Identification of Geometrical Error on Multi-Axis Machine Tools Based on a Laser Tracker

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Abstract. The geometrical errors are affected by many factors for a multi-axis machine tool, such as materials, manufacturing, assembly, measurement, control, and environmental. The geometrical error will eventually be reflected in the accuracy of the workpiece; therefore, for each part of the machine tool, the measurement of geometric error is essential. Most geometrical errors are measured separately for each axis. The single geometrical error measurement method is time-consuming. The multiple geometrical error measurement methods have some limitations based on different instruments. Laser tracker based on GPS (Global Positioning System) positioning principle can measure the dimensional coordinate. Thus, the laser tracker measured geometrical errors in high efficiency, high precision, wide range. This paper introduces the method of measuring the multi-axis machine geometrical error by using a laser tracker with a 1280mm×1280mm×240mm range and compares the measurement result from the traditional method. The results show the laser tracker method has high measurement accuracy, and rapid measurement and compensation of geometrical errors are achievable on a large-stroke machine tools.

1. Introduction

With the rapid development of measurement technology, three-dimensional dynamic tracking measurement technology is developing step by step. Laser tracking measurement is widely used because of its high speed, wide range, high precision, and portable belt. At present, the commercial laser tracker has Leica, Faro, Hexagon, and API [1].

The laser tracker enables rapid measurement of a machine tool. There are three main categories: time-sharing station method, multi-station method, single station method[2].

For the single station method, the rotary axes and linear axes are calibrated by a laser tracker. Etalon laser tracker on a five-axis linkage NC machine [3]. Acosta presents a program that uses a self-centering sensor and a laser tracker to verify the identification of independent position geometry errors in rotating index tables [4]. The tracker based on the polar coordinating system measurement principle will enlarge the measurement error by the angle measurement. The robotic drilling and machining are real-time compensated by one laser tracker [5]. To improve the measurement accuracy of laser tracker, some scholars have proposed multi-station of a single laser tracker, the multi-station method applies multiple laser trackers to obtain the distance from the target by placing multiple laser trackers at different measurement positions, and the actual position coordinate of the measurement target are solved by the
position constraint relationship. Wang et al [6, 7] proposed the theory of time-sharing and multi-station measurement, according to the principle of the global positioning system, using laser trackers to measure the target point in different locations continuously. Furthermore, the theory of the laser tracker based on the multi-lateration method are also proposed in [8]. Moreover, Wang et al. [9] also proposed a new method for separating geometric errors of the rotation axis through a laser tracker. Aguado studied the quadrilateral, trilateral measurement, least squares adjustment and different self-calibration procedures measurement of the laser tracker, as well as the range and applicability of each method relative to the laser tracker's measurement noise [10]. In order to reduce the measurement uncertainty of the laser tracker, it is recommended to use the Monte Carlo method to optimize the laser tracker configuration station for large parts with non-uniform temperature fields [11]. In order to develop an LT multi-station measurement coordinate measuring machine (CMM) uncertainty analysis method, a laser tracker is used to measure a CMM with a range of 300×200×300mm³ [12].

Because the multi-station measurement method only obtains the distance, and the accuracy of the multi-station measurement method is superior to that of single laser tracker. The main advantage is that the laser tracker can directly measure the position of measurement points in the workspace, and has high measurement efficiency. For the measurement of laser tracker, the difficulty of current research is the distribution of measurement points and stations of laser tracker, and the identification method of geometric error combined with volumetric error model to reduce the measurement error impact on measurement results.

2. Principle

The measurement principle of laser tracker (LT) is shown in Figure 1. During the measurement, the reflector is installed on the end actuator of the machine tool and moves along the preset measurement path together with the end actuator. LT placed in different positions will track the position of the reflector, and the distance $L_{i,j}$ between the reflector and the datum sphere is measured. In order to accurately measure the distance $L_{i,j}$ with high accuracy, the end effector will stop at each measurement point $p_j(x_j,y_j,z_j)$.

