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Development of a Simple laser-based 2D Compensating System for the Contouring Accuracy of Machine tools

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***Abstract*—**The dynamical contouring error is a critical element for the accuracy of machine tools. The contouring error is defined as the difference between the processing actual path and commanded path, which is implemented by following the command curves from feeding driving system in machine tools. The contouring error is resulted from various factors, such as the external loads, friction, inertia moment, feed rate, speed control, servo control, and etc. Thus, the study proposes a 2D compensating system for the contouring accuracy of machine tools. Optical method is adopted by using stable frequency laser diode and the high precision position sensor detector (PSD) to perform no-contact measurement. Results show the related accuracy of position sensor detector (PSD) of 2D contouring accuracy compensating system was ±1.5 μm for a calculated range of ±3 mm, and improvement accuracy is over 80% at high-speed feed rate.

***Keywords*—**position sensor detector, laser diode, contouring accuracy, machine tool

I. Introduction

IN generally, the performance inspection for a machine tool includes geometric error inspection and dynamic performance inspection. The conventional systems, such as laser interferometer, double ball bar (DBB) and plane encoder, have been widely adopted for performance inspection for a machine tool.

The laser interferometer is adopted for geometric error inspection. Its measurement range and resolution could reach 1m and 1 nm [1] respectively, but were restricted by the difficult set-up, expensive price, incompetence when measuring dynamic performance, and other defects; thus, the double ball bar (DBB) and plane encoder are adopted for circle contouring or contouring tests in dynamic performance inspection.

Since 1982, when the DBB was put forward by Bryan [2-3], it has become the most popular equipment for testing the dynamic performance of machine tools, with the features of easy set-up, low cost, wide application, easy operation, and so on. However, the DBB's only applicable for the circle contouring test and is unsuitable for high-speed contouring.

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The LBB system was proposed by Ziegert et al. [4] in 1994. Compared with DBB systems, the system adopts a laser interferometer to overcome the defect of the small measuring range. This system introduces several weaknesses at the same time, however, such as incompetence in the small-range circle contouring test and increased systematic cost. Srinivasa et al. [5] also used the LBB system for spindle thermo drift.

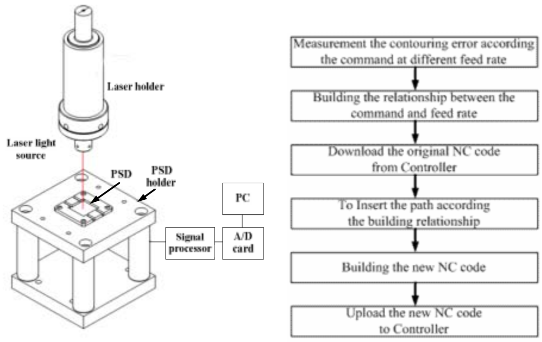
The plane encoder is a diffraction grating type encoder to measure two-dimensional position of an optical head by using a grid plate where grids are aligned orthogonal to each other [6]. The cross grid encoder can measure the contouring error in the two-dimensional (2D) plane for an arbitrary reference trajectory. It is widely used in the accuracy calibration of robot manipulators [7] or machine tools [8]. Various types of other two-dimensional position encoders have been also proposed in the literature (e.g. [9]). Since the 2D contouring error of a machine tool is generally much smaller in relative to the travelling distance, in its graphical display, the error is often magnified to some given scale with respect to the reference trajectory. It is clear that the magnified trajectory cannot be continuous at any unsmooth corners. The commercial software ACCOMEN 2.8 [10] is developed by Dr. Johannes Heidenhain GmbH to be used with the KGM series for the data acquisition and the visual display of its measured profiles, gives the same plot.

From the comparison between the optical measurement and the traditional method, the proposed system has following advantages: (a) the uncertainty can be reduced; (b) the friction can be ignored; (c) the magnetism can be ignored and (d) the signals of the proposed system can be used not only to measure the contouring accuracy but also to obtain other parameters of machine tools.

II. The Measuring Principle and Instrument Configuration

A. Overall system layout

This system includes a laser light source, a position sensor detector (PSD), signal processor, an A/D card and a PC as shown in Fig.1(a). A Li type battery is employed and built-in in the aluminium fixture for the laser light source. The weight of the fixture is less than 200 g and the length is less than 10 cm with a diameter of 4 cm. In addition to the characteristic that the battery is installed internally, the laser is fixed at the front end. Adjusting screws are provided to give small eccentricity and wobble of the setting-up errors during the test. The user interface is used to modify the NC code from the CNC controller according to the contouring error measurement result. The standard operation procedure (SOP) of the simple laser-based 2D compensating system is shown in Fig.1(b).



