Volumetric Error Identification and Measured Data Correction for On-Machine Measurement and Inspection Systems

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Abstract: Needs for higher accuracy on machined components are always on the rise. Inspection of parts in situ has the significant advantage to rapidly rework the part based upon inspection results. Objectives of this research are quick calibration of volumetric errors of machine tools and proper assessment of machined shapes distorted by machine tool error sources by correction of measured data. In order to realize the objectives a three-dimensional reference artifact is invented and fabricated. Measurement results on the machine tool can be corrected according to the identified volumetric error map. The accuracy of the proposed method is verified by comparing the identified volumetric error map with the diagonal test results of ANSI/ASME B.5 using a laser interferometer.

Keywords: Invar, Measured data correction, On-machine measurement and inspection systems, Reference artifact, Touch trigger probe, Volumetric error identification.

1. Introduction

In the conventional quality control system, a workpiece machined on a machining center requires to be moved to a coordinate measuring machine (CMM) for checking its dimensional accuracy. After developing touch trigger probes, on-machine probing has found a broad range of applications where it is vital to automated production processes. The inspection of parts in situ has the significant advantage of possibly being able to immediately rework the part based upon the inspection results. On-machine measurement and inspection systems (OMMIS) can allow manufacturers in many industries to deliver precise components, minimize scraps, and maximize productivity.[1-3]

The use of a machine tool as a CMM has some significant liabilities that need to be carefully considered before employing this measurement technique. In particular, the on-machine inspection process is oblivious to all error sources common to both the production and inspection processes. For example, if the machine tool’s axes are out-of-square, the cutting process will produce an out-of-square part. The inspection process, using the same out-of-square axes, will consequently measure the part to be perfect. The key component of the OMMIS, therefore, is a proper assessment of machined shape by correction of measured data that is distorted by machine tool error sources. For this purpose, a method for quick and accurate assessment of dominant error sources of the machine tool is needed at the moment of measurement.

If a machine tool is to be made use of a measuring system like a CMM, calibration of machine tool errors with reference artifacts such as step gauges, ring gauges, hole and ball plates, and so on are required. However, above mentioned artifacts are one or two dimensional gauges, and therefore more than two setups are required for identification of volumetric errors. Fixed head type probes that are mainly used for machine tools cannot access to the artifacts.

In this paper, a three-dimensional reference artifact is invented and fabricated. A volumetric error identification method is also proposed for quick and accurate assessment of machine tool errors by direct measurement of the artifact on the machine tool. Measurement results are accurately corrected according to the identified volumetric error map. Accuracy of the proposed method is confirmed by comparing the identified volumetric error map with the diagonal test of ANSI/ASME B.5 using a laser interferometer.

2. Simple Volumetric Error Model

A correction process of measured data on the machine tool requires a volumetric error model that can calculate correction amounts at measured positions. Previous works for volumetric error models mainly focus on accurate prediction of volumetric errors that will arise during the whole machining processes.[4-5] These models include complex model parameters. Experiments required for the parameter estimations are impossible jobs or difficult and time-consuming processes.

The on-machine inspection technique aims to use a machine tool as a measuring machine. It can be used to assure workpiece accuracy for a moment on the way of the machining processes. Since the machine
conditions are not changed drastically during the short measurement time and thermal errors have slowly time varying characteristics, a simple volumetric error model that contains dominant error sources of the machine tool is more effective for correction of measured data rather than the complex prediction model. A simple volumetric error model is developed as follows:

\[
dX = \delta_x(x) + \sum_{i=1}^d \Delta \alpha_i + P_x + PZXz \\
dY = \delta_y(y) + \sum_{i=1}^d \Delta \beta_i + P_y + PXYx - PYZz \\
dZ = \delta_z(z) + \sum_{i=1}^d \Delta \gamma_i + P_z
\]  

