Enhancement of dimensional accuracy of micro features by applying parametric error compensation to the miniaturised machine tool

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Abstract: Imperfections in the miniaturised machine tool will affect dimensional accuracy of micro components. It is necessary to measure these errors and apply compensation to improve their performance. In the present work, parametric errors of a miniaturised vertical milling machine were measured using capacitance sensors and the data is analysed using computational geometric techniques. Kinematic model of micro machine is developed and the error compensation is applied. To investigate the effect of error compensation on the dimensional accuracy of components, experiments were conducted while the machine tool is operating under point to point (PTP) control and continuous control. Machined profiles before and after compensation were inspected using a CMM and found that the profiles machined after applying compensation had better dimensional accuracy. This is due to the improvement of tool positioning accuracy after compensation. The details of measurement, modelling, error compensation, experiments and the results are presented in this paper.

Keywords: micro machine; parametric errors; error compensation; computational geometric techniques; CGT.


Biographical notes: G.L. Samuel is currently an Assistant Professor at Department of Mechanical Engineering, Indian Institute of Technology Madras (IIT Madras). He received his PhD in Mechanical Engineering from IIT Madras. He has a post doctoral research experience of two years at Kyungpook National University, South Korea. His areas of interest are micro-machines, computer-aided design and manufacturing, measurements and computer-aided inspection, error compensation of machine tools and vision system.
1 Introduction

Miniaturation has become a trend in product design nowadays where in efforts are made to increase the utilisation of manufacturing equipment and systems to produce micro-scale components and products. This concept has revolutionised the manufacturing industry by changing the way machine, processes and materials are viewed. Micro machining became one of the most successful fields of engineering in the modern industry. Miniature components are increasingly needed for a wide range of application in the fields of aerospace, semi-conductor and electronics and communication industry, defence, optics, medical robotics, biotechnology and consumer products. The materials used for miniaturised parts include stainless steel, brass, aluminium and glass.

To manufacture miniature parts, the technologies available are the microelectronic fabrication techniques and ultra-precision conventional machining methods. However these techniques have some limitations, such as inability to handle wide range of materials, poor accuracy, high cost of equipment, etc. In order to manufacture more complex micro parts effectively, various micromachining technologies have been developed in recent years. Also miniaturised machine tools utilising the conventional machining techniques are becoming popular as they save energy and space. The micro mechanical systems have the advantage of increased productivity, efficiency, flexibility, high surface integrity, low cost and can use various materials including steel. As these miniaturised machine tools inherit the well known conventional CNC technology, it is easy to implement them in micro machining. Miniaturised machine tools/micro machines using ultra-precision conventional machining technique, offer high accuracy without the limitation of material type. This technology gained attention with the development of a miniaturised lathe for the manufacturing micro mechanical parts matching the micro size of the work piece by Lu and Yoneyama (1999).

Accurate positioning of tools is very important in miniaturised machine tools as the precision of machined parts depends on accuracy of position of the cutting tool relative to the part being machined. However, it is a technological challenge and expensive to completely eliminate errors in machine tools and to manufacture accurate machines. Many errors will be introduced during manufacturing, assembly and operation of the machine tools. Errors which considerably affect performance of a machine tool are thermal errors, force induced errors, controller errors, linear and rotary motion axis errors, assembly errors, parametric errors, etc. In miniaturised machine tools the accuracy is affected primarily by the parametric/geometric errors of the machine tool. These errors are caused by imperfect manufacturing, misalignment and structural element static deflection or wear or aging. These quasi-static errors account for about
70% of total errors in a machine tool and as such are a major focus of error compensation research. Traditional way to deal with these errors is to strengthen and improve machine tool element structure. However, it is noted that, no matter how well a machine is designed, there is a limit to the accuracy that could be achieved (Ramesh et al., 2000). Also, this approach involves a high degree of investment as machine costs rise exponentially with the level of accuracy demanded. In order to overcome these limitations, error compensation technique for machine tools has been introduced.

