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Analysis method for investigating the influence of mechanical components on dynamic mechanical error of machine tools

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ABSTRACT

In machine tools, the difference between the position of the tool center point and that of position detectors of the control system leads to a dynamic mechanical error, which is obtained as the difference between the feedback-controlled table position and the position of the tool relative to the table (tool–table relative position). In this paper, analysis methods are proposed to roughly determine the component of the mechanical system that causes the dynamic mechanical error. Two methods, a two-encoders method and a four-accelerators method, for investigating the influence of the mechanical component on the dynamic mechanical error are proposed. In both methods, the frequency response function between the feedback-controlled table position and the tool–table relative position is evaluated. By the proposed methods, the dynamic mechanical error of a high-precision machining center in the *X* and *Y* directions is analyzed for frequencies up to 200 Hz. It was found that the entire frequency range could be divided into three distinct subranges depending on how the component of the mechanical system influences the dynamic mechanical error at different frequencies. The analysis results indicated that in the low-frequency range, the dynamic response of the driven component plays a dominant role in influencing the dynamic mechanical error. Then, the dynamic mechanical error of the experimental machine was measured for small circular motions. The dynamic mechanical error occurred at the micrometer level. The dynamic mechanical error can be estimated from the frequency response function measured by the proposed method.

1. Introduction

In recent times, demands for high-precision machining that can achieve a geometric accuracy of submicrometer level are increasing to produce high-precision dies and molds for optical parts. High-precision machining requires not only accuracy but also productivity. Therefore, dynamic contouring errors of machine tools must be suppressed under high-speed conditions. Linear motor drives are widely used to enhance the response and reduce the motion error due to friction [1–3]. The dynamic response of the control system and the mechanical system also influences the dynamic contouring error under high-speed conditions. In particular, the dynamic response of the mechanical system causes the dynamic mechanical error which is defined as the difference between the position of the tool relative to the work table and the table position measured by position detectors of the control system.

A number of control schemes have been proposed to reduce the dynamic contouring error in multi-axes motion. Methods for tuning control parameters have been used to match the response to commands among all axes [4]. Model-reference feedforward (MR-FF) controllers are also used so that the feedforward and feedback controller can be designed independently to match the dynamic response [5,6]. The cross-coupled control (CCC) method proposed by Koren et al. is a popular method to compensate contouring errors [7–9]. In CCC, the error is calculated from the deviation of each axis. The above approaches are effective in reducing the dynamic contouring error at the position detector.

However, to date, few studies have investigated the dynamic mechanical error of machine tools. Franse et al. experimentally evaluated the dynamic response of an ultraprecision machine tool to external disturbance forces [10]. Pereira et al. measured the dynamic mechanical error of a coordinate measuring machine performing circular probe motions [11]. Although the error is modeled as a function of normal acceleration in their study, the error model is obtained by fitting measurement data. The influence of the mechanical system on the error is not explained clearly.

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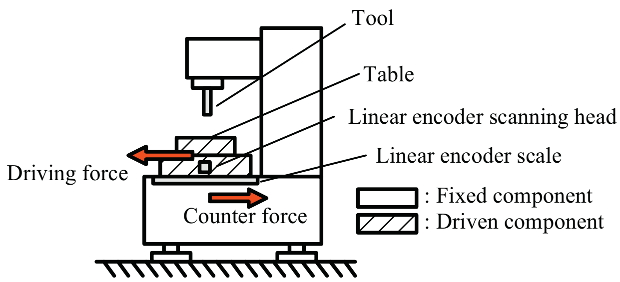

Fig. 1. Schematic of a machine tool during table motion.

Modal analysis is effective to analyze the dynamic response of the mechanical system and determine the cause of an undesirable relative position between two components. However, it is practically difficult to determine the cause of the dynamic mechanical error because the error is influenced by two relative positions.

In this study, analysis methods are proposed to roughly determine the component of the mechanical system that causes the dynamic mechanical error. In this analysis, the dynamic mechanical error is also estimated from the table position measured by position detectors of the control system. The dynamic mechanical error of a high-precision machining center is analyzed with the proposed method. Then, the dynamic mechanical error of the machining center for circular motions is measured to compare the measured error and the error estimated with the proposed method.