(a) 2D compensating system (b) SOP

Fig. 1 Sketch of the the simple laser-based 2D compensating system

B. Setting error analysis of the PSD

As shown in Fig. 2, the setting errors on the PSD could be divided into three cases (represented as α , β , and γ respectively). When there are no setting errors on the PSD, their signals were

$$x = r(\theta)\cos(\theta) \tag{1}$$

$$y = r(\theta)\sin(\theta) \tag{2}$$

where γ is radius and θ is angle. When a setting error β occurs on the PSD, equation (1) should be amended to

$$x' = \frac{r(\theta)\cos(\theta)}{\cos(\beta)} \tag{3}$$

When a setting error α occurs on the PSD, equation (2) should be amended to

$$y' = \frac{r(\theta)\sin(\theta)}{\cos(\beta)} \tag{4}$$

When setting errors α , β , and γ occur on the PSD simultaneously, equations (3) and (4) should be amended to

$$x'' = \frac{r(\theta)\cos(\theta)\cos(\gamma)}{\cos(\beta)} + \frac{r(\theta)\sin(\theta)\sin(\gamma)}{\cos(\alpha)} \tag{5}$$

$$y'' = \frac{r(\theta)\cos(\theta)\sin(\gamma)}{\cos(\beta)} + \frac{r(\theta)\sin(\theta)\cos(\gamma)}{\cos(\alpha)} \tag{6}$$

where $r(\theta)$ is the radius of the contouring test in machine tools. Because the measurement range of this system is small, the setting error can be neglected. In this experiment, to check if the laser beam was projected on the PSD vertically, a light spot of laser was reflected from the PSD to the laser diode front end. If the light was visible from the other end, it could be viewed as vertical.

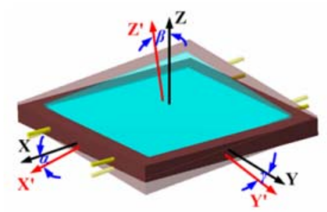
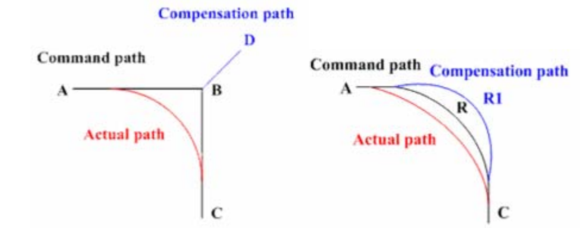


Fig. 2 Sketch of the setup error for the PSD

C. Error compensation method

At a high-speed feed rate, the performance of the controller, driver, and transmission parts will affect the efficiency of numerical control (NC) code implementation. In the present paper, some error compensation methods are put forward to improve the machine tool's performance at high-speed contouring without having to change any parts. The high-speed contouring in this experiment had two paths: linear and radius command paths. Both paths are frequently used in cutting processes. This paper put forward one contouring error compensation method for the 2D path. By adding contouring paths, the compensation methods could decrease the machine tool's contouring test error at high-speed feed. This compensation method would prolong the duration of the contouring test, but only by a little when compared to the whole contouring time.

The path of error compensation method in the 2D path contouring test is shown in Fig. 3. A→B→C (A→R→C) was the command path, and A→B→D→B→C (A→R1→C) was the new path. The space position of D (R1) in the new path depended on the machine tool's feed rate.



(a) linear path (b) radius path

Fig. 3 Sketch of the compensation method of the simple laser-based 2D compensating system

III. DYNAMIC CONTOURING TESTS

A. Calibration test for the PSD of 2D contouring accuracy compensating system

The position sensor detector (PSD) of proposed system is set up to detect the path command of CNC machine tool. The linearization of the X-axis and Y-axis of the position sensor detector (PSD) must be calibrated before using the proposed system. Calibration test for position sensor detector of the proposed system was carried out by the laser interferometer. The resolution of the laser interferometer linear measurement system is 1 nm for displacement.

In this experiment, three tests were performed by moving the dual-axis stage for a distance of ±750 μm. Calibration test results are shown in Fig.4. Results show the calibration curve for the position sensor detector (PSD) is almost coincident with the HP 5529A Laser interferometer within the range of ±3 mm. The related accuracy of position sensor detector (PSD) of 2D contouring accuracy compensating system was ±1.5 μm for a calculated range of ±3 mm. Standard deviations (STDEV) of the X-axis and Y-axis measurements of position sensor detector (PSD) were about 0.2 μm and 0.45 μm for a calculated range of ±3 mm.

The stability of position sensor detector (PSD) of 2D contouring accuracy compensating system was 2.5 µm for a calculated time of 30 minutes.

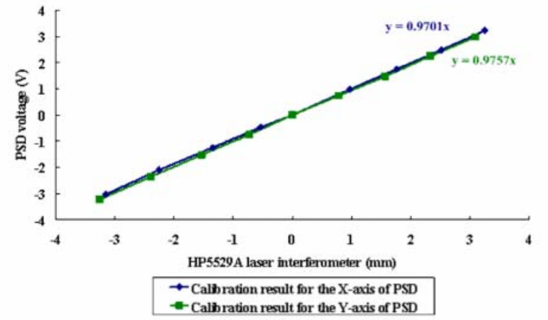


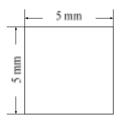
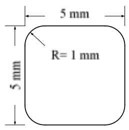
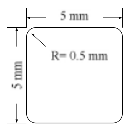
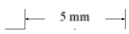
Fig. 4 Calibration result for the PSD of 2D contouring accuracy compensating system

B. Verification test for the 2D contouring accuracy compensating system

The novel 2D contouring accuracy compensating system is verified by the Heidenhain Grid Encoder (KGM 182, Linear Axes series). The X- axis and Y- axis displacement resolution of the Grid Encoder is ± 2 µm. The measurement different at corner between the command path and actual path is also used to build the compensation table.

