Determination of volumetric machine tool errors by using a hole-bar material standard (Multi-Feature Bar – MFB)

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Introduction :
Volumetric accuracy
Introduction:
Volumetric accuracy

5-axis machine tool
(Mikron UCP710 at LURPA)

Swiveling axis

Rotary Table

Kinematic Architecture

Fabien VIPREY
JRP-TIM: Final Workshop at PTB, May 18th, 2016
Introduction: Volumetric accuracy

5-axis machine tool
(Mikron UCP710 at LURPA)

Kinematic Architecture

Swiveling axis

Rotary Table

Gap between theoretical kinematic and real kinematic
Introduction: Volumetric accuracy

5-axis machine tool
(Mikron UCP710 at LURPA)

Causes of this effect:

Swiveling axis
Rotary Table

Kinematic Architecture

Gap between theoretical kinematic and real kinematic

Geometric errors $\sim 70\% - 90\%$
Thermo-mechanical phenomena
Environmental hazards
Dynamic forces
Heats
CNC
Vibrations

[Fabien2016]
[Schwenke2008]
Maximum range of relative deviations between actual and ideal position and maximum range of orientation deviations in the volume concerned, where the deviations are relative deviations between the tool side and the workpiece side of the machine tool [ISO230-1,2012]:

\[
\begin{pmatrix}
\text{axis}_{\text{eff}} - \text{axis}_{\text{nom}} \\
C'_{\text{L}_{\text{eff}}} - C'_{\text{L}_{\text{nom}}}
\end{pmatrix}
= 
\begin{pmatrix}
\delta r \\
\delta u
\end{pmatrix}
= V_{xyz}
\]
Introduction: Volumetric accuracy

Maximum range of relative deviations between actual and ideal position and maximum range of orientation deviations in the volume concerned, where the deviations are relative deviations between the tool side and the workpiece side of the machine tool [ISO230-1,2012]:

\[
\begin{pmatrix}
axis_{eff} - axis_{nom} \\
C_{eff} - C_{nom}
\end{pmatrix}_{6 \times 1} =
\begin{pmatrix}
\delta r \\
\delta u
\end{pmatrix}_{6 \times 1} = V_{xyz}
\]
Introduction: Volumetric accuracy

Maximun range of relative deviations between actual and ideal position and maximum range of orientation deviations in the volume concerned, where the deviations are relative deviations between the tool side and the workpiece side of the machine tool [ISO230-1,2012]:

$$\begin{pmatrix} axis_{eff} - axis_{nom} \\ C_{L_{eff}} - C_{L_{nom}} \end{pmatrix}_{6 \times 1} = \begin{pmatrix} \delta r \\ \delta u \end{pmatrix}_{6 \times 1} = V_{xyz}$$

The aim of this study is to develop a novel material standard to identify motion errors:

- Usable on CMM, 3 or 5 machine tool, by on-line measurement, to insure traceable and accurate results
- With large field of its application: Metrology room or Manufacturing shop
Introduction: Literature review

- **Hole plate** [Trapet1991]
- **Ball plate** [Bringmann2009]
- **Hole Bar** [Lim2005]
- **Ball Bar** [Zhang1991]

Conventional method [ISO 230], [ISO 10360], [ISO 10791], [ISO 13041], [ISO 3070]

Laser Interferometry (On-line measurement) [Schwenke2005], [Chen1999]
Introduction: Literature review


Conventional method [ISO 230], [ISO 10360], [ISO 10791], [ISO 13041], [ISO 3070]  Laser Interferometry (On-line measurement) [Schwenke2005], [Chen1999]
Actual Hole-Bar in literature:

- One linear positioning error $E_{xx}$
- One linear positioning error $E_{xx}$ and one horizontal straightness $E_{yx}$

Identification of an additional parameter:

- One linear positioning error $E_{xx}$ and two straightnesses $E_{yx}$ and $E_{zx}$

Development of a novel Hole-Bar with patterns
- Maximization of the number of geometric errors to identify for each position of the Hole-Bar
• Development of the Novel Hole-Bar
  • Principle
  • Technical attributes
• Calibration
  • Reversal technique
  • Intercomparison
• Application on Machine tool
  • Measurement process
  • Geometric model
  • Results
• Conclusion
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (\(\Delta\))
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction (Δ)

Integral real surfaces (Skin Model)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)

Principle of the new Hole-Bar

Extraction (Skin model shapes)

[ISO 5459:2011]
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)

**Association (Least square)**
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)

Datum
(Situation feature of the associated surface)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)

**Association**
(Least square)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction ($\Delta$)
The design of the Hole-Bar consists in a repetition of a 3D pattern in one direction \((\Delta)\)

The identified points \(O_i = (x_i, y_i, z_i)\) offers 3 intrinsic geometric parameters: 1 linear positioning and 2 straightnesses.
Technical attributes of Hole-Bar (Invar)
Technical attributes of Hole-Bar (Invar)
Technical attributes of Hole-Bar (Invar)
Technical attributes of Hole-Bar (Invar)
Technical attributes of Hole-Bar (Invar)

Mistake-proofing
Technical attributes of Hole-Bar (Invar)
Technical attributes of Hole-Bar (Invar)

First mode of vibration
Fabrication modes of vibration

Setting-up on points of minimum deformation
Technical attributes of Hole-Bar (Invar)