(1)

where \(dX\), \(dY\) and \(dZ\) are components of volumetric errors according to working coordinates of a machine tool, \(x\), \(y\) and \(z\). \(\delta_x(x)\), \(\delta_y(y)\) and \(\delta_z(z)\) are positioning errors along \(X\)-, \(Y\)- and \(Z\)-Axis respectively. \(\sum \Delta \alpha_i\), \(\sum \Delta \beta_i\) and \(\sum \Delta \gamma_i\) are thermal drifts of the workspace origin of machines in direction of \(X\)-, \(Y\)- and \(Z\)-Axis respectively. \(P_x\), \(P_y\) and \(P_z\) are thermal expansions, and \(PXY\), \(PYZ\) and \(PZX\) are squareness errors between axis pairs due to the thermal distortion. This model can be easily constructed by the error synthesis method.[2,5]

3. Error Identification

For quick identification of the model parameters, \(PXY\), \(PYZ\), \(PZX\), \(\sum \Delta \alpha_i\), \(\sum \Delta \beta_i\), \(\sum \Delta \gamma_i\), \(P_x\), \(P_y\) and \(P_z\), a three-dimensional reference artifact is designed and fabricated, and then measured on machine tool using a touch trigger probe. Identification of positioning errors will not considered in this paper, because these errors can be easily calibrated using equipments such as a laser interferometer or a step gauge, and then automatically compensated for by machine controllers.

Fig. 1 shows the reference artifact composed of a square, a metrology block and two columns. The metrology block is fixed on the table close to machine’s workspace origin. The square and two columns can be quickly installed on the table without interfering with the workpiece machined when the on-machine measurement is required. The reference artifact is calibrated by a CMM, and then referenced in the measurement on the machine tool. The artifact is made of invar – a material with an extremely low thermal expansion coefficient. So we can minimize thermal variation of the artifact.

3.1 Identification of \(PXY\), \(PYZ\), \(PZX\)

A square can be installed on the machine table in different posture according to the parameters to be identified. Fig. 2 shows schematic diagrams to calibrate squareness errors, \(PXY\), \(PYZ\), \(PZX\). To identify the parameter \(PXY\) when \(X\)- and \(Y\)-Axis of the machine tool have an inclination of \(\alpha_z\) and \(\beta_z\) respectively, and also the square has an inclination angles of \(\delta_1\) and \(\delta_2\) due to misalignment, four measurement points, \(A(x_1, y_1, z_1)\), \(B(x_2, y_2, z_2)\), \(C(x_3, y_3, z_3)\), \(D(x_4, y_4, z_4)\), have to be successively measured from the square lying on a \(X\)-\(Y\) plane. In this case, the stylus tip is moved along \(X\)- and \(Y\)’-Axis, respectively. Real
contact points become $A'(a_1, y'_1, z), B'(a_2, y'_2, z), C'(x'_3, b_3, z)$ and $D'(x'_4, b_4, z)$. The squareness error between X- and Y-Axis, $P_{XY}$, can be derived from geometric relationships between the square and the stylus tip, and then expressed as follows:

$$P_{XY} = \beta - \alpha = \frac{x'_2 - x'_1}{b_2 - b_1} + \frac{y'_1 - y'_2}{a_2 - a_1} + (\delta_2 - \delta_1)$$  \hspace{1cm} (2)

where $\delta_2 - \delta_1$ is the error of the square. It was calibrated on a CMM.

In a similar way, $P_{YZ}$ and $P_{ZX}$ can be obtained as eqs. (3)–(4) by assumption that Y- and Z-Axis of machine tool have an inclination of $\beta_x$ and $\gamma_x$, and X- and Z-Axis have an inclination of $\alpha_y$ and $\gamma_y$ respectively as shown in Fig. 2.

$$P_{YZ} = \beta_x - \gamma_x = \frac{z'_1 - z'_2}{b_2 - b_1} - \frac{y'_1 - y'_2}{a_2 - a_1} + (\delta_2 - \delta_1)$$  \hspace{1cm} (3)

$$P_{ZX} = \alpha_y - \gamma_y = \frac{z'_1 - z'_2}{b_2 - b_1} + \frac{x'_1 - x'_2}{c_2 - c_1} + (\delta_2 - \delta_1)$$  \hspace{1cm} (4)

Therefore, substituting both the measured values of the square on the machine tool and the calibrated value by a CMM into the eqs. (2)–(4), the squareness errors between axis pairs can be calibrated.

