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Tool collision detection in high-speed feeding based on disturbance observer

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Abstract

It is important to take countermeasures against tool collision to avoid serious damage to the machine tool. Though rapid collision detection is needed, the introduction of additional sensors to a machine tool is not desirable owing to cost, machine-tool stiffness, and failure rate considerations. In this study, a sensor-less tool collision detection method is proposed on the basis of the disturbance observer theory. It only uses the servo information of a ball-screw-driven stage and does not require external sensors. The proposed method successfully detects the collision between a tool and a workpiece in less than 3 ms with a feed rate of 50 m/min.

Keywords: disturbance observer, tool collision, in-process monitoring, sensor-less, breakage;

1. Introduction

Tool collision can easily occur in a machine tool due to erroneous operations or incorrect tool-path designs. In particular, operational errors often occur in multi-axis machine tools because of their complexity. Tool collision leads to serious damage to the tool, the workpiece, and the machine tool. Therefore, it is important to take countermeasures against tool collision to avoid serious damage to the machine tool.

Several studies have presented tool-path planning methods to avoid collisions [1, 2, 3]. Although they are able to prevent the collision in advance, they take a considerable amount of time and require a special system to create an accurate model for each machine tool. Other studies, on the other hand, have tried to develop damage reduction methods [4]. These methods rely on immediate collision detection to reduce damage. In particular, in high-speed feeding, the detection time must be as short as possible because the kinetic energy of the stage is too large to allow an abrupt stop. However, these countermeasures generally require additional sensors such as acceleration sensors and dynamometers, and have the associated disadvantages such as a high cost, a reduction of machine-tool stiffness, and an increase of failure rates.

The disturbance observer is a sensor-less technique that efficiently monitors the machining state. It estimates the disturbance in a control system using only the servo information. Kakinuma et al. showed that chatter vibrations can be detected in milling by analyzing the estimated disturbance torque from the spindle control system [5]. Furthermore, recent publications showed that small cutting edge fractures can also be detected by analyzing the disturbance force estimation in the ball-screw-driven stage [6, 7]. These methods do not require additional sensors, which can have a negative impact on machining space. Furthermore, it has been shown experimentally that the disturbance observer has sufficient accuracy to monitor the cutting state. The disturbance observer has the potential to realize monitoring systems for other problems in machine tools, e.g., tool collisions.

In this study, we propose a sensor-less tool collision detection method for high-speed feeding based on the
disturbance observer theory. The disturbance observer is installed in the ball-screw-driven stages in a machine tool. The collision between a tool and a workpiece generates a large reaction force in the ball-screw-driven stage, which can be detected by the disturbance observer. The validity of the proposed method was verified through several collision tests in the x- and z-directions.

2. Theory for detecting tool collision

2.1. Disturbance observer

A disturbance observer is generally utilized to ensure the robustness of a control system [8]. It is able to estimate disturbances in a control system using only servo information without any additional sensors. It can also be used as a sensor because the disturbance observer includes useful information for determining the state of the control system. Tool collision can generally be detected by the disturbance observer in the ball-screw-driven stages, because it is simply a disturbance preventing the accurate movement of the stages. To monitor the fluctuation of the estimated disturbance force due to tool collision, a disturbance observer was installed in the x- and z-axis of the ball-screw-driven stage.

The dynamic equation of a single-axis stage in z direction is represented as follows:

\[ M_z \ddot{z} = K_s l_u^{ref} - F_l \]  \hspace{1cm} (1)

where \( M_z \) [kg] is the mass of the movable parts in the stage including the workpiece, \( \ddot{z} \) [m/s²] is the acceleration of the movable parts, \( K_s \) [N/A] is the thrust force coefficient, \( l_u^{ref} \) [A] is the current reference, and \( F_l \) [N] is load force, which includes the collision, frictional, and gravitational forces. If the disturbance force is defined as the sum of the load force and fluctuations due to parameter variation, it can be estimated from a nominal plant model, as shown in Eq. 2.

\[ F_{\text{dis}} = \frac{g_{\text{dis}}}{s + g_{\text{dis}}} \left[ F_l + (M_z - M_{zn})xz^2 + (K_{tn} - K_u)l_u^{ref} \right] = \frac{g_{\text{dis}}}{s + g_{\text{dis}}} \left( K_{tn} l_u^{ref} - M_{zn} xz^2 \right) \]  \hspace{1cm} (2)

where \( g_{\text{dis}} \) [rad/s] is the cutoff frequency of the disturbance observer, \( M_{zn} \) [kg] is the nominal mass value of the movable parts, and \( K_{tn} \) [N/A] is the nominal value of the thrust force coefficient. To suppress high-frequency noise amplified by differential processing, a first-order low-pass filter is generally installed to the disturbance observer, as shown in Eq. 2. Figure 1 presents a block diagram of the disturbance observer.

