the machine tool are summarized in Table 1 and 2. The disturbance observer was installed to the position control system. At the same time, single frequency component short-time Fourier Transform (SFT) analysis was also carried out to confirm the effect of the RDF. Each performance of tool fracture detection is evaluated by comparing the magnitude of each spectrum density. Figure 4 shows the appearance of the drilling tests.

![Fig. 4. Appearance of drilling test](image)

| Table 1. Cutting condition |
|---------------------------|
| Rotational speed (min⁻¹)  | 9000       |
| Feed rate (mm/min)        | 1800       |
| Depth of holes (mm)       | 20         |
| Type of cut               | Wet cutting|

| Table 2. Machine-tool characteristics |
|---------------------------------------|
| Rotary encoder resolution ( pulses/rev) | 20 bit |
| Ballscrew pitch (mm/rev)              | 16     |
| Sampling time (ms)                    | 0.125  |
| Mass of x stage (kg)                  | 109.0  |
| Mass of y stage (kg)                  | 240.0  |
| Cut-off frequency $g_{dis}$ (rad/s)   | 3500   |

![Fig. 5. (a) A sample of non-fractured drill, (b) one of sample of fractured drills which has 3.157 mm² fractured area](image)
4.2. Result of the drilling tests

Figure 5 (a) and (b) show a non-fractured drill and one of fractured drills respectively. Behavior of spectrum density of 500th order RDF for 150Hz in drilling processes is shown in Fig. 5. As shown in Fig. 6, though almost no significant change is observed in the result of the drilling test with a non-fractured drill, spectrum density of RDF remarkably increases during drilling with the fractured drill. Figure 7 shows the spectrum density of SFT utilizing the same data of the same cutting test with a fractured drill. There is no remarkable difference between both methods in the result of the test with the fractured drill. Nonetheless, in the test with non-fractured drill, the spectrum density of RDF is smaller than the result of SFT. In case of using the non-fractured drill, the main cause of exerting the spectrum density in drilling is not the spindle rotation but the influences of noises in the signals in the driven stage control system. RDF clearly can reduce the influence of these noises. Therefore, RDF can more properly distinguish a fractured drill from a non-fractured drill.

To evaluate the repeatability and reliability of the proposed method, 20 times drilling test were carried out with each drill. Fractured areas of 3 types of fractured drills are shown in Table 3. The detection accuracy of RDF and SFT is investigated by calculating the averages of spectrum density for 0.3s in drilling process. Figure 8 shows the relation between the fractured area and the average of the RDF spectrum density. All fractured drills show larger spectrum density than non-fractured one. This tendency also can be found in the relation between RDF and SFT.

| Fractured area (mm²) | Non-fractured drill | Fractured drill 1 | Fractured drill 2 | Fractured drill 3 |
|----------------------|---------------------|-------------------|-------------------|-------------------|
|                      | 0.000               | 1.046             | 1.947             | 3.157             |

Fig. 6. Behavior of spectrum density of RDF: red line represents the result of the test with fractured drill; green line represents the result of the test with non-fractured drill

Fig. 7. Behavior of spectrum density of SFT: red line represents the result of the test with fractured drill; green line represents the result of the test with non-fractured drill

Fig. 8. Relation between fractured area and the average of spectrum density of RDF

Fig. 9. Relation between fractured area and the average of spectrum density of SFT
Table 4. Spectrum density of each test, (a) RDF, (b) SFT

|            | Fractured drill 1 | Fractured drill 2 | Fractured drill 3 |
|------------|-------------------|-------------------|-------------------|
| (a)        |                   |                   |                   |
| Non fractured drill | 1.852             | 2.044             | 5.291             |
| Average    | 0.358             | 2.044             | 5.291             |
| Maximum    | 0.648             | 3.093             | 6.347             |
| Minimum    | 0.207             | 1.221             | 3.368             |

|            | Fractured drill 1 | Fractured drill 2 | Fractured drill 3 |
|------------|-------------------|-------------------|-------------------|
| (b)        |                   |                   |                   |
| Non fractured drill | 2.577             | 2.424             | 5.587             |
| Average    | 0.804             | 2.424             | 5.587             |
| Maximum    | 1.207             | 3.320             | 6.646             |
| Minimum    | 0.465             | 1.548             | 3.440             |