Huang and Ni (1995) assessed these errors effectively in order to enhance the accuracy of the system by error compensation technology. Yang et al. (1997) developed a real time error compensation system to reduce cutting force induced planar errors of a conventional two axis turning centre. A kinematic error model accounting for geometric and thermal errors in a three-axis CNC vertical machining centre is developed by Okafor and Ertekin (2000). Rahman et al. (2000) proposed methods for modelling, measurement and compensation of errors in multi axis machine tools. An efficient online error compensation scheme for multi-axis CNC machine was proposed based on shape function (Wang et al., 2002). A generalised geometric error model for five axis CNC machining centre was studied by Jha and Kumar (2003). Lei and Hsu (2002, 2003) developed a real time error compensation technique for five axis CNC machine tool using 3D probe ball and spherical test method.


Generally, the error models used for error compensation are identified using least square method (LSM). However, LSM does not effectively minimise the error in the machine tools. Also the results obtained from error compensation using LSM are unevenly distributed across the work piece (Tajbakhsh et al., 1997). It is also observed from literature, that only few attempts have been made to study error compensation in miniaturised machine tools and to improve the accuracy of the machined profiles. In the present work, measurement of geometric errors of a three axis miniaturised vertical machine tool (mVMT) is carried out using capacitance sensors. Straightness and squareness errors are determined by fitting a straight line to the profile of each axis based on computational geometric techniques (CGT). A mathematical model of the machine tool is derived to describe the relationship between different axes of the miniaturised machine tool. Parametric error compensation is applied to the motion of carriages, utilising machine tool model and estimated errors. A computer program is developed to apply compensation to the carriage movement during machining. Experiments are conducted by cutting desired tool paths before and after compensation. Machined profiles are verified by measuring various dimensions using coordinate measuring machine (CMM). Dimensional errors in manufactured features are also compared with those obtained by applying compensation based on LSM. It is observed that accuracy of parts has significantly improved after applying compensation using the proposed method.
2 Machine tool inaccuracies

Generally, multi axis machine tools are made up of linear and rotary axis combined in series between the work piece and cutting tool. Machine axes inherently have unintended motions other than their intended linear or rotary displacement. There is an accuracy/cost trade-off that limits the precision of the axis’ motion. Error motions of each of the axes combine to cause a resultant volumetric error between work piece and the tool. If these motions are examined carefully, they can be decomposed into the fundamental six degrees of freedom corresponding with a chosen coordinate system. These errors are usually referred to as: straightness, roll, pitch and yaw for linear axes. Straightness error is in the two directions perpendicular to the motion axis, and roll, pitch and yaw are the rotational motions about the coordinate axes. These axis errors along with the orientation errors between the axes such as squareness error are often referred to as the parametric errors.

The ASME B5.54 (1992) standard defines parametric errors as the fundamental error motions of the machine tool described relative to some coordinate system. The parametric errors include straightness errors, rotational errors and alignment errors such as squareness error. Parametric errors are also often referred to as geometric or kinematic errors. For a three axis milling machine, there are 21 parametric errors; six errors for each of the three axes which include linear and rotary errors and three squareness errors between the axes.

3 Measurement of parametric errors

In error compensation technique, necessary information about the machine tools axes is generally obtained using conventional measurement techniques and methodologies ranging from the use of laser interferometers, electronic levels, mechanical squares, straight edges and other devices. Among these error measurement systems, laser interferometer system is widely used. However, for a laser interferometer system, it is necessary to set up the optics and align laser path before every measurement. Moreover, measurement requires much time and effort, as only one error component can be measured in each setup (Chen et al., 1999, 2001). Furthermore, these methods are not feasible to measure geometric errors on the present mVMT due to less working volume and difficulty in mounting the optics on machine tool. In order to overcome these difficulties, capacitance sensors are used for measuring the geometric errors. Advantages of capacitance sensor include high accuracy (about 50 nanometers), adequate sensing range (about 250 μm), multi-degree of freedom measurement and low cost.