2. Method for analyzing dynamic mechanical error

2.1. Concept of the method

Fig. 1 shows the schematic of a machine tool during table motion. The table position is detected and controlled with a linear encoder. In Fig. 1, it is assumed that the scanning head of the linear encoder is attached to the driven component of the machine and the scale of the linear encoder is fixed on the fixed component. During table motion phase, if the position of the linear encoder differs from the tool center position, a difference will occur between the position of the tool relative to the table and the table position measured by the linear encoder because of the dynamic response of the mechanical system to the driving force and counter force. In this paper, this difference is defined as the dynamic mechanical error. Henceforth, the position of the tool relative to the table is referred to as a T–T (tool–table) relative position. The table position measured by the linear encoders is referred to as a feedback-controlled table position.

The mechanical system of the machine tool should be modified to reduce the dynamic mechanical error. Modal analysis is effective to analyze the dynamic response of the mechanical system and determine the cause of an undesirable relative position (such as a relative vibration) between two components. However, because the dynamic mechanical error is influenced by two relative positions, it is difficult to determine which relative position causes the error.

In this paper, two analysis methods are proposed to roughly determine the cause of the dynamic mechanical error. One method is referred to as a two-encoders method (2E method) and the other is referred to as a four-accelerometers method (4A method). In both methods, the frequency response function $G_{et}(s)$ between the feedback-controlled table position and the T–T relative position is obtained to evaluate the dynamic mechanical error. The frequency response function $G_{ferel}(s)$ between the driving force and the feedback-controlled table position and the frequency response function $G_{ftrel}(s)$ between the driving force and the T–T relative position are measured to investigate which response influences $G_{et}(s)$. Once the cause of the dynamic mechanical error is determined by the proposed method, the modal analysis can be used to decide the component to be modified in detail. The function $G_{et}(s)$ can be also used to estimate the dynamic mechanical error from the feedback-controlled table position. The details of these methods are as follows.

2.2. Two-encoders method

The function $G_{et}(s)$ is obtained by the following equation:

$$G_{et}(s) = \frac{G_{ftrel}(s)}{G_{ferel}(s)} \tag{1}$$

To obtain the functions $G_{ferel}(s)$ and $G_{ftrel}(s)$, the feedback-controlled table position and the T–T relative position are measured with the linear encoder and a 2D grid encoder (such as KGM, HEIDENHAIN). The driving force can be calculated from the motor current feedback and the force constant of the drive system.

The dynamic mechanical error is directly measured by the 2E method. Compared to the 4A method, the 2E method can achieve higher resolution in position measurement and higher sensitivity in the low-frequency range of 0 to several Hz.

2.3. Four-accelerometers method

The function $G_{et}(s)$ is obtained by the following equation:

$$G_{et}(s) = \frac{G_{ftrel}(s)}{G_{ferel}(s)} = \frac{G_{ftool}(s) - G_{ftable}(s)}{G_{fscale}(s) - G_{fhead}(s)} \tag{2}$$

where $G_{ftool}(s)$, $G_{ftable}(s)$, $G_{fhead}(s)$, and $G_{fscale}(s)$ are frequency response functions between the driving force and the absolute positions of the tool tip, the table, the scanning head of the linear encoder, and the scale of the linear encoder, respectively. Each frequency response function is measured with an accelerometer. The driving force can be obtained as described in Section 2.2.

Compared to the 2E method, the cause of the dynamic mechanical error can be determined more clearly in the 4A method because the influence of the dynamic responses of the fixed and driven component on $G_{ferel}(s)$ and $G_{ftrel}(s)$ can be analyzed. However, the sensitivity of the accelerometers in the low-frequency range limits the bandwidth of the measurement.

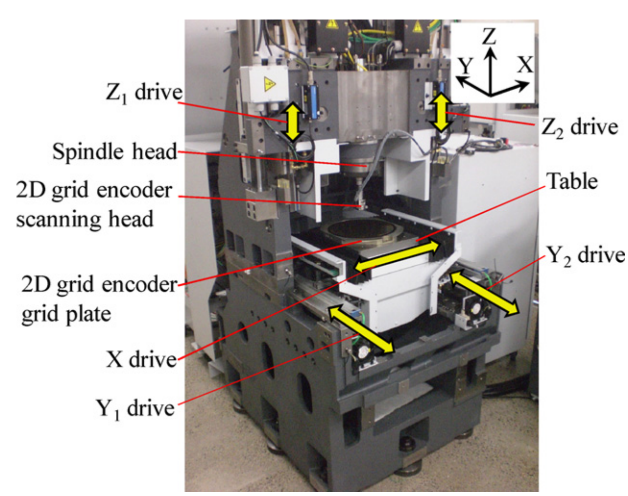

Fig. 2. Photograph of the machine tool used in the experiment.