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Online Evaluation Method of Machining Precision Based on Built in Signal Testing Technology

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Abstract

Online machining precision evaluation is of great significance for lowering manufacturing cost and improving manufacturing efficiency. The open numerical controller provides an opportunity to access the signals of servo drivers during the machining process and makes the online monitoring of the machining process realizable. In this paper, a novel online evaluation method of the work piece machining error is proposed based on homogeneous coordinate transformation and built-in signal testing technology. A gear grinding process is monitored experimentally, and it is shown that the proposed method is effective at detecting work piece machining errors.

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1. Introduction

Efficiency and precision are the most important elements in modern manufacturing, so there is a growing trend to use high speed and high precision (HSHP) machine tools in the manufacturing industry. However, the factors that affect the machining precision of an HSHP numerical control (NC) machine tool are distinct from those of the common NC machine tool. The HSHP NC machine tool is a complex system, because the mechanical characters and control characters are coupled. The characters of an HSHP NC machine tool not only depend on the geometric precision of a part but also on the assembly quality and the controller’s parameters. Additionally, an HSHP NC machine tool acts differently at different loads.

In the machining process, the dynamic characters of NC machining tools affect the manufacturing precision of a part. Hence, it is necessary to monitor the machining process and establish the relationship between the machining quality and the dynamic characters of a machining tool. Currently, we measure part precision after machining, which is convenient for small parts but troublesome, time consuming and expensive for large parts such as gears and gearbox components. Hence, finding a way to test the quality of the machined part is useful in reducing the production time and cost.

The contour error of a machine tool is divided into two categories: the quasi-static geometric errors and the dynamic geometric errors [1], which are caused mainly by the dynamic character of the machine tool. The dynamic character is one of the significant factors that determine the precision of a machine tool. At present, the main instruments for testing the dynamic character of machine tools are ball bar [2], cross grid encoders [3], and laser interferometers. A new test device consisting of a ball bar with an encoder and its measurement principle are proposed for measuring the circular motion trajectories of machine tools [4]. A 3D test device and an R-test method for measuring dynamic path deviations are introduced [5]. A sensorless or built-in test method monitors the motion status and detects the faults such as pitting and backlash [6]. The encoder and linear encoder signals calculate the frequency response function and
predict the tracking and contour errors [7]. The spindle current estimates the cutting force of the machine tool and finds the relationship between the cutting force and the current signal [8, 9]. By comparing the difference of the position signal between a new machine tool and an old machine tool, the wear status of the feed system is detected by the proposed sensorless signal analysis method [10]. Current and position signals sampled from a running machine tool are used to diagnose the fault in the feed axis, and the wear location of the worm gear is detected [11]. Steven et al. review the progress in machining process monitoring over the past decades and point out that process monitoring is useful for enhancing machining quality and reducing cost [12]. The machining process is an error reappearing and forcing process. The geometric error or fault of a ball screw and guide will influence the work piece machining precision. Because the error of each axis could be detected from the encoder signals through built-in signal testing and analyzing, the method of monitoring the machining precision by built-in signal testing technology is considered in this paper.

In this paper, an online machining process monitoring and a work piece precision estimation method are proposed based on built-in signal testing technology and homogeneous coordinate transformation. The content of the paper is as follows. The signal analysis and error modeling methods are briefly introduced in section 2. The experimental grinding is described in section 3. The measurements are analyzed and compared with those of the three-coordinate measuring machine (CMM) in section 4. The conclusions and future work are presented in section 5.

2. The Signal Gathering and Analysis Method

2.1. Signal testing method

There are three useful built-in signals in open NC that can be obtained from the drivers: the velocity feedback signal, the position feedback signal and the current monitoring signal. The three pass connector extracts the position and velocity signals by a count card without affecting the communication. A normal data acquisition system driver port provides the current signal. The position and velocity signals are usually in 1Vpp or TTL format, and the current signal is a ±5V signal. In order to get the position, velocity and current signals simultaneously, the test executor should design a synchronized solution for the data acquisition system. The signal sampling method is shown in Fig. 1.

The relationship between current signal and torque of the feed axis is explained as follows.

When the motor drives the ball screw and moves the table, the relationship of the current and the load is according to the following formula:

$$T = K_i i = J\dot{\theta} + \tau_a + \tau_f$$  \hspace{1cm} (1)

where $T$ is the motor torque, $K_i$ is the current coefficient, $J$ is the rotary inertia, $\theta$ is the angle of the motor, $\tau_a$ is the disturbance moment, and $\tau_f$ is the friction torque.