Assuming that the parameter variation is sufficiently small, the disturbance force becomes equal to the load force applied to the control system. In this case, the load force can be estimated by utilizing the servo information and the parameters of the nominal model as follows:

\[ \tau_{\text{react}} = \frac{l}{2\pi} F_{\text{react}} \]  \hspace{1cm} (6)

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

\[ F_{\text{react}} = M_z \ddot{z} + F_{\text{col}} + M_z \ddot{\theta} + (D \ddot{z} + C \text{sgn}(\ddot{z})) \]  \hspace{1cm} (7)
where $F_{\text{col}}$ [N] is the collision force, $g$ [m/s²] is the gravitational acceleration, $D$ [N/(m/s)] is the damping coefficient of the stage, and $C$ [N] is the coulomb friction of the stage.

Thus, Eq. 4 can be transformed based on Eqs. 5–7, as shown in Eq. 8.

$$\frac{2\pi}{l}K_{\text{x}}^{\text{ref}} = M_a\ddot{z} + F_{\text{col}} + M_a g + \left(D_a\ddot{z} + C_a \operatorname{sgn}(\dot{z})\right)$$

(8)

where $M_a = M + J_a \left(\frac{2\pi}{l}\right)^2$, $D_a = D + D_a \left(\frac{2\pi}{l}\right)^2$, and $C_a = C + \frac{C_a}{C_a}$.

Although the mass of the workpiece changes during machining, its variation is generally small compared to the mass of the stage. Assuming that the variation of the inertia and the torque coefficient is sufficiently small, the collision force can be estimated as shown in the following equation:

$$F_{\text{col}} = \hat{F}_1 - M_{\text{ana}}g - (D_{\text{ana}}\ddot{z} + C_{\text{ana}} \operatorname{sgn}(\dot{z}))$$

(9)

where $\hat{F}_1$ [m/s] is the estimated velocity of the stage, and each parameter is the nominal one of Eq. 8.

A first-order low-pass filter is generally used in the disturbance observer input side of the disturbance observer. Figure 2 presents the block diagram of the proposed collision force estimation algorithm for the z-axis ball-screw-driven stage. Furthermore, this estimation algorithm can be utilized for x-axis ball-screw-driven stage by eliminating the gravity compensation.

Thus, the collision force can be estimated from the servo information based on the disturbance observer theory. Although some experiments are required to create an accurate friction model, we utilized a simple friction model that includes the viscous and coulomb friction in the interest of keeping it versatile.

3. Experiment

3.1. Experimental setup

The tool collision experiments in the x- and z-directions were carried out on a 3-axis vertical machine tool (Brother TC-S2C tapping center). The machine tool characteristics are summarized in Table 1. The nominal values introduced to the nominal model of the ball-screw-driven stages are given in Table 2. Figure 3 shows the setup of the collision tests. 3 mm, 5 mm, and 7 mm diameter HSS drills were used in the collision tests in the x-direction, and 3 mm diameter long HSS drills were used in the collision test in the z-direction. All collision tests were carried out at the maximum feed rate of 50 m/min because collision detection is needed at high feed rates.

Table 1. Machine tool characteristics

<table>
<thead>
<tr>
<th>parameter</th>
<th>x-axis</th>
<th>z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary encoder resolution</td>
<td>20bit</td>
<td>20bit</td>
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<tr>
<td>Ball screw pitch for x- and z-axis</td>
<td>16</td>
<td>16</td>
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<tr>
<td>Sampling time [ms]</td>
<td>0.125</td>
<td>0.125</td>
</tr>
<tr>
<td>Maximum feed rate of stages [mm/min]</td>
<td>50000</td>
<td>50000</td>
</tr>
<tr>
<td>Mass of z stage [kg]</td>
<td>175.0</td>
<td>175.0</td>
</tr>
<tr>
<td>Mass of x stage [kg]</td>
<td>55.0</td>
<td>55.0</td>
</tr>
</tbody>
</table>

