Perpendicularity errors calibration of rotation axis with linear axis using laser tracker

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Keywords: perpendicularity error; calibration; laser tracker;

Abstracts: As the perpendicularity errors between the rotation axis and linear axis have large influence the accuracy of the large gantry machine tool. A method for perpendicularity errors calibration of five-axis gantry machine tool was proposed. A Leica laser tracker was used to collect the error components values for its faster inspection, highly reliable and easy to set up. The error components were identified through least square estimation arithmatic with Metrolog software. The perpendicularity errors between the rotation axis and linear axis were obtained through the fitting center of two following circle and linear axis. The measurement results achieved by the proposed method showed that the perpendicularity was well according with the design requirements.

1. Introduction

Today, with the rapid developing of aerospace or automobile industries, large span gantry machine center are demanding increasingly for the complexity of surfaces in turbine blade or car body manufactured. As for multi-axis machine centers, the accuracy and precision was determined mainly by the geometrical capabilities of machine tools. Geometrical accuracy was the critical limitations in determining the product quality. As for large five-axis gantry machine tool, the perpendicularity errors between the rotation axis and linear axis have great influenced on the accuracy. Calibration was necessary because of these errors are enlarged by the Abbe offset. The result is the position of the tool tip shifted from the nominal position. So machine tools must be calibrated before operation, which can verify a competent geometrical property and then they can offer substantial benefit to a wide range of applications with high quality and better reliability. Now the machine tool factories all adopt the error compensation method to increase the precision of machining center. Calibrating these errors with measuring devices are an important step for error compensation. The calibration result was one of the decisive factors on the machining tolerances that can be achieved by the machine tool.

According to the calibration procedure of machine tool, appropriate test methods and instruments are the precondition of the machine tool calibrating. The procedures of calibration were divided to measurement, error parameter identification, error compensation. The objectives of calibration were realizing the error parameters identification and errors correction based on the process of measuring data. Considerable works have been done to calibrate machine tool accuracy in the past. But the perpendicularity errors of the rotation axis with linear axis are seldom researched in the recent years, but most work were geometric errors such for position error, straightness. A rigid body kinematic was used to establish a general methodology of error model by Donmeztal. Kiriden and Ferrera used a conventional n order polynomial equation to build the errors model of a machine tool. They supposed that the model was a function according to the positions of each axis. The error calibration methods can be categorized into two types: direct and indirect ways. The direct method also called parametric method which was based on measuring each component error independently. As for the parametric error modeling method, a series of links connected by joints is simplified for machine tool. By using inverse kinematics analysis method, the errors of components at a specific position can be identified. Each component' error was measured by conventional equipment such as laser interferometer and electronic level. The indirect method was realized by measuring errors with some type of artifacts or kinematic reference standards, such as step gage, a ball bar, etc, and estimating component errors based on the inverse kinematic analysis. Bryain first introduced the double ball bar(DBB) method to assess the machine accuracy in volumetric workspace. Ball bar can directly used to measure the machine tool's deviations from the nominal circuit trajectory and then analyze the circular trace' results to estimate errors such as backlash, reversal spikes, cyclic error and servo mismatch. Because a laser tracker can track the target and measure the position in three dimensions, errors can be measured in any machining direction as long as the laser beam was not blocked. The calibration was fast and easy to perform. Now laser trackers are widely used in dimensional measurement of large objects, position accuracy of machine tools and CMM industrial, assemble of objects one to another. In this paper, laser tracker was chose to calibration the perpendicularity errors of the rotation axis with linear axis. The calibrating machine tool in this paper was a Posdein five-axis Gantry High speed machine tool [1, 2, 3, 4].