If the velocity is constant, the moment of inertia will be omitted, that is, $J\dot{\theta} = 0$, and the formula changes to

$$i = \frac{\tau_a + \tau_f}{K_i}$$  \hspace{1cm} (2)

Hence, the current signal can reveal the abnormal characters of the feed axis.

The information of the feedback signals is shown as follows.

For the closed feedback NC machine tool, the relationship between the velocity feedback signal $\theta_{\text{sw}}$ and the position feedback signal $d_{\text{sw}}$ is

$$k \cdot \theta_{\text{sw}} = d_{\text{sw}}$$  \hspace{1cm} (3)

where $k = p/i$, $p$ is the pitch of ball screw, and $i$ is the reduction ratio in the motor and ball screw feed system. In practice, a difference inevitably exists in the two signals.

$$E = k \cdot \theta_{\text{sw}} - d_{\text{sw}}$$  \hspace{1cm} (4)

The deviation $E$ is mainly caused by the geometric error, the elastic deformation, the dynamic character variation, and the control system parameter:

$$E = \Delta_c + \Delta_d + \Delta_g$$  \hspace{1cm} (5)

where $\Delta_c$ is the control error, $\Delta_d$ is the dynamic error, and $\Delta_g$ is the mechanical error.

The error $E$ has two meanings: first, it detects the fault of the feed system; and second, it reflects the system control stability. For this reason, the deviation $E$ is used as the signal to evaluate the space error of the machining process.

2.2. The model of space error

The NC machine tool usually has five axes, which contain three line motion axes and two rotary axes. The tool and the work piece move relative to each other, while the work piece is cut into the desired shape. In this process, there is deviation between the theoretical track and the actual path because of the influence of the cutting force and the dynamic character of the machine tool. As introduced in 2.1, the deviation between the
theoretical track and the actual path is implied in $E$ for each axis that participates in the machining process. In order to get the machining error, the position of the involved axis should be transformed to the absolute coordinate system (ACS), which is linked with the bed. The $X_A$, $Y_A$, and $Z_A$ axes are the same as the machine coordinate system (MCS) axes $X_M$, $Y_M$, and $Z_M$. The transformation formula is

$$
\begin{bmatrix}
^{*}P_x \\
^{*}P_y \\
^{*}P_z \\
1
\end{bmatrix} =
\begin{bmatrix}
^R_x & ^R_y & ^R_z \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
^{*}P_x \\
1
\end{bmatrix}
$$

where $^{*}P$ is the point position in MCS and $^{*}P$ is the transformed point position in ACS. And the parameters $^R$ and $^R$ are the rotary and offset coordinate transform coefficients, respectively.

After transformation, the difference between the velocity feed signal and the position encoder is the work piece shape error. If all three axes of the ACS are described by the error value, it would not be useful for the space error description. In this paper, the main motion direction is chosen for the expansion coordinate axis; the other two axes describe the cutting errors, as shown in the following formula:

$$
\begin{bmatrix}
^{*}P_x \\
^{*}P_y \\
^{*}P_z \\
1
\end{bmatrix} =
\begin{bmatrix}
^R_{x1} & ^R_{x2} & ^R_{x3} & \delta_x \\
^R_{y1} & ^R_{y2} & ^R_{y3} & \delta_y \\
^R_{z1} & ^R_{z2} & ^R_{z3} & \delta_z \\
0 & 1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
^{*}P_{ax} \\
^{*}P_{ay} \\
^{*}P_{az}
\end{bmatrix}
$$

where $^{*}P_{ax}$ and $^{*}P_{ay}$ are the cutting errors in the MCS, $^R$ is the rotary transformation coefficient, and $\delta$ is the offset transformation coefficient.

3. Experiments

The proposed method is implemented on the YK73200 NC gear grinding machine tool. This machine tool has five ganged axes and a profile modification axis. The X and A axes are fixed on the bed; the Z axis is set up on the A axis and rotating with it; the Y axis is stacked up on the Z axis and the direction is perpendicular with the Z axis; and the C axis is assembled on the X axis as shown in Fig. 2 (a). The controller is the NUM 1050 NC controller.