Table 5. Difference of the spectrum density of each test, (a) RDF, (b) SFT

|                | Ratio of average spectrum density of fractured drill and non-fractured one | Difference from max. of non-fractured drill to min. of fractured one |
|----------------|---------------------------------------------------------------------------|---------------------------------------------------------------|
| (a)            |                                                                           |                                                               |
| Fractured drill 1 | 5.173                                                                     | 0.449                                                        |
| Fractured drill 2 | 6.156                                                                     | 0.573                                                        |
| Fractured drill 3 | 14.78                                                                     | 2.720                                                        |
| (b)            |                                                                           |                                                               |
| Fractured drill 1 | 3.204                                                                     | 0.348                                                        |
| Fractured drill 2 | 3.014                                                                     | 0.341                                                        |
| Fractured drill 3 | 6.947                                                                     | 2.233                                                        |

the fractured area and the average of the SFT spectrum density (cf. Fig. 9). In the light of detection accuracy, it is necessary to clarify the difference between fractured drills and non-fractured drills. Though the spectrum density is hardly different between RDF and SFT in the tests with fractured drills, spectrum density of RDF is smaller than one of SFT in the test with a non-fractured drill. Table 4 summarizes the result of the test with each fractured drill such as maximum, minimum and average of spectrum density. Table 5 summarizes the difference of spectrum density of a non-fractured drill and fractured drills such as subtraction of minimum value of fractured drill and maximum value of non-fractured drill. As shown in Table 5, using RDF more obviously makes the difference of whether fractured or not.

From these results, the proposed method can detect tool fractures which have more than 1 mm² without external sensors. In addition, the proposed RDF is effective to enhance the detection accuracy. Though fracture of each drill is evaluated with fractured area in this study, there is no large difference between the average spectrum density of fractured drill 1 and 2. It is suggested that a shape of a fractured drill influences spectrum density as well as fractured area. Thus, in our future work, enhanced criteria for tool fracture evaluation would be developed by taking into account of shape of fracture.

5. conclusion

In this study, a novel sensor-less tool fracture detection method applying disturbance observer is proposed. Furthermore, the rotational digital filter for the tool fracture detection is developed, which passes only a signal moving in an especial rotational direction. Since disturbance observer can estimate disturbance force including high frequency information, the infinitesimal vibration produced by drilling with a fractured tool can be caught up. Furthermore, the rotational digital filter can detect the tool fracture-induced fluctuation more effectively than Fourier Transform. The experimental result of the drilling tests shows that the proposed method has the ability to discriminate fractured drills from non-fractured drills without any external sensor.

References

[1] A. Thangaraj, P. K. Wright, Drill wear and failure prediction for untended machining, Robotics and Computer-Integrated Manufacturing, Vol. 4, No. 3/4, (1988) 429-435.
[2] M. Takatsuto, N. Takada, K. Kato, K. Kishi, Judgment of Tool Life in Drilling Using Acoustic Emission, JSME International Journal Series C, Vol. 37, No. 1, (1994) 224-229.
[3] M. Routio, M. Säynätjoki, Tool wear and failure in drilling of stainless steel, Journal of Materials Processing Technology, 52 (1995) 35-43.
[4] Xiaoli Li, Kit Tso, Jun Wang, Real-Time Tool Condition Monitoring Using Wavelet Transforms and Fuzzy Techniques, IEEE Transactions on Systems, Man, and Cybernetics, Vol. 30, No. 3, August 2000, 352-357.
[5] B. Y. Lee, Y. S. Tarng, Drill fracture detection by the discrete wavelet transform, Journal of Materials Processing Technology, 99 (2000) 250-254.
[6] Young Jun Choi, Min Soo Park, Chong Nam Chu, Prediction of drill failure using features extraction in time and frequency domains of feed motor current, International Journal of Machine Tools and Manufacture, 48 (2008) 29-39.
[7] Ohnishi K., Estimation, Inclination and Sensor-less Control in Motion Control System. Proceeding of the IEEE 82, 8 (1994) 253-265.
[8] Yasuhiro Kakinuma, Yui Sudo, Tojiro Aoyama, Detection of chatter vibration in en milling applying disturbance observer, Annals of the CIRP 50 (2011) 109-112.