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Monitoring and source tracing of machining error based on built-in sensor signal

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Abstract

Online monitoring and source tracing of machining error is of great significance for ensuring machining quality and improving machining efficiency. For an open numerical controller, the built-in sensors signals can be captured through driver interface in machining process. These signals contain various information of machining conditions of machine tool. The capture and analysis of the built-in sensors signals can be used for the online monitoring and source tracing of machining error. In this paper, an novel approach is developed for machining error monitoring and source tracing based on built-in sensor signal analysis and multi-body system theory. A ball screw grinding process was monitored, and the analysis results show the validity of the approach.

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Keywords: Open CNC; Built-in sensor signal; Machining error monitoring; Source tracing.

1. Introduction

Precision is crucially an important target for manufacturing industry. In the machining process, many factors affect the machining accuracy such as tool wear, deformation errors induced by cutting force, thermal errors and kinematics errors of the machine tool. Among them, the error caused by the performance of the machine tools is one of the important source of inaccuracy, especially in precision manufacturing process.

There is a growing trend to use high speed and high precision (HSHP) numerical control (NC) machine tools in manufacturing process of the precision parts. The HSHP NC machine tool is a complex electromechanical system, so the motion precision of an HSHP NC machine tool not only depends on the geometric precision of a part and assembly quality but also on the controller's parameters and the cutting force. In the manufacturing process of the precision parts, the dynamic motion characters of NC machining tools is one of the significant factors that determine machining error of a part. Hence, it is necessary to monitor running state of the NC machining tool in the machining process and establish the relationship between the machining error and the dynamic characters of a machining tool. Furthermore, the information of running state is a result of many factors of a machining tool, so dynamic characters analysis made source tracing of machining error available .

The dynamic geometric error is the key factors causing contour error of a part in precision machining process, which are caused mainly by the dynamic character of the machine tool. Currently, the main instruments for testing the dynamic geometric error 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]. Usually, dynamic geometric errors are measured by above instruments before machining or in rest time. The test results show the normal dynamic characters of the machine tool, but could not reflect the dynamic motion state of the machine tool in cutting process . A built-in sensor test method is proposed and used for the motion status monitoring and the fault diagnosis such as pitting and

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backlash [6]. By comparing current position information of the build-in sensors with those which were taken when the machine was new, the wear status of the ball screw is detected by the proposed sensorless signal analysis method[10]. The spindle current and feed current are used to estimate the cutting force of the machine tool and the relationship between the cutting force and the current signal is build [8, 9]. position signals or Current sampled from a running machine tool are used to diagnose the fault in the feed axis or the tool [11,12]. Built-in sensor signal contains a wealth of dynamic characteristic information and can be acquired in machining process. furthermore, the errors of each axis could be detected from the position signals through built-in signal testing and analyzing. The method of monitoring and source tracing of the machining error based on built-in signal is considered in this paper.

In this paper, machining error monitoring and source tracing method is proposed based on built-in sensor signal analysis and multi-body system theory. The content of the paper is as follows. The signal analysis and machining error modeling methods are briefly introduced in section 2.The grinding experiment of the ball screw is described in section 3. The result of experiment is analyzed in section 4. The conclusions are presented in section 5.

2. The Signal Analysis and Machining Error Modeling Method

2.1. Build-in sensor signal acquisition method

In the cutting process, built-in sensor signals of the NC machine tools contain a large amount of dynamic characteristics information. Encoder and grating scale are motion precision measuring and feedback equipment in motion control system, and the position feedback signal and the velocity feedback signal directly reflect the dynamic motion state of the feed system. Additionally, the current monitoring signal of the motor can reflect the change of load. These three useful built-in signals in open NC can be obtained from the drivers. by a three pass connector and a count card, the position and velocity signals can be extracted without affecting the communication, the signal sampling principle is shown in Fig. 1. The current signal can be obtained from test port of the driver. The position and velocity signals are usually in 1Vpp or TTL format, and the current signal is a ±5V signal.