In the present method, five capacitance sensors are used for measuring simultaneously straightness in horizontal and vertical directions, roll, pitch and yaw of each axis. The information of gap between the sensor and the target is interpreted using appropriate algorithms to obtain the required errors (Lee et al., 2004). The mVMT with three linear axes is shown in Figure 1 and the specifications are shown in Table 1. Measurement set up consisting of five capacitance sensors and a target mounted on miniaturised machine tool for measuring the geometric errors is shown in Figure 2.
Table 1  Specification of a miniaturised machine tool

<table>
<thead>
<tr>
<th></th>
<th>X axis</th>
<th>Y axis</th>
<th>Z axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke [mm]</td>
<td>70</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Load capacity [Kgf]</td>
<td>20</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Size of stages [mm]</td>
<td>120×120</td>
<td>120×120</td>
<td>80×160</td>
</tr>
<tr>
<td>Weight [Kg]</td>
<td>2.5</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Overall dimensions</td>
<td>350×250×400 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution [μm]</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. speed [mm/s]</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driving/control</td>
<td>Step motor, micro-stepping</td>
<td>Closed loop control</td>
<td></td>
</tr>
<tr>
<td>Feedback device</td>
<td>Linear encoder with 50 mm resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of spindle</td>
<td>High speed air spindle</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 1  Miniaturised vertical machine tool (mVMT) (see online version for colours)
Initial adjustments are carried out to eliminate the misalignment between the axis of motion of carriage and measurement axis. Gap between capacitance sensors and the target is adjusted in such a way that the distance between them is in measuring range throughout the carriage motion. Machine reference point is determined for each carriage and the measurements are taken from these points. Carriage is moved in steps of 1 mm along the axis of motion and the gain from the capacitance sensors are noted at each step. Using data obtained from capacitance sensors, translational and rotational errors of machine tool are computed. This procedure is repeated for each carriage. Plots of translational errors for x, y and z axis are shown in Figures 3(a), 3(b) and 3(c) with thin lines. Similarly, rotational errors such as roll, pitch and yaw are represented in Figures 4(a), 4(b) and 4(c).

Geometric error measurement experiments are repeated after applying error compensation based on the proposed method, discussed in the following sections. Geometric error profiles of each carriage after compensation are represented by dark lines in Figures 3 and 4.

4 Determination of parametric errors

The geometric profiles shown in Figures 3(a), 3(b) and 3(c) are analysed using CGT to determine straightness and squareness errors. The profile of y-axis in horizontal plane shown in Figure 5(a) is considered for explaining the evaluation procedure. Initially, a convex hull of the profile is constructed using divide and conquer algorithm (Preparata and Shamos, 1985). The convex hull of this profile is shown in Figure 5(b). Points 1, 2, 3, 14, 26, 28, 29, 30, 23 and 9 (in anti clock wise order) lie on the convex hull. Antipodal pairs for each point on convex hull are determined using the method described by Preparata and Shamos (1985). Using these antipodal pairs, a set of parallel lines passing through antipodal points and resting on edges of the hull are established. A pair of parallel lines with least distance between them and containing the convex hull, is considered for determining straightness error. A line parallel to this pair of parallel lines and at equal distance from them is considered as the required assessment line for given
profile as shown in Figure 5(c). Distance between assessment line and each point on profile is considered as the translational error and it is used in the machine model for applying error compensation.

**Figure 3** Translational errors before and after compensation (a) X-carriage (b) Y-carriage (c) Z-carriage (see online version for colours)
Figure 4  Rotational errors before and after compensation (a) X-carriage (b) Y-carriage (c) Z-carriage (see online version for colours)
**Figure 5** Evaluation of straightness error (a) horizontal straightness profiles of Y-carriage (b) convex hull of the profile (c) fitting assessment line
Figure 6 illustrates determination of squareness error between each pair of machine tool axes. Squareness error between two axes is determined using the assessment lines fitted for each profile. For instance to determine the squareness error S_{xy}, between XY plane, the profile of X-axis and Y-axis in horizontal plane are considered and the assessment lines are fitted based on method explained earlier. The angles, \theta_{xx} and \theta_{yx}, between these lines and X and Y axis respectively, are determined. The Squareness error can be expressed as \( S_{xy} = \theta_{xx} + \theta_{yx} \) or \( 90 - \alpha \), where \( \alpha = 90 - (\theta_{xx} + \theta_{yx}) \), as shown in Figure 6. Similarly squareness error between YZ and ZX planes can be determined.