![Figure 1. Measurement principle of laser tracker.](image)

As shown in figure 1, the machine coordinate system is XYZ. Therefore, the LT coordinate is the LT$(u_i,w_i,h_i)$. The letter $i$ is the serial number of the LT, and the letter $j$ is the serial number of the measuring point. Thereupon, the function among the LT, $p_j$ and the $L_{i,j}$ is:

$$
\begin{align*}
(u_i - x_j)^2 + (w_i - y_j)^2 + (h_i - z_j)^2 &= L_{i,j}^2 \\
L_{i,j} &= L_{i,0} + \Delta L_j 
\end{align*}
$$

where the $L_{i,0}$ is the distance from the first measuring point, the $\Delta L_j$ is the distance variation relative to the first measuring point. The nominal coordinates $p_j(x_j,y_j,z_j)$ ($j=1,2,3,\ldots,n$) of the measurement point are known, the $\Delta L_j$ is measured by LT, and the coordinates LT$(u_i,w_i,h_i)$($i=1,2,3,4$) is given by:
Equation (2) is obtained by substituting the nominal coordinates \( p_j \) into equation (1) and using the least square method. Due to the high price of commercial laser trackers, multiple laser trackers increase the measurement costs. In order to reduce the measurement costs, a multi-station time-sharing measurement method based on laser trackers is proposed. In addition, the laser tracker is used to repeatedly measure the distribution of the measuring point at four different positions. The multi-station time-sharing measurement process places higher demands on the repeatability of the machine tool. Hence in this article, the geometric error of machine tool is measured by the multi-station time-sharing method. Equation (1) can be written in the following notation:

\[
\sum_{j=1}^{n} u_j^2 - 2u_jx_j + x_j^2 + w_j^2 - 2w_jy_j + y_j^2 + h_j^2 - 2h_jz_j + z_j^2 - L_{ij}^2 = 0
\]

The position coordinates of the laser tracker \( LT_i(u_i, w_i, h_i) \) and the coordinates of the measurement points are brought into equation (3) to obtain:

\[
\mathbf{KP}_j = \mathbf{D}_j
\]

where

\[
\begin{bmatrix}
  u_2 - u_1 \\
  w_2 - w_1 \\
  h_2 - h_1 \\
  u_3 - u_1 \\
  w_3 - w_1 \\
  h_3 - h_1 \\
  u_4 - u_1 \\
  w_4 - w_1 \\
  h_4 - h_1
\end{bmatrix}
\]

\[
\begin{bmatrix}
  x_j \\
  y_j \\
  z_j
\end{bmatrix}
\]

\[
\begin{bmatrix}
  \frac{1}{2} \sum_{j=1}^{n} (x_j^2 + y_j^2 + z_j^2 - L_{ij}^2)
\end{bmatrix}
\]

The matrix \( \mathbf{K} \) is related to the coordinates of the \( LT_i \), and the coordinates are obtained by equation (2). The matrix \( \mathbf{D}_j \) is related to the coordinates of the LT and the distance \( L_{ij} \). When the rank of matrix \( \mathbf{K} \) is equal to 3, there is a unique solution to the coordinate of measurement points \( \mathbf{P}_j \).

3. Experiment

The use of LT to measure the geometrical error is applied on the multi-axis machine tool with a 1280mm×1280mm×240mm range. Firstly, the measurement path is set according to the positions of four laser trackers to prevent measurement interference as shown in figure 2. To obtain high accuracy geometric error measurement results, the \( h_i \) of the LT is a different value. The threshold standing specifies the maximum length change which may not be exceeded to recognize a standstill, therefore, the threshold standing is usually set as 5μm in this paper. The timeout specifies the time to recognize a standstill, therefore, the distance \( L_{ij} \) is measured more accurately when the timeout is bigger. As shown in figure 2, the geometric error of the machine tool has been measured 2 times. Each measurement takes about 230 minutes. The measurement result is shown in Figure 3.

The measurement process is based on the FRB (Full Rigid Body) model, and the output result is the geometric error of the X(YZ) axis. Every axis has six geometrical errors include the positioning error, two straightness, roll, yaw, pitch. As shown in figure 3(a), the two measurements are in good agreement; the positioning error of axis X is up to about 80 μm, the straightness of axis X is less than 6 μm. The
The yaw of axis X has a significant repeatability error from position -400mm to 200mm. As shown in figure 3(b), the positioning and the roll of axis Y are extensive and reach about 40 μm and 40 arcsecs. The straightness of axis Y is less than 4 μm. Although, as shown in figure 3(c), the two measurements are in good agreement, the positioning of axis Z is large and reaches to 180 μm. The yaw of axis Z is less than 3 arcsecs.

Figure 2. Measurement principle of laser tracker.

(a) 6 geometric errors of axis X

(b) 6 geometric errors of axis Y
4. Conclusions
The laser tracker can easily measure all the geometrical errors of the multi-axis machine for high accuracy and rapid measurement. In addition, the laser tracker measurement has good repeatability. Laser trackers can measure 21 geometrical errors in the machine tool for 1 meter in 230 minutes. The results show that the three-axis positioning errors of the machine are large, the straightness of axis X/Y is small. With the development of the precision machine tools and the measurement industry, the tracker has become an ideal instrument for calibrating CNC (computer numerical control) equipment.

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