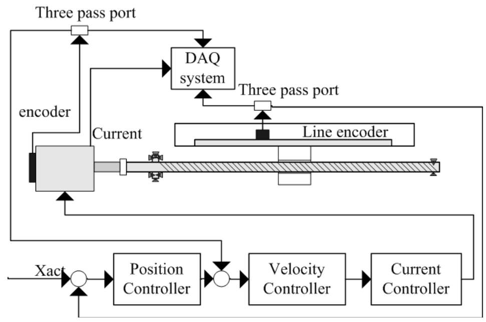


Fig. 1. signal sampling principle of build-in sensor

2.2. Signal analysis

For the closed feedback NC machine tool, the relationship between the velocity feedback signal θ_{en} and the position feedback signal d_{sl} is

$$d_{sl} = \frac{p}{i} \cdot \theta_{en} \tag{1}$$

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

$$e = d_{sl} - \frac{p}{i} \cdot \theta_{en} \tag{2}$$

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

$$e = f(\Delta_g, \Delta_c, \Delta_g) \tag{3}$$

where Δ_g is the mechanical error, Δ_c is the control error, and Δ_d is the dynamic error.

2.3. The machining error model

Machining error usually appears as the spatial location offset of tool actual cutting path compared to ideal cutting path. The tool and the work piece move relative to each other, while the work piece is cut into the desired shape. Because of the influence of the cutting force and the dynamic character of the machine tool, the actual cutting path usually deviates from the theoretical track. The machining error modeling aims to establish a relationship between actual motion state and the pose errors of the machine tool, which is the common premise of error monitoring and analysis.

All kinds of machine tools have two motion chains which contain several motion components connected in series . One is from machine bed to workpiece, and the other is from machine bed to cutting tool, which are represented by workpiece kinematic chain and cutting tool kinematic chain, respectively. Fig.3 shows the topological configuration of a large precision thread grinding NC machine tool. Modeling the machining error uses the multi-body system theory. The homogeneous coordinate transformation matrix form cutting tool to workpiece is established and used to describe the relationship between position information of motion axes and cutting path of cutting tool relate to workpiece.

$$T_{wtP}=[\prod_{k=n}^{k=1} T_{L^k(w)L^{k-1}(w)}]^{-1}\prod_{k=m}^{k=1} T_{L^k(t)L^{k-1}(t)} \qquad (4)$$

$$T_{wtV}=[\prod_{k=n}^{k=1} T_{L^k(w)L^{k-1}(w)}(R)]^{-1}\prod_{k=m}^{k=1} T_{L^k(t)L^{k-1}(t)}(R) \qquad (5)$$

where T_{wtP} and T_{wtV} are position and orientation coordinate transformation matrix of the cutting tool relative to the workpiece respectively. $T_{L^k(w)L^{k-1}(w)}$ and $T_{L^k(w)L^{k-1}(w)}(R)$ are position and orientation coordinate transformation matrix of the adjacent parts of workpiece kinematic chain. $T_{L^k(t)L^{k-1}(t)}$ and $T_{L^k(t)L^{k-1}(t)}(R)$ are position and pose coordinate transformation matrix of the adjacent parts of cutting tool kinematic chain. n is the number of component in workpiece kinematic chain, and m is the number of component in cutting tool kinematic chain.

$$T_{L^k(w)L^{k-1}(w)}=\begin{bmatrix}\mathbf{R}_{k,k-1} & p_{k,k-1}\\ \mathbf{0} & 1\end{bmatrix} \qquad (6)$$

$$T_{L^k(w)L^{k-1}(w)}(R)=\begin{bmatrix}\mathbf{R}_{k,k-1} & \mathbf{0}\\ \mathbf{0} & 1\end{bmatrix} \qquad (7)$$

where $p_{k,k-1}$ is the position vector of the origin of the adjacent parts coordinate system. $\mathbf{R}_{k,k-1}$ is orientation matrix. Every part of the machine tool usually have one motion type such as translation or rotation.