The rotational errors profiles are represented as 2D plots taking position on the carriage along X-axis and the angular deviation along Y-axis, as shown in Figures 4(a), 4(b) and 4(c). The error values are determined directly from these profiles using linear approximations.

Figure 6  Squareness error between each pair of axis

5 Mathematical model of miniaturised machine tool

Multi axis machines are composed of sequence of elements that are connected by joints that provide either translation or rotary motion. The geometric error model of the machine tool is generally constructed based on rigid body kinematics, homogeneous transformations and small angle approximations (Ahn and Cho, 1999).

Figure 7 shows the six error components of X-carriage, when the desired direction of motion is along X-axis. As the intended direction of motion is X, the translation error along X-axis is denoted by \( \delta_x(x) \), where the subscript x represents the axis along which the error occurs and letter in brackets represent intended direction of motion. In this paper, for convenience, it is represented as \( \delta_{xx} \). Following this convention error components of X-carriage are represented as follows:

\( \delta_{xx} \)  translational error along X-axis (linear displacement)
Enhancement of dimensional accuracy of micro features

\[ \delta_{yx} \] translational error along Y-axis (horizontal straightness)

\[ \delta_{zx} \] translational error along Z-axis (vertical straightness)

\[ \varepsilon_{xx} \] rotational error about X-axis (roll)

\[ \varepsilon_{yx} \] rotational error about Y-axis (pitch)

\[ \varepsilon_{zx} \] rotational error about X-axis (yaw)

\textbf{Figure 7}  Error components of X-carriage (see online version for colours)

Similarly, if desired direction of motion is along Y-axis, the error parameters can be represented as: \( \delta_{xy}, \delta_{yy}, \delta_{zy}, \varepsilon_{xy}, \varepsilon_{yy} \) and \( \varepsilon_{zy} \). The error components, when the desired motion is along Z-axis are: \( \delta_{xz}, \delta_{yz}, \delta_{zz}, \varepsilon_{xz}, \varepsilon_{yz}, \varepsilon_{zz} \).

Squareness errors between the three axes can be represented as:

\[ S_{xy} \] squareness error in XY plane

\[ S_{yz} \] squareness error in YZ plane

\[ S_{xz} \] squareness error in XZ plane

In general a homogeneous matrix in three-dimensional space can be represented by \( 4 \times 4 \) matrix (Okafor and Ertekin, 2000).

\[
1_{T_2} = \begin{bmatrix}
R_{13 \times 3} & R_{13 \times 4} \\
F_{13 \times 3} & 1 \times 1
\end{bmatrix} \begin{bmatrix}
\text{Rotation matrix} & \text{Position vector} \\
\text{Perspective transformations} & \text{Scaling}
\end{bmatrix} = \begin{bmatrix}
n_x & s_x & a_x & P_x \\
n_y & s_y & a_y & P_y \\
n_z & s_z & a_z & P_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (1)

where \( n, s, a \) represent orientation of coordinate system with other coordinate systems.

Considering the kinematic links between the three coordinate systems of the micro machine, the desired position of the tool can be determined by

\[
[T_T] = [T_2][\delta_2] [T_1][\delta_1] [T_0][\delta_0]
\] (2)

where
[\mathbf{T}_T] – required position of the tool

[\mathbf{T}_T] [\mathbf{T}_x] [\mathbf{T}_y] – kinematic transformation matrices in x, y and z-directions respectively

[\boldsymbol{\delta}_x] [\boldsymbol{\delta}_y] [\boldsymbol{\delta}_z] – error components of x, y and z axes respectively.

