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Sensor-less micro-tool contact detection for ultra-precision machine tools utilizing the disturbance observer technique

Yasuhiro Kakinuma (2)*, Satoko Nagakari

Department of System Design Engineering, Faculty of Science & Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama 223-8522, Japan

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ABSTRACT

When molds for micro products are repaired, micromachining is typically required after the welding or cladding process. The contact position of the tool to the cladded material needs to be set before micromachining. However, precise setting of the tool to the workpiece is a technically difficult operation that requires manual adjustment and the introduction of external sensors. This paper proposes an observer-based automatic detection method for micro tool contact. An ultra-precision machine tool driven by a linear motor was utilized to demonstrate the effectiveness of the proposed sensor-less tool contact detection method. Experimental results showed that the observer-based tool detection method can detect submicron-level contact, which cannot be achieved manually.

1. Introduction

Many machine manufacturers have introduced various configurations of multi-axis machines with a command resolution of 1 nm or 1 Å for the table movement. While advances in machine capabilities continue, peripheral technologies for achieving the integrity of the form accuracy and surface quality are not quite able to match the level of precision of such machines [1,2]. For example, the compensation or repairing process of precision lens molds requires a precise tool/workpiece setting that affects the accuracy of the machining process. However, achieving a precise tool/workpiece setting is a technically difficult operation that generally requires manual adjustment and takes a long time.

To address this challenge, researchers have followed diverse approaches depending on the sensor principle and functionality, such as the vision sensor, laser beam, and acoustic emission sensor [2–4]. However, the above techniques require equipping a machine tool with external sensors; this is not always suitable for practical applications because of the sensor costs, increased maintenances, amount of space required for mounting, and manual adjustment required for setting. Therefore, a skill-independent and robust technology for precise tool/workpiece setting is required.

Much research has been conducted on servo information-based process monitoring, which is less accurate than external sensor-based monitoring but is also less complex and more suitable for practical application [4]. In particular, the disturbance observer (DOB), which is a well-known control technique, can be applied to estimate the cutting force for process monitoring [5]. The cutting force (hereafter "tool contact force") should be applied the moment the tool comes in contact with the workpiece. Therefore, a disturbance observer can be helpful for tool contact detection.

In this paper, we propose an external sensor-less method to precisely and automatically detect tool contact during micro end milling. The challenge of an external sensor-less method for tool contact detection is reducing any resulting surface damage to less than the required tolerance of the cutting accuracy while generating a contact force that can be distinguished from noise. To evaluate the effectiveness of the proposed method, several contact tests were carried out in the z-axis direction.

2. Principle of micro-tool contact detection

2.1. Disturbance observer

A DOB is a well-known method for estimating the disturbance force [6,7] and may be applicable to micro-tool contact detection. The disturbance force F_{dis} derived from the dynamic equation of the machine–tool table is represented as follows:

$$F_{dis} = K_{tn} I_a^{ref} - M_n z \tag{1}$$

where M is the mass [kg], z is the acceleration [m/s^2], K_t is the thrust force coefficient [N/A], I_a^{ref} is the current reference [A], and the subscript "n" indicates the nominal value. Fig. 1 shows a block diagram of the DOB. If the friction of the stage motion and parameter variation from the nominal value are sufficiently small, the disturbance force can be regarded as an external load, such as the tool contact force and cutting force. In this study, the accuracy of tool contact detection based on a DOB was assessed according to the surface damage to the workpiece that occurred during detection.

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[*] Corresponding author.
E-mail address: kakinuma@sd.keio.ac.jp (Y. Kakinuma).

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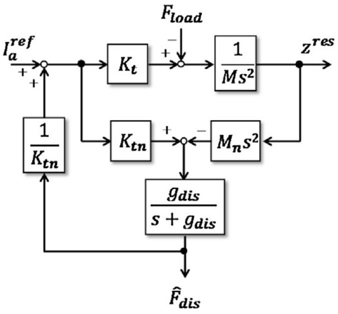

Fig. 1. Block diagram of a DOB.

2.2. Micro tool contact detection method

When a micro end mill tool is used, the estimated disturbance force is too small to distinguish from the noise, which easily leads to low-accuracy and low-robustness contact detection. Thus, three solutions were considered in this research.