Table 2. Parameters in designed model

<table>
<thead>
<tr>
<th>parameter</th>
<th>x-axis</th>
<th>z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal total mass of movable parts [kg]</td>
<td>227.0</td>
<td>380.0</td>
</tr>
<tr>
<td>Nominal damping coefficient [N/(m/s)]</td>
<td>667</td>
<td>1968</td>
</tr>
<tr>
<td>Nominal coulomb friction [N]</td>
<td>104</td>
<td>240</td>
</tr>
<tr>
<td>Cutoff frequency of disturbance observer [rad/s]</td>
<td>1500</td>
<td>1500</td>
</tr>
</tbody>
</table>

3.2. Idling test

Idling tests were carried out to determine a threshold defining tool collision on the estimated disturbance force. Figure 4 presents the behavior of the estimated disturbance force in the idling tests in the x- and z-directions. Though the threshold should be high enough to prevent a misdetection, it should also be as low as possible for increasing sensitivity. The characteristics of the estimated disturbance force should therefore be taken into consideration to define a proper threshold.

Figure 5 shows the probabilistic distribution of the estimated disturbance force during high-speed feeding. The average $\mu$ is -14.7 N in the x-direction and 10.8 N in the z-direction, and the standard deviation $\sigma$ is 81.3 N in the x-direction and 128.6 N in the z-direction. Each distribution of
the estimated disturbance force in x- and z-direction is similar to a normal distribution. To confirm if the distribution of the estimated disturbance force can be regarded as normality, chi-square goodness-of-fit tests were carried out at the 0.05 level of significance as shown in Table 3. The chi-square statistic in x-direction is 108.4, which is less than the critical value of 113.1, and the one of z-direction is 134.5, which is less than the critical value of 168.6. These results conclude that there is a good fit between the estimated disturbance force and the normal distribution.

Based on statistical theory, the $\mu+5\sigma$ line is chosen as the threshold. The proposed method detects a tool collision if the estimated disturbance force of three successive samples exceeds the threshold. Though the probability of $\mu+5\sigma$ in a normal distribution is $2.87 \times 10^{-7}$ and not small enough to avoid a misdetection, the probability that three samples exceed the $\mu+5\sigma$ line is only $8.61 \times 10^{-21}$, which is expected to happen once every $4.6 \times 10^8$ years when the sampling
frequency is 8000 Hz. The validity of the threshold is verified through collision experiments.

3.3. Collision test

Figure 6 shows the behavior of the estimated disturbance force in the collision tests in the x-direction. The fluctuation due to the collision can be observed in each result. The estimated disturbance force clearly exceeded the threshold with the 7 mm and 5 mm drills as shown in (a) and (b). However, as shown in (c), the fluctuation due to the collision with the 3 mm drill was too small. Figure 7 represents the result in the z-direction. The estimated disturbance force clearly exceeded the threshold twice. This could be due to the broken tool hitting the workpiece again after the first collision. Figure 8 is an extended figure focusing on the fluctuation due to the collision in Fig. 6 (a). The collision time is estimated from the position data. Given the response time for the detection, the proposed method successfully detected the collision in 2.9 ms. While the response would depend on the tool stiffness, the experimental results show that the proposed method detects the collision in a remarkably short time without any external sensors.

As a result, in high-speed feeding, the proposed method has enough accuracy in the x-direction to detect a collision between the workpiece and tools of diameter greater than 5 mm. Furthermore, it is possible to detect the collision between the tools and the workpiece in z-direction even if their diameters are as small as 3 mm. The proposed method can realize high-response tool collision detection by simply deciding some nominal parameters. In future work, we will consider other conditions such as different feed rates and methods to distinguish the collision force and the cutting force to expand the versatility of the proposed method.

4. Conclusion

We proposed a sensor-less tool collision detection method based on disturbance observer theory. The collision force can be estimated by using the disturbance observer because the collision is regarded as a disturbance of the control system of the ball-screw-driven stages. The experimental results clearly show that the collision can be detected solely from the servo information as a fluctuation of the estimated disturbance force. Furthermore, the estimation is sufficiently accurate that it could detect tool collision for tools with a diameter greater than 5 mm in the x-direction and as low as 3 mm in the z-
direction by defining a threshold based on the normal distribution.

References