### 3.2 Identification of $\sum \Delta a_i, \sum \Delta b_i, \sum \Delta c_i$

Fig. 3 shows a schematic diagram for coordinate frame acquisition established on the metrology block for thermal drifts identification. Fifteen points (five points per each plane) are measured and then transformed to three plane equations as follows:

$$i_x + j_y + k_z = l_i$$

$$i_x + j_y + k_z = l_i$$

$$i_x + j_y + k_z = l_i$$  \hspace{1cm} (5)

where $(i, j, k)_i, i = 1, 2, 3$ is a unit normal vector to the $i^{th}$ plane, and $l_i$ is the distance of the $i^{th}$ plane from the workspace origin of machine. The workpiece coordinate origin, $O_W$, is the intersection of the primary, secondary and tertiary planes, and can be determined as follows:

$$\Delta P = \Delta P'_3 - \Delta P'_2 = [\Delta P_x, \Delta P_y, \Delta P_z]'$$  \hspace{1cm} (8)

where $\Delta P_x, \Delta P_y$ and $\Delta P_z$ can be represented as volumetric error components like the eq. (1). However, the thermal drifts of the workspace origin of machine, $\sum \Delta a_i, \sum \Delta b_i, \sum \Delta c_i$, can be eliminated because the
position vector $\Delta P'_g$ is a difference between two column positions. Therefore, the thermal expansion of each axis, $P_1, P_2, P_3$, can be expressed as follows:

$$P_1 = (\Delta P_x - PZX z) / x$$
$$P_2 = (\Delta P_y - PXY x + PYZ z) / y$$
$$P_3 = \Delta P_z / z$$

(9)

Since the squareness errors due to the thermal distortion of each axis, $PXY, PYZ, PZX$, can be calibrated as described in section 3.1, the thermal expansion of each axis, $P_1, P_2, P_3$, can be identified by substituting the calibrated values into eq. (9).

4. Experiments

In order to verify the accuracy of the proposed method, the diagonal test of ANSI/ASME B.5 using a laser interferometer has been performed. After warming up the vertical machining center, the reference artifact is measured on the machine tool and the volumetric error map is constructed by substituting the identified model parameters into eq. (1). It takes about 6 minutes to measure the artifact. A software-based compensation system is implemented for the diagonal test, which can modify the current position based on the identified error map. Fig. 5 shows the result of the diagonal test. The positioning errors in diagonal direction have been reduced from 22μm to 10μm after compensation. And then, the machine tool is heated up by moving X-, Y-, and Z- Axis at 6m/min and rotating the spindle at 3000rpm at the same time to simulate the actual machining conditions that include the thermal interactions among error sources. The artifact is measured again and the model parameters are updated. The positioning errors in diagonal direction after the heating process have been reduced from 45μm to 10μm after compensation of volumetric errors based on the updated error map.

5. Conclusions

A method for a proper assessment of machined shape by correction of on-machine measured data has been studied. A simple volumetric error model that contains dominant error sources of the machine tool is adopted for correction of the measured data. A three-dimensional reference artifact is invented and fabricated to identify the model parameters through the process- intermittent measurement using a touch trigger probe. A volumetric error identification method is also proposed for the quick and accurate assessment of the present machine conditions by direct measurement of the artifact on the machine tool. The diagonal test of ANSI/ASME B.5 using a laser interferometer has confirmed the validity of the proposed method.

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