The first solution is to suppress the noise for the estimated disturbance force. The noise is mainly classified into three types depending on the cause: low-frequency noise caused by magnetic poles, noise related to spindle rotation, and high-frequency noise caused by quantization error. Countermeasures were taken against the first two noise types. To detect the tool contact, the DC component of the force that includes the low-frequency noise does not necessarily have to be used because the impulse force generated at the moment of tool contact has a wideband frequency component [8]. Hence, to eliminate the low-frequency noise, the deviation of the current estimated disturbance force from its past moving average at the t_kth number of intervals is represented in Eq. (2). This plays the same role as a high-pass finite impulse response filter.

$$\Delta F_{dis}(t_k) = F_{dis}(t_k) - \frac{1}{T_s r}\sum_{i=t_k-r-1}^{t_k-1} F_{dis}(\mathrm{i}) \qquad (2)$$

Here, T_s [s] is the sampling time of the controller, and r is the data amount of the moving average. A notch filter is utilized for the noise related to spindle rotation.

The second solution is to monitor not just the simple disturbance force deviation but also the time variation of the deviation calculated by the least-squares method. In this case, the force deviation is approximated as a linear function of the time for the short period ΔT. By using the number of samples N for ΔT, ΔT is represented as $T_s \times N$. By fitting the linear model $\Delta F_{disk}(t : t_k - \Delta T < t < t_k) = a_k t + b_k$ to ΔT, the coefficient a_k is equivalent to the time variation of the force deviation and is calculated as follows:

$$a_k = \frac{N\sum t_k \Delta F_{dis\_k} - \sum t_k \Delta F_{dis\_k}}{N\sum t_k^2 - \left(\sum t_k\right)^2} \qquad (3)$$

This time variation of the force deviation can be regarded as a second-order differential of the estimated disturbance force with a focus on the influence of the current force. In terms of a computational approach, the time variation of the disturbance force deviation can be continuously obtained simply by replacing the oldest data with the newest data for each interval of the servo control cycle. Therefore, the computational load is low.

After reducing the noise from the originally estimated disturbance force by using the above two solutions, the threshold of tool contact needs to be decided without manual setting. The third solution is to determine the threshold according to probability theory. The threshold value is set as $\mu + \alpha\sigma$ (μ: average of the noise, σ: standard deviation of the noise, α: a fixed number) by using data of a_k before the contact [9] and should be set higher than the noise but as low as possible at the same time. In this research, $\mu + 4\sigma$ was experimentally adopted. To make the detection method more robust, tool contact was considered to be detected when the coefficient a_k exceeded the threshold value three times in succession. Assuming that the data is independent, the probability of erroneous detection would only be 3.19×10^{-14} if the noise distribution is normal.

2.3. Proposed algorithm for micro-tool contact detection

In this study, micro-tool contact detection was conducted by using the servo information of the z-axis stage. Fig. 2 presents the flowchart of the proposed tool contact detection. As the z-axis stage approaches the workpiece before tool contact, the following algorithm is performed:

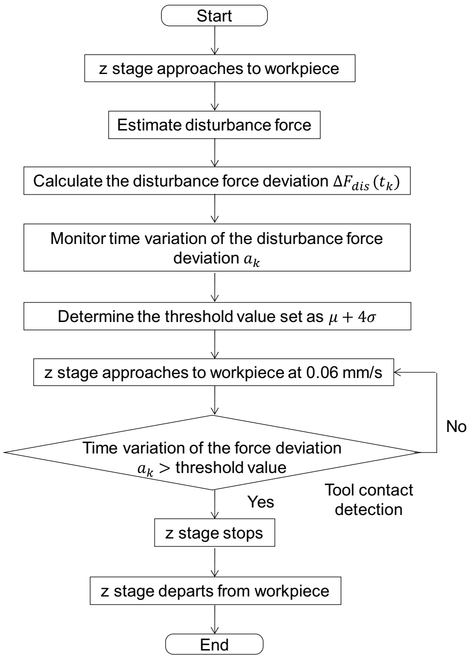

Fig. 2. Flowchart of the tool contact detection method.

- A notch filter depending on the spindle rotation is applied to the disturbance force estimated with the DOB;
- After the deviation of the current disturbance force is calculated, the time variation of the force deviation as given in Eq. (3) is monitored in real time.
- Based on the measured average of the time variation and the standard deviation, the threshold value of the tool contact detection is set according to probability theory.

The position where the time variation of the force deviation exceeds the threshold value is regarded as the contact position. After tool contact is detected, the z-axis stage stops and departs from the workpiece.

3. Experimental procedure

The proposed micro-tool contact detection method is intended for a function of ultra-precision or high-precision machine tools and was implemented in a prototype three-axis high-precision machine tool, as shown in Fig. 3(a). Shaft-type linear motors and air sliders were employed so that the cogging and frictional forces would be negligible during movement of the stage. The air sliders were equipped with air balancers to mechanically compensate for the gravitational force. Thus, an external force such as the tool contact force could be considered to be the same as the disturbance force estimated by a DOB. The servo controller with 800 MHz CPU and PWM amplifier with 16bit digital current control are utilized and the proposed algorithm is directly implemented to the servo

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