2. Kinematic sketch of the five-axis gantry machine tool

Equipping two extra rotary axes and motorized spindle, Five-axis machine tool can obtain higher metal cutting rate, higher surface quality and low cutting time compared with three axis machine tool. In this project, a five-axis large gantry machine tool was used to research. The test machine tool is a five-axis gantry type machine tool with a workspace volume of 10m×3.0m×2.5m. It has five degrees of freedom: three translational motions(X,Y,Z) and two rotational motions(A,C). The translational axes which consisting of two rails, a bridge, a mast and a carriage, used to control the position of the tool. At the end of mast with two rotational axes determines the orientation of the tool. A block scheme of a typical five-axis machine tool was shown in Fig1. The machine tool used in this paper has a spindle tilt-rotary type configuration and was capable of simultaneous movement in three translational and two rotational axes. So it was well suited for providing precisely access to large modules or dies components, extraordinary in the aerospace industry. There are eight coordinate systems from CS0 to CS7 attached to different movement elements of the five-axis gantry machine tool [6].

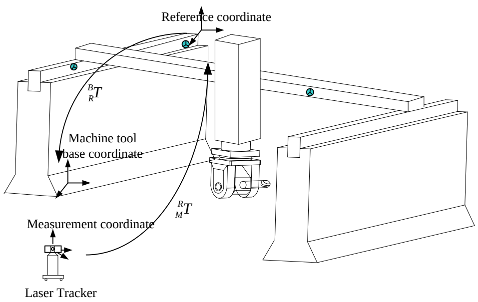

Fig.1 The scheme of the five-axis gantry machine tool

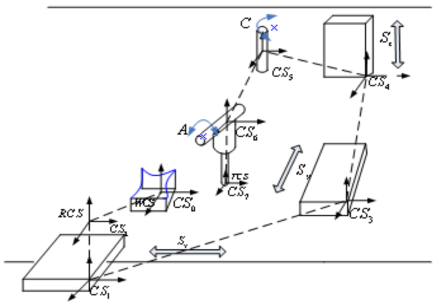

Fig.2 The coordinate scheme of the five-axis gantry machine tool[6]

The machine tool coordinate frame was CS0 and the local coordinate frames CS1~CS7 are set up on X axis, Y axis, Z axis, C axis, A axis, spindle and tool respectively. The symbols CS0 to CS7 represent the links of the kinematic chain. A joint is connected with two adjacent elements to promote relative motions between two elements. When assign the type of joint, translational or rotational and the machine workbench position in the chain, the machine tool configuration was established. The kinematic chain of the five axis machine tool was shown in Fig.2.

3. Perpendicularity error mapping by a laser tracker

Geometrical errors originated from the manufacturing stage or assembly defects of elements from machine tools and gravity loading of components. These errors included link length error, angular error, straightness error, squareness error, perpendicularity error and zero shift error of axis. However, the measurement of rotary axis errors was difficult and time-consuming process especially for the perpendicularity error. For detailed measurement of the perpendicularity error for the machine tool, a laser tracker Leica LTD 840 was employed here to gather the error data based on the error model. The principle of laser tracker was combination of the technology of laser interferometer which measure relative distance and optical encoders to measure azimuth and elevation of a beam-steering mirror. The measuring accuracy of the LTD840 is pointed to ± 10 um for testing static target. A typical work principle of a laser tracker was showed in Fig.3. First, the laser tracker was placed on a corner of the operation room and then the reflector mirror was mounted on the spindle which was inserted in tool center point. The testing laser beam emitted from the laser tracker aimed on the reflector mirror with a hand joystick. Then the spindle of the machine tool moved to a new point. Simultaneously the laser beam was reflected to the laser tracker and the point position was calculated through distance, azimuth and elevation. At last the position of any given points in the space can be accurately identified [7]. The measuring process with a laser tracker was shown in Fig.4.

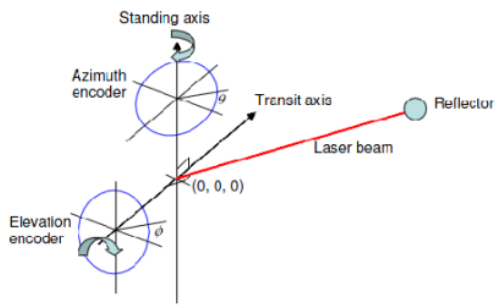

Fig.3 A typical work principle of a laser tracker [8]