The kinematic transformation matrices of x, y and z axes can be written as

\[
\begin{bmatrix}
1 & 0 & 0 & x_T \\
0 & 1 & 0 & y_T \\
0 & 0 & 1 & z_T
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & y_T \\
0 & 1 & 0 & y_T \\
0 & 0 & 1 & y_T
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & z_T \\
0 & 1 & 0 & z_T \\
0 & 0 & 1 & z_T
\end{bmatrix}
\] (3)

Considering the components of geometric errors of each slide in the miniaturised machine tool, the error matrices can be represented as follows:

\[
[\boldsymbol{\delta}_x] =
\begin{bmatrix}
1 & -\varepsilon_{zx} & \varepsilon_{xy} & \delta_{xx} \\
\varepsilon_{zx} & 1 & -\varepsilon_{x} & \delta_{xy} \\
-\varepsilon_{xy} & \varepsilon_{xy} & 1 & \delta_{xy} \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (4)

\[
[\boldsymbol{\delta}_y] =
\begin{bmatrix}
1 & -\varepsilon_{zy} & \varepsilon_{yz} & \delta_{yy} - S_{xy} y \\
\varepsilon_{zy} & 1 & -\varepsilon_{zy} & \delta_{zy} \\
-\varepsilon_{yz} & \varepsilon_{yz} & 1 & \delta_{xy} \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (5)

\[
[\boldsymbol{\delta}_z] =
\begin{bmatrix}
1 & -\varepsilon_{zz} & \varepsilon_{xz} & \delta_{zz} - S_{xz} z \\
\varepsilon_{zz} & 1 & -\varepsilon_{zz} & \delta_{xz} \\
-\varepsilon_{xz} & \varepsilon_{xz} & 1 & \delta_{xz} \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (6)

Using the relation given in equation (2) and simplifying the equations, the position of the required point can be determined by

\[
P_x = \delta_{xx} + \delta_{xy} + \delta_{xz} - \varepsilon_{zx} y + \varepsilon_{zy} z - S_{xy} y - S_{xz} z - \delta_{xy} \varepsilon_{zx} - \delta_{xz} \varepsilon_{xy} + \delta_{xy} \varepsilon_{xy} + \delta_{xz} \varepsilon_{xz} + \varepsilon_{zx} \varepsilon_{zy} + \varepsilon_{zy} \varepsilon_{zx}
\] (7)

\[
P_y = \delta_{yx} + \delta_{zy} + \delta_{yz} - \varepsilon_{zy} y + \varepsilon_{zx} z - S_{zy} y - S_{yz} z + \delta_{zy} \varepsilon_{zy} + \delta_{yz} \varepsilon_{yz} + \varepsilon_{zy} \varepsilon_{zy} + \varepsilon_{zy} \varepsilon_{zy}
\] (8)

\[
P_z = \delta_{zx} + \delta_{xz} + \delta_{xz} + \varepsilon_{zx} y + \varepsilon_{xz} z - \delta_{zx} \varepsilon_{zx} - \delta_{xz} \varepsilon_{xz} - \delta_{x} \varepsilon_{xz} - \delta_{xz} \varepsilon_{x} + \delta_{zx} \varepsilon_{zy} + \delta_{xyz} \varepsilon_{zy} + \varepsilon_{zx} \varepsilon_{yz} + \varepsilon_{xz} \varepsilon_{xz} + \varepsilon_{xz} \varepsilon_{xz} + \varepsilon_{xz} \varepsilon_{xz}
\] (9)
Coordinates of a required point after compensation can be computed using equations (7), (8) and (9). Values of various error components determined using CGT explained in Section 4, are used in equations (7), (8) and (9).

6 Machining experiments

Two sets of experiments were conducted to verify influence of parametric error compensation. In the first experiment, machine is operated under point to point (PTP) control. Compensation is applied to coordinates of points where the holes need to be machined. The tools moves to coordinates of the required points recomputed after compensation. The designed location of holes is shown in Figure 8(a). The holes machined before and after compensation are shown in Figures 9(a-1) and 9(a-2).