The cutter motion path m_w and orientation path $\vec{V}_w$ in the workpiece coordinate system as shown in the following formula:

$$m_w=T_{wtP}m_t \quad m_t=(t_x,t_y,t_z,1)^T \qquad (8)$$

$$\vec{V}_w=T_{wtV}\vec{V}_t \quad \vec{V}_t=(v_x,v_y,v_z,1)^T \qquad (9)$$

where m_t is position of the cutter location point in cutting tool coordinate system. $\vec{V}_t$ is orientation vector of cutter in cutting tool coordinate system.

The actual cutting path and orientation path could be obtained by substituting actual motion position into cutter motion path model. Similarly, the ideal cutting path and orientation path could be calculated. As previously mentioned, machining error appears as the spatial location offset of tool actual cutting path compared to ideal cutting path. The machining error model is expressed as:

$$E_m=m_w^{real}-m_w^{ideal} \qquad (10)$$

$$E_v=\vec{V}_w^{real}-\vec{V}_w^{ideal} \qquad (11)$$

3. Experiments

The proposed method is implemented on the *CKG6800* large precision NC thread grinding machine tool. This machine tool has four motion axes. The Z axes and spindle are fixed on the bed; the X axis is assembled on the Z axis and connected with the grinding wheel head; the work piece is set up on the spindle and rotating with it; as shown in Fig. 2 (a). The controller is the *SINUMERIK 840D NC* controller.

This NC machine tool has three axes, which contain two linear motion axes and one rotary axis. The topological structure of the machine tool as shown in Fig.3. In the monitoring process, a ball screw is grinding whose lead is 40mm. In the grinding process the ball

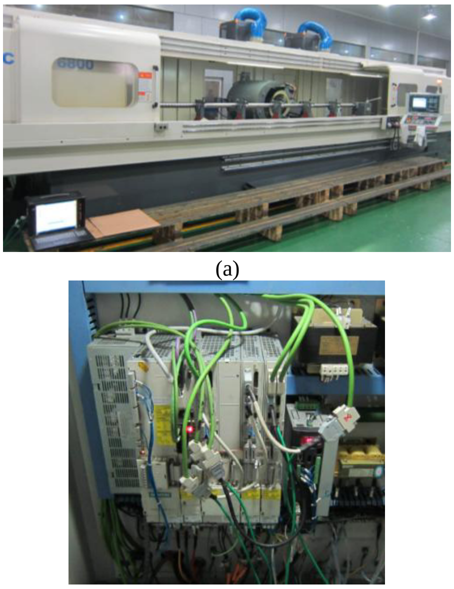


Fig .2. (a) The tested precision thread grinding NC machine tool ; (b) the signal connection implement.

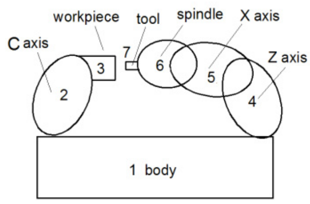


Fig .3. Topological structure of the threat grinding NC machine tool screw, was grinded 22times. Each time, the X axis feed depth is 30µm ,the wear correction value of the grinding wheel is 80µm and the C axis rotation speed is 18r/min.

In this experiment, the position signals of the Z, X axes and the rotation angle signals of C axis are gathered synchronously. These signals are sampled using the data acquisition system that can gather the 1Vpp, TTL, and ±10V format signals simultaneously. The sampling frequency is 1 kHz. The experimental implement is as shown in Fig. 2 (b). As well as the whole grinding process, the process without grinding is sampled with an identical parameter setup for comparison.

The sampled data are shown in Fig. 4 (a) and (b).