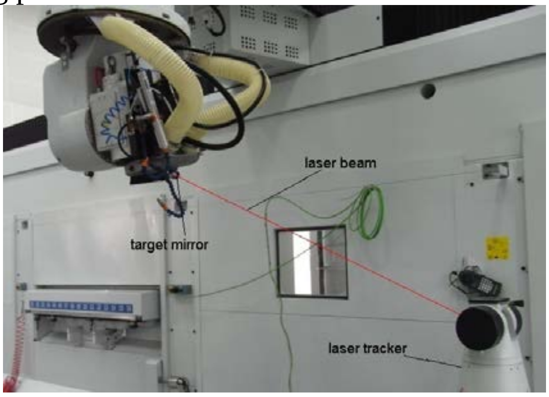

Fig.4 Error measurement setup of a laser tracker

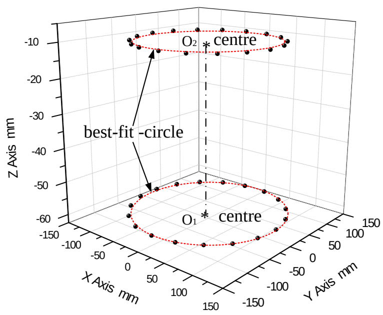

Fig 5 The central line calculation of the C-axis

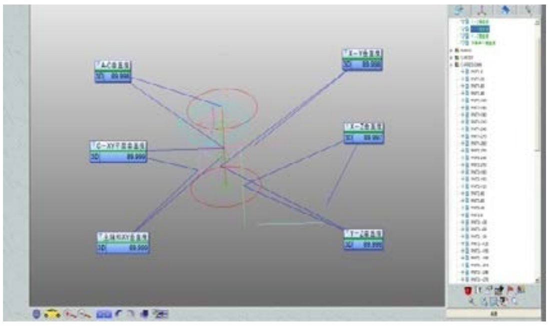

Fig.6 The Perpendicularity between C and XY plane

There are six perpendicularity error components for this five-axis gantry machine tool [5]. Multiple measuring steps were taken to get the error data. Given the Perpendicularity between C axis and XY plane as example, first a point on the C axis was choose and the reflector was mounted on this point. The laser tracker recorded the initial position of the point. And then the C axis rotated for 360^0 and stopped every 5^0 in order that the laser tracker can calculate the positions of these points in the whole working space. Next the C axis moved 800mm along the Z axis direction and the procedure keep. The above measuring procedure continued ten times. At last, the circuit trajectory of C axis was presented which was fitted by a least square estimation and the central line of C axis was get with Metrolog software. The measurement results were showed in Fig.5 and Fig 6.

4. Parameter identification of error components

The machine tool was measured at different nominal positions. The linear equation AX=b was established to calculate the errors. Where vector X contained the coefficient of error component model, b was the vector of laser tracker measuring results and A was the matrix here the laser tracker measurements were taken. Therefore a least square estimation method was used to estimate the coefficients of the error compensation model. The perpendicularity accuracy results were showed in the Table 1.

Table1 The perpendicularity accuracy results

number	item	Measurement data
CG1110	Perpendicularity between Y-Z	0.016 / 500
CG1111	Perpendicularity between X-Y	0.016 / 500
	Perpendicularity between X-Z	0.027 / 500
CG1112	Perpendicularity between C and XY plane	0.005 / 300
CG1113	Perpendicularity between B axis and C axis	0.022 / 300
CG1122	Perpendicularity between spindle and B axis	0.004 / 80
CG0340	Perpendicularity between spindle and X、Y axis	0.005 / 300

5. SUMMARY

In this paper, a scientific approach was put forward to fast calibrate the perpendicularity errors of a five-axis gantry machine tool with laser tracker. This experiment results have performed the geometrical perpendicularity error inspection in five hours and identified the error components. The validity of the calibration way with laser tracker was demonstrated. However dynamic errors were not considered in this paper for the complex in the error modeling. So a relation object between static and dynamic errors for multi-axis machine tools should be established for future research.

Acknowledgment

The work was supported by the high educational research Foundation of Anhui province. (KJ2016A885).

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