Figure 8 Designed profiles for cutting experiments (a) Experiment 1: PTP control (b) Experiment 2: continuous path control (see online version for colours)

In second experiment, tool path is controlled continuously by applying compensation to the tool path in steps of 0.01mm. At every step, the coordinates are recomputed and tool moves to that location while machining the desired profile. Designed tool path for this experiment is shown in Figure 8(b). Required profile is machined in one pass before and
after compensation. The machined profiles before error compensation and after applying compensation based on proposed method are shown in Figures 9(b-1) and 9(b-2).

For carrying out machining experiments, work piece is loaded on the machine after making initial adjustments. Cutting conditions such as temperature, cutting speed, feed, depth of cut, etc., are maintained constant while machining components before and after compensation to minimise influence of external factors. Various parameters selected while machining are: tool diameter: 1 mm, spindle speed: 40,000 RPM, feed rate: 1 mm/sec and depth of cut: 0.5 mm. The material used in the present work is brass with composition; copper about – 98%, Zn – 2% and lead – 0.05%.

Figure 9  Machined components (a) Experiment 1: PTP control (b) Experiment 2: continuous control (see online version for colours)

Figure 10  Machine set up for cutting experiments (see online version for colours)
A computer program for error compensation is developed using C++ and implemented through national instruments (NI) FlexMotion software for controlling tool path of the micro machine. Machining setup and close up view is shown in Figure 10. After machining the profiles, they are measured using a CMM to verify the dimensional accuracy. Dimensions of each component of the profiles and the required angles are measured for verification.

7 Results and discussion

Table 2 show results of straightness error and squareness error values obtained using translational error profiles shown in Figure 3. It is observed that translational errors in carriage movement have been decreased significantly after error compensation based on proposed method. Maximum straightness error value after compensation is 1.07 micron compared to 4.02 before compensation. Geometric path of the carriage after compensation is smooth with less deviation along the desired direction of motion. After compensation, path of carriage is closer to reference axis and squareness error is reduced to very small value as shown in Table 2.

Table 2 Results of geometric error evaluation

<table>
<thead>
<tr>
<th></th>
<th>Before compensation (estimated using LSM)</th>
<th>After compensation (estimated using CGT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Straightness error [μm]</td>
<td>Squareness error [μm]</td>
</tr>
<tr>
<td></td>
<td>Horizontal Vertical</td>
<td>Horizontal Vertical</td>
</tr>
<tr>
<td>X axis</td>
<td>4.02</td>
<td>3.75</td>
</tr>
<tr>
<td>Y axis</td>
<td>2.14</td>
<td>0.87</td>
</tr>
<tr>
<td>Z axis</td>
<td>2.71</td>
<td>1.97</td>
</tr>
<tr>
<td></td>
<td>$S_{xy} = 0.000428$</td>
<td>$S_{xy} = 0.000251$</td>
</tr>
<tr>
<td></td>
<td>$S_{xz} = 0.000524$</td>
<td>$S_{xz} = 0.000087$</td>
</tr>
</tbody>
</table>

Rotational errors such as roll, pitch and yaw decreased after error compensation, as observed from their profiles in Figure 4. However, it may be noted that the three axis machines consists of three linear stages/carriages and it is difficult to compensate rotational errors by software compensation.

Results of dimensional error measurement in component machined in first experiment, using PTP controls are shown in Table 3. Design specification for distance between centres of holes on outer square is 10 mm. Diameter of the inner circle on which the holes are located is 7 mm as shown in Figure 8(a). Dimensions of the machined components before and after compensation are given in Table 3. Error in component machined before compensation is high with maximum deviation of 0.8913 mm from specified value. Dimensions of component machined with compensation based on proposed method (CGT) are closer to the design specification with maximum deviation of ~0.2039 mm. Machining experiment is also repeated by applying compensation using LSM. Dimensional values of component machined after compensation using LSM are also shown in Table 3, for comparison. In component machined with LSM based compensation, shape formed by the four holes seems to be distorted from required square with two sides larger. This may be due to effect of uneven distribution of compensation across work space when LSM is used for compensation.
Table 3  Results of dimensional evaluation, Experiment 1

