A new method for directly measuring the position errors of a three-axis machine. Part 1: theory

B. Li · X. Y. Mao · H. M. Shi · H. Q. Liu · X. Li · P. G. Li

Received: 27 April 2006 / Accepted: 4 September 2006 / Published online: 25 October 2006
© Springer-Verlag London Limited 2006

Abstract This paper presents a measurement method and instrument to measure position changes in a three-axis machine workspace. The proposed instrument, named 3D step gauge, includes two parts. One is composed of three LVDTs and installed in the main spindle. The other is a plate that is fixed on the worktable. Many triangular pyramids are distributed on the plate. Each pyramid profile plane is the basic measurement plane for the LVDTs. When the spindle moves relative to the plate, the LVDTs’ tip ends slide on the pyramid profile planes. From the datum measured by the LVDTs, the differential position changes of the spindle can be obtained by the pyramid’s constructional parameters. In addition, the error effect analysis is used to investigate the accuracy of the method with respect to the factor of the device constructional parameters. In addition, the error effect analysis is used to investigate the accuracy of the method with respect to the factor of the device constructional parameters. Part 1 of this paper gives the basic theory of measuring the differential position changes in the multi-axis machine workspace. Part 2 gives the application of this theory and so the position error in the multi-axis machine workspace can be directly measured. This proposed method and the instrument have been tested using an actual machine tool. The measurement results show good repeatability and high accuracy.

Keywords Machine tool · Differential position changes · Three-dimensional measurement · Measurement device

1 Introduction

The basic function of the numerical control (NC) machine tools is to realize the accurate relative motion and the accurate position according to the NC program. The motion accuracy and positioning accuracy (so-called geometric accuracy) are the most important performance indexes of the NC device [1], and those geometric errors mainly include the errors induced by the manufacture, assembly, and component wear. To reduce these errors by the error compensation, the error measurement instrument is one of the most important techniques [2]. At present, the instruments used for identifying the single-axis position accuracy involve step gauge, linear grating, and laser interferometer [3, 4]. The instruments used for 2D (plane) position accuracy involve the KGM (Kreuz Gitter Meßsystem in German) and DBB (the double ball bar system) [5–7]. The KGM has limited measurement range and the DBB can only measure in the radius direction. All the devices above cannot measure the position error in the multi-axis machine workspace. Even having known the 2D position error in some plane, we cannot consider that we have known the position error in the multi-axis machine workspace. Nevertheless, the effectiveness of a volumetric error compensation scheme relies highly on the sufficient and reliable information of the measured position error. To get these volumetric errors directly, we must use the special instrument. At present, several devices and methods have been developed to directly measure the position error [8–10]. Ziegert developed an instrument called a laser ball bar. To obtain the volume error, three measurements must be taken at three reference points. Shih-Ming Wang et al. used the developed ball-bars to directly identify the position errors in machine tool workspace. However, these special instruments are very complicated and the calibration progress is a lengthy, time-consuming process [11].
This paper presents a new measurement method for the point-to-point measurement of differential position changes in a three-axis workspace. The proposed instrument includes two parts. One is composed of three LVDTs and installed in the main spindle. The other is a plate that is fixed on the worktable. When the spindle moves, the LVDTs measure the pyramid profile planes’ relative position changes in the Z-direction. From the datum measured by the LVDTs, the differential position changes of the spindle can be obtained by the pyramid’s constructional parameters. In part I of this paper, we present the basic theory of measuring the differential position changes in the multi-axis machine workspace. In part II, the procedures of applying this device to measure the position error are expressed in detail. In Section 2 of this part, the basic measurement theory about the position changes in the multi-axis machine workspace. To make this theory more comprehensible, just one LVDT and one profile plane of the pyramid are used to introduce the basic theory. Then the measurement theory about the position changes is introduced in detail.

The proposed instrument uses the pyramid’s three profile planes and three LVDTs to get the differential position changes in the multi-axis machine workspace. To make this theory more comprehensible, just one LVDT and one profile plane of the pyramid are used to introduce the basic theory. Then the measurement theory about the position changes is introduced in detail.

2 Basic theory

Figure 1 shows the distance measurement with one profile plane, A, and one LVDT, M. Point P in the x-z plane is the projection of point O on plane, A. Point B can be obtained by moving the point O along the path OC and CB on the plane A. These two paths are parallel to x-z plane and y-z plane, respectively. Then if a vertical LVDT label by M travels from the start point P along the path POCB to the end point B, the position changes of the LVDT, (Δx, Δy, Δz), can be expressed as:

\[ \delta = \Delta x \cdot A_x + \Delta y \cdot A_y + \Delta z \]  \hspace{1cm} (1)

where \( \delta \) represents the measured differential length change of the tip end of the LVDT. \( A_x = \tan \beta, A_y = \tan \alpha \), \( \beta \) represents the angle between OC and the x-y plane, \( \alpha \) represents the angle between BC and the x-y plane. \( A_x \) and \( A_y \) can be calibrated as follows:

\[ A_x = \frac{\delta_x}{\Delta y} \cdot T \]

\[ A_y = \frac{\delta_y}{\Delta y} \cdot T \]

\[ A_z = \frac{\delta_z}{\Delta z} \cdot T \]

where \( \Delta x' \) and \( \Delta y' \) are the calibrated distances in the \( x \) and \( y \) direction, respectively. \( \delta_x \) and \( \delta_y \) are three LVDTs measurement datum from the side face in the \( x \) and \( y \) direction, respectively.

From Eq. (1) this position changes, \((\Delta x, \Delta y, \Delta z)\), cannot be determined and two other similar measurements are required. Based on the three measurements, the following equations can be obtained:

\[
\begin{bmatrix}
\frac{\delta_{1x}}{\Delta y'} & \frac{\delta_{1y}}{\Delta y'} & 1 \\
\frac{\delta_{2x}}{\Delta y'} & \frac{\delta_{2y}}{\Delta y'} & 1 \\
\frac{\delta_{3x}}{\Delta y'} & \frac{\delta_{3y}}{\Delta y'} & 1 \\
\end{bmatrix}
\begin{bmatrix}
\Delta x \\
\Delta y \\
\Delta z \\
\end{bmatrix}
= \begin{bmatrix}
\delta_1 \\
\delta_2 \\
\delta_3 \\
\end{bmatrix}
\]  \hspace{1cm} (2)

or

\[ TX = \delta \]  \hspace{1cm} (3)

where \( \Delta x' \) and \( \Delta y' \) are the calibrated distances in the \( x \) and \( y \) direction, respectively. \( \delta_x \) and \( \delta_y \) (i=1,2,3) are three LVDTs measurement datum from the side face \( A, B \) and \( C \) of the triangular pyramid in the \( x \) and \( y \) direction, respectively. \( \delta \) represents the measured distance change vector. \( X \) represents the position change vector. \( T \) represents the position matrix in Eq. (2).

In the above derivation, the coordinates used in the equations are expressed with respect to the machine’s