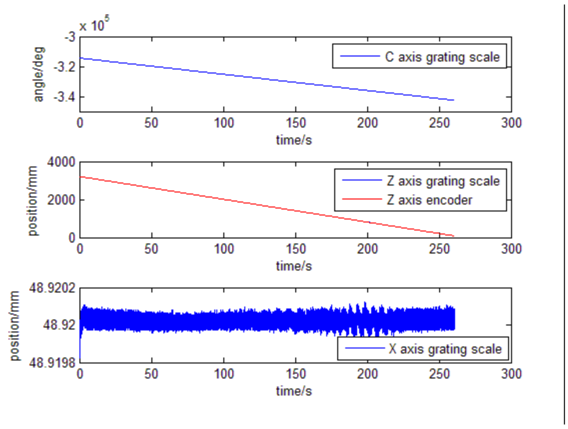
4. Analysis and discussion

In this situation, the workpiece is set up on the C axis by two rotation centers , and the origin of the workpiece coordinate system (WCS) is set on the centre of cross section at the beginning of thread. The directions of the three axes are the same as the machine coordinate system (MCS). According to the topological structure of the machine tool, the coordinate transformation matrix of the cutter relative to the workpiece is expressed as follows:

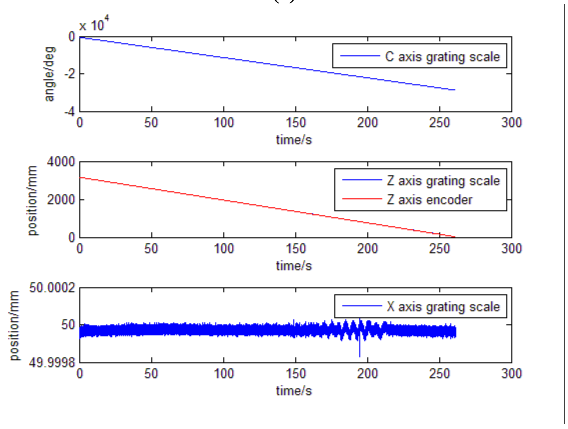
$$T_{w,t} = \left[T_{2,1}T_{3,2}\right]^{-1} T_{4,1}T_{5,4}T_{6,5}T_{7,6} = \begin{bmatrix} \cos C & -\sin C & 0 & X+W_x \\ \sin C & \cos C & 0 & 0 \\ 0 & 0 & 1 & Z+W_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

where C, X, Z are the motion position of the cutter in the MCS, and W_x and W_y are the coordinate position of the origin of the WCS in the MCS.

The actual cutting path and ideal cutting path was obtained by substituting actual motion position and ideal position into cutter motion path model. By the proposed method in 2.3, the spatial location offset of tool actual cutting path compared to ideal cutting path was calculated and attached to ideal cutting path that was reduced 1000 times. The space error of cutter path is as shown in Fig.5.

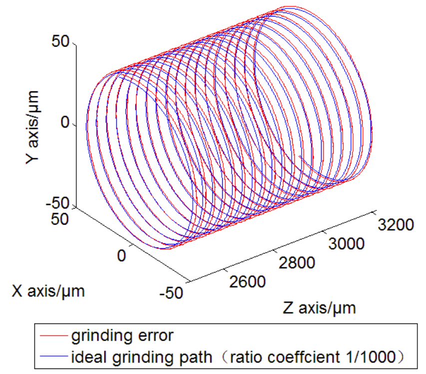


(a)

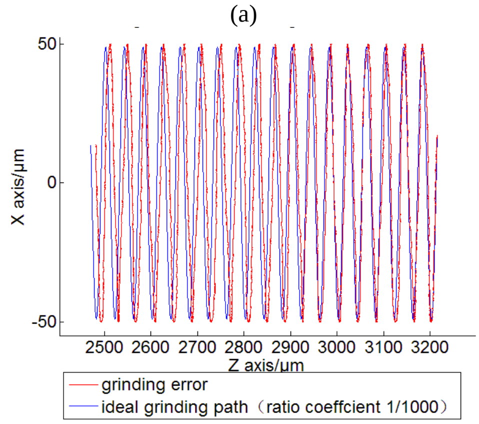


(b)

Fig. 4. Monitoring data gathered from the built-in signal in the grinding process (a) and in the no load condition(b).



(a)



(b)

Fig. 5. Space error of cutting path between z2500 to z3200 in grinding process (a) and the projection in XY plane (b).