In this experiment, the smooth function of the controller is turn on. The feed rate of verification test is set up between 1000 to 6000 mm/min. Results show the measure path of 2D contouring accuracy compensating system is almost coincident with the Grid Encoder within the feed rate between 1000 to 6000 mm/min. Table I shows the verification results for the 2D contouring accuracy compensating system.

TABLE I
VERIFICATION RESULTS FOR THE 2D CONTOURING ACCURACY COMPENSATING SYSTEM

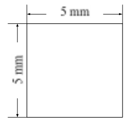
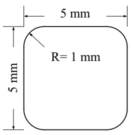
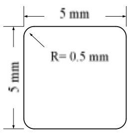
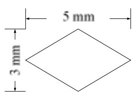
Command path	Feed rate (mm/min)	2D contouring accuracy compensating system		***Heidenhain*** Grid Encoder	
		X-axis error (µm)	Y-axis error (µm)	X-axis error (µm)	Y-axis error (µm)
	1000	88.3	87.6	89.2	87.3
	2000	169.7	168.2	175.9	177.8
	3000	257.5	264.9	267.5	265.0
	4000	356.2	352.7	354.8	353.4
	5000	443.5	452.0	445.4	444.5
	6000	536.8	530.8	533.7	530.8
	1000	11.7	14.3	17.3	13.8
	2000	83.6	61.3	62.2	59.3
	3000	130.6	132.3	127.7	128.8
	4000	199.8	206.2	204.9	205.4
	5000	276.9	259.3	262.2	265.0
	6000	295.4	292.9	288.1	289.5
	1000	34.5	32.3	29.4	30.8
	2000	104.7	97.3	100.8	104.0
	3000	142.1	141.3	144.2	143.9
	4000	177.5	168.3	169.5	169.7
	5000	199.6	194.5	195.4	194.9
	6000	222.2	227.4	222.5	220.1
	1000	152.5	89.6	153.7	89.1
	2000	305.5	183.5	309.0	180.0
	3000	456.5	278.7	455.1	271.7
	4000	618.1	364.7	612.4	362.4
	5000	768.4	450.4	767.6	449.5
	6000	920.8	538.3	923.2	536.7

C. Error compensation for the contouring test

Modifying the original NC code is used to compensate the contouring error in the 2D contouring accuracy compensating system. The suitable space position in the new path depended on the compensation table. The CNC setup block of the developed interface is used to connect with CNC controller.

In this experiment, the smooth function of the controller is keep turn on. The feed rate of verification test is set up at high-speed 6000 mm/min. Results show the improvement accuracy of 2D contouring accuracy compensating system is over 80% at high-speed feed rate. Table. II shows the compensation results for the 2D contouring accuracy compensating system.

TABLE II
COMPENSATION RESULTS FOR THE 2D CONTOURING ACCURACY COMPENSATING SYSTEM AT HIGHS-SPEED FEED RATE 6000 MM/MIN

Command path	Before compensation		After compensation		Improve accuracy	
	X-axis (µm)	Y-axis (µm)	X-axis (µm)	Y-axis (µm)	X-axis (%)	Y-axis (%)
	536.8	530.8	80.6	81.6	84.90	84.63
	295.4	292.9	53.9	53.2	81.29	81.62
	222.2	227.4	13.3	12.5	94.02	94.32
	920.8	538.3	11.8	24.8	98.72	95.38

IV. CONCLUSION

In this study, a novel 2D contouring accuracy compensating system has been developed. This system breaks through the bottleneck of small-working-range high-speed contouring test systems and provides a proper machine tool measurement facility, especially for processing small workpieces. This developed measurement system has the following features.

- It breaks the limits of the traditional measurement systems that measured only one axis geometric error at a time.
- It can be used to obtain high-accuracy high-repeatability measurement results. The contouring accuracy will attain to ±1.5 µm by using the compensating system. The stability of the PSD was about 2.5 µm at 30 minutes.

- The system employed a PSD and laser diode. As the measurement range was small, the setting error can be decreased to lowest value without affecting measurement accuracy.
- The system structure can be applied widely; it can measure not only the dynamic performance of a CNC machine tool but also the dynamic performance of most linear machine tool tables.
- The system is easy to set up, and the time for adjustment and measurement is short.

In the present paper, the error compensation methods have been established, which are suitable for the 2D command contouring tests respectively. Verified by the high-speed contouring error compensation experiment, the compensation result was satisfactory and could decrease the contouring test error significantly.

Acknowledgment

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