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>Before compensation</th>
<th>After compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Dimensions (mm)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>After compensation</strong></td>
<td><strong>LSM</strong></td>
</tr>
<tr>
<td>Distances of points on the outer square</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1–P2</td>
<td>10.4187</td>
<td>10.1947</td>
</tr>
<tr>
<td>P2–P3</td>
<td>9.7997</td>
<td>10.3424</td>
</tr>
<tr>
<td>Radius of points on the circle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>3.8154</td>
<td>3.2851</td>
</tr>
<tr>
<td>P7</td>
<td>3.0542</td>
<td>4.0899</td>
</tr>
<tr>
<td>P8</td>
<td>4.3913</td>
<td>3.4691</td>
</tr>
<tr>
<td>P9</td>
<td>3.9929</td>
<td>3.8625</td>
</tr>
</tbody>
</table>

| Dimensional error (mm) | | |
| Distances of points on the outer square | | |
| P1–P2 | 0.4187 | 0.1947 | –0.0053 |
| P2–P3 | –0.2003 | 0.3424 | –0.1906 |
| P3–P4 | –0.2592 | –0.2154 | –0.1357 |
| P4–P1 | –0.1527 | –0.2255 | –0.0249 |
| Radius of points on the circle | | |
| P6 | 0.3154 | –0.2149 | –0.0891 |
| P7 | –0.4458 | 0.5899 | 0.1009 |
| P8 | 0.8913 | –0.0309 | –0.1651 |
| P9 | 0.4929 | 0.3625 | –0.2039 |

Table 4(a) shows dimensions of component shown in Figure 8(b), machined with continuous control. It is noted from the results that dimensional errors have decreased after applying compensation using CGT compared to error values in component machined without compensation. On the other hand, error in component machined with LSM compensation has large variation in error values ranging from –0.4997 to 0.0468 mm.

Angular errors of profiles machined before and after compensation are given in Table 4(b). Angles $\theta_1$ to $\theta_4$ should be 45° where as $\theta_5$ to $\theta_8$ should be 90° as per the design specification of the component. However, angular errors values vary from 2.6673° to –1.3327° in profiles machined with out compensation. In case of component machined with compensation based on LSM, error values vary from –0.6365° to 0.8804°. Angular accuracy of profile machined with compensation based on proposed method appears to be consistent with variation from 0.3404° to –0.4046°. From results of angular errors in the components it can be seen that the component machined after compensation using present method is much superior. Required angles between a pair of lines are measured by fitting straight lines to the machined profile using CMM.
Table 4  Results of evaluation of machined profile, Experiment 2

(a) Dimensional errors:

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Before error compensation</th>
<th>After error compensation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LSM</td>
<td>CGT</td>
<td>LSM</td>
<td>CGT</td>
</tr>
<tr>
<td>AB</td>
<td>4.798</td>
<td>4.5003</td>
<td>4.9895</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>5.5305</td>
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(b) Angular errors:

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8 Conclusions

Performance of miniaturised machine tool can be improved effectively by parametric error compensation. The geometric errors in miniaturised machine tool can be measured effectively using capacitance sensors. Analysis of geometric profiles of machine tool using CGT is effective in reducing inaccuracy in error parameter estimation. Required assessment feature can be established using concepts of convex hull and antipodal pairs efficiently. Proposed method significantly smoothened variations in geometric profiles of translational errors in X, Y and Z axes. It is observed from the dimensional error evaluation of machined components that, the components machined with error compensation based on LSM are not consistent compared to compensation applied using proposed method. Compensation based on computational geometry is observed to be more uniformly distributed over the work space resulting in consistent improvement in the dimensional accuracy of machined parts. CGT can be extended for compensating geometric errors in five axis machine tools.

References


ASME B5.54 (1992) *Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers*, AMSE.