The lead errors of the part in the grinding process is as shown in Fig. 6. There is an accumulative error of lead along with length of the ball screw. In whole length of the ball screw, the accumulative error is about 32μm. In addition, the lead error have obvious fluctuation from 2000 mm to 3200 mm of the Z axis. The monitoring result of lead error agrees with the test result in the field. The lead error of the part in no load grinding process was compared with the result in grinding process, as shown in Fig.6. In the two conditions, the trend and the amplitudes of the curves of lead error are similar. This shows that the main factor affecting the lead error is the motion error of Z axis rather than the cutting forces. The motion error of the feed axis is usually affected by the geometric precision, assembly quality and the controller's parameters.

In order to improve the precision of the ball screw, the control mode was changed from semi closed loop control mode to whole closed loop control mode. Simultaneously, the pitch compensation value was set to 30μm. The motion test without grinding was performed in different cutting conditions and the result is as shown in Fig.7. Max fluctuation of the lead error under different cutting condition is as shown in Table 1.When the feed speed of Z axis is reached 250mm/min, 400mm/min, 500mm/min, 1000mm/min, and 1250mm/min, the maximum fluctuation of lead error calculated by monitoring model is 4μm, 7.2μm, 8.9μm, 22.3μm and 29.3μm, respectively. Hence, In order to reduce the lead error fluctuation of the ball screw, The feed speed of Z axis must be limited.

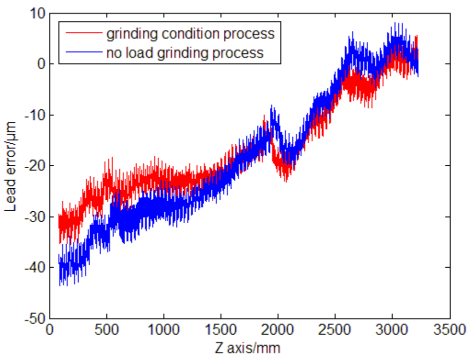


Fig. 6. Monitoring results of the lead error in the grinding process and the no load grinding process.

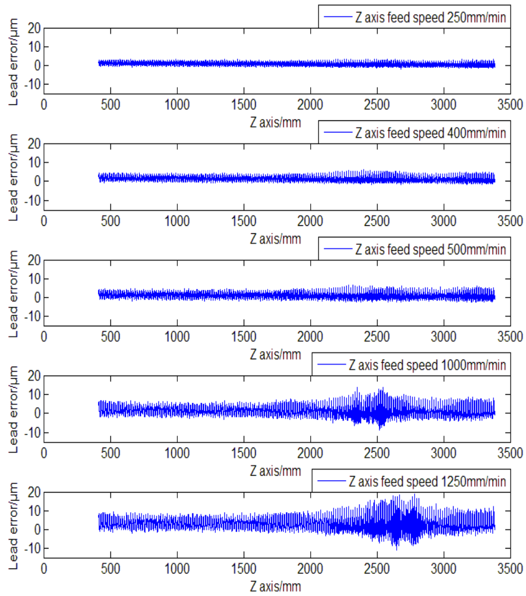


Fig.7. Lead error monitor results under different cutting condition in the no load grinding process

Table 1. Max fluctuation of the lead error under different cutting condition.

Z axis feed speed (mm/min)	Lead (mm)	C axis rotation speed (r/min)	Max lead error fluctuation (μm)
250	10	25	4
400	16	25	7.2
500	10	50	8.9
1000	40	25	22.3
1250	50	25	29.3

5. Summary

High speed and high precision machine tool is an important equipment in modern manufacturing industry and often used in the precision part machining process. The dynamic motion characters of the machining tools is the one of the significant factors influencing machining precision. In this paper, machining error monitoring and source tracing method are proposed based on built-in sensor signal analysis and multi-body system theory. This method was used to monitoring and analysis the lead error in the ball screw grinding process and provided support for cutting parameter selection. The geometric error of the machine tool is not considered in the proposed method; therefore, there is a difference between the monitoring result and the genuine precision.

Acknowledgements

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