In this experiment, the position signals of the A, C, Z, and Y axes are gathered synchronously along with the Y axis velocity feedback signal. These signals are sampled using the data acquisition system developed by the authors that gathers the 1Vpp, TTL, and ±10V format signals simultaneously. In the monitoring process, a cylindrical gear part profile is ground. The modulus of the gear is 25 with 60 teeth, and the width of the gear is 200 mm. In the machining process, the Z axis feeds in 4 times: 2 times for coarse grinding and 2 times for fine grinding. The C axis rotates to grind different teeth, and the A axis, X axis and Y axis are static. The feed speed of the Z axis is 2400 mm/min, and the sampling frequency is 1 kHz. The motion process without grinding is sampled with an identical parameter setup for comparison.

The experimental implement is shown in Fig. 2 (b), and the sampled data are shown in Fig. 3 (a) and (b).
4. Analysis and discussion

In Fig. 3 (a) and (b), an analysis of the complete reciprocating process of the Z axis is shown. The trend and the amplitudes of the curves of the A and C axes in this process are similar with and without grinding; however, the amplitude and the trend of the Y data clearly vary. The points of inflection in the curves with and without grinding are invariable: those for the C and Y axes appear unusual at 1/3 the sample points of that for the Z axis. The data of the Y velocity feedback signal act differently in the two testing conditions. In the no-load situation, the data and the position signal behave differently. In the grinding condition, the data and the position signal have the same trend.

The data were analysed by the proposed method in 2.2. In this situation, the ACS is set up on the bed, and the origin of the ACS is set on the circle centre of the gear part. The directions of the three axes are the same as the MCS, following the right hand rule. The tool coordinate system (TCS) is set at the initial point of the trace. Relative to the ACS, the TCS origin offsets the origin of the ACS by -750 mm and revolves around the X and Z axes. The coordinate transformation process is described mathematically as follows:

\[
\begin{bmatrix}
\frac{\Delta P_x}{\frac{\Delta P_y}{\frac{\Delta P_z}}}
\end{bmatrix} =
\begin{bmatrix}
\cos C_{w} & \sin C_{w} & 0 & 0 \\
\sin C_{w} & \cos C_{w} & 0 & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\frac{\Delta P_x}{\frac{\Delta P_y}{\frac{\Delta P_z}}}
\end{bmatrix}
\]

where \(\Delta P_x\), \(\Delta P_y\), \(\Delta P_z\) are the coordinate values of the grinding point in the ACS, and \(\gamma_{w}, \gamma_{z}, \gamma_{a}, \gamma_{c}\) are the motion errors of the Y, Z, A, and C axes in the TCS. The results are shown in Fig. 4 (a) and (b).

In the two conditions, the shape of the space error curve is similar. The space error occurs mainly in the Y direction, and the error in the X direction is insignificant. The back and forth process is different in the no-load condition, and in the grinding process, the difference appears only in the 80mm region of the Z axis. The curves can be divided into four parts: in the first part, from 20 mm to 43 mm of the Z axis, the space error increases in the positive direction; in the second part, from 43 mm to 86 mm, the space error crosses the zero point to the minimum value; in the third part, from 86 mm to 209 mm, the error gently returns to the positive
value; and in the last part, there are small changes. The maximum error value in the grinding process is 0.0087 mm in the Y direction and 10⁻⁴ mm in the X direction, and the value is 0.0013 mm and 10⁻⁴ mm, respectively, during the no-load condition. The resulting error when grinding is about 8 times that in the no-load condition.

The three-coordinate measuring machine test result is compared with the estimated result, as shown in Fig. 5. The trend of the curve in the test report is similar to that of the estimated curve. There are also three reversal points, and the point position of the test result curve is the same as the estimated curve. However, the test error value is different from the estimated error value. The biggest tooth alignment error in the test report is 0.0142 mm, although the corresponding estimated error is 0.0055 mm. These values are reasonable, because the geometric error and tool deformation are not considered in this method.

The proposed reason for this abnormal tooth alignment error is the abnormal motion of the Y axis; the error compensation method of the tooth alignment error will be explored in future studies.

The use of high speed and high precision machine tools is an important factor in improving productivity. The manufacturing efficiency will undoubtedly be improved once the machining precision of machine tools can be estimated in the machining process. In this paper, an online manufacturing precision estimation method is proposed based on built-in signal testing technology and homogeneous coordinate transformation. This method is successfully used in the gear part grinding process to estimate the tooth alignment error. The estimated result agrees with the CMM test report. However, the geometric error of each axis is not considered in the proposed method; therefore, there is a difference between the estimated method and the CMM test. Hence, the result can only be used as a reference of the genuine precision.

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Fig. 5. CMM test result of the gear tooth