First mode of vibration

Setting-up on points of minimum deformation
Technical attributes of Hole-Bar (Invar)

Point curve joint
Point surface joint
Spherical joint
Coordinates of points of interest
Coordinates of points of interest

Nominal coordinates (3D-CAD model)

$$\forall i \in [1; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix}_{R_{HB}}$$
Coordinates of points of interest

Nominal coordinates (3D-CAD model)

\[ \forall i \in [1 ; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix}_{R_{HB}} \]

Real coordinates (real geometry)

\[ \forall i \in [1 ; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix}_{R_{HB}} + \begin{pmatrix} E_{xx_{HB}}(i) \\ E_{yx_{HB}}(i) \\ E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}} \]
Coordinates of points of interest

Nominal coordinates (3D-CAD model)

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Calibration of the Hole-Bar on accurate CMM \( \rightarrow \) insures traceable measurements on machine tool

The reversal technique and substitution technique are applied to assess the calibration.
Coordinates of points of interest

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Real coordinates (real geometry)

\[ \forall i \in [1; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L + E_{xx_{HB}}(i) \\ 0 + E_{yx_{HB}}(i) \\ 0 + E_{zx_{HB}}(i) \end{pmatrix}_{R_{HB}} \]

Calibration of the Hole-Bar on accurate CMM \(\Rightarrow\) insures traceable measurements on machine tool

The reversal technique and substitution technique are applied to assess the calibration.
Calibration: Reversal technique

$E^{NR}_{yx\ HB(i)}$ (No Reversal)  
$i =$ Number of point of interest on Multi-Features Bar (HB)

$E_{xx\ CMM}(X)$  
$X$ : Joint parameter of X-axis

Reversal way

$E^{R}_{yx\ HB(i)}$ (Reversal)  
$E_{xx\ CMM}(X)$
Calibration: Reversal technique

Linear positioning error along $X_{HB}$

$$E_{XXHB}(i) = \frac{1}{2} \left[ M^{NR}_X(i) + M^R_X(i) \right] - (i-1) \times L - E_{XXCMM} - \epsilon_{ZZCMM}$$
Calibration: Reversal technique

$E_{xx HB}^{NR}(i)$ (No Reversal)

$E_{xx HB}^{R}(i)$ (Reversal)

$E_{xx CMM}(X)$

$X$: Joint parameter of X-axis

Linear positioning error along $X_{HB}$

$$E_{xx HB}^{x}(i) = \frac{1}{2} \left[ M_{x}^{NR}(i) + M_{x}^{R}(i) \right] - (i-1) \times L - E_{xx CMM} - \epsilon_{ZZ CMM}$$
Calibration: Reversal technique

Linear positioning error along $X_{HB}$

$$E_{XX_{HB}}(i) = \frac{1}{2} \left[ M_x^{NR}(i) + M_x^{R}(i) \right] - (i-1) \times L - E_{XX_{CMM}} - \epsilon_{ZZ_{CMM}}$$

Nominal geometry

Random error

Straightness error along $Y_{HB}$ and $Z_{HB}$

$$E_{YX_{HB}}(i) = \frac{1}{2} \left[ M_y^{NR}(i) - M_y^{R}(i) \right] - \epsilon_{YX_{CMM}}$$

$$E_{ZX_{HB}}(i) = \frac{1}{2} \left[ M_z^{NR}(i) - M_z^{R}(i) \right] - \epsilon_{ZX_{CMM}}$$

Measurement

MFB calibration set-up on CMM at LNE

$E^{NR}_{yx HB}(i)$ (No Reversal)

$E^{R}_{yx HB}(i)$ (Reversal)

$E_{xx CMM}(X)$

$X$ : Joint parameter of X-axis

$E_{xy CMM}(1)$

$E_{xy CMM}(2)$

$E_{xy CMM}(3)$

$E_{xy CMM}(4)$

$E_{xy CMM}(5)$

$E_{xy CMM}(6)$

$M^R_Y(1)$

$M^R_Y(2)$

$M^R_Y(3)$

$M^R_Y(4)$

$M^R_Y(5)$

$M^R_Y(6)$
∀i ∈ [1 ; N],
\[
\begin{pmatrix}
  x_i \\
  y_i \\
  z_i
\end{pmatrix}_{RHB} = 
\begin{pmatrix}
  (i - 1) \times L + E_{XXHB}(i) \\
  0 + E_{XYHB}(i) \\
  0 + E_{ZXHB}(i)
\end{pmatrix}_{RHB}
\]
## European Participants for intercomparison

### Type of CMM

<table>
<thead>
<tr>
<th>NMI</th>
<th>Type of CMM</th>
<th>Size of CMM (mm³)</th>
<th>U of CMM (μm+L(m)×μm)</th>
<th>T in metrology room (°C)</th>
<th>Along the CMM-axis</th>
<th>Operator</th>
<th>Signatory of CIPM MRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNE</td>
<td>Renault Automotion 251310</td>
<td>2500 x 1300 x 1000</td>
<td>4.5 + L x 4.0</td>
<td>20.26 ± 0.03</td>
<td>Z-axis</td>
<td>Fabien Viprey</td>
<td>Yes</td>
</tr>
<tr>
<td>CMI</td>
<td>SIP CMM5</td>
<td>710 x 710 x 550</td>
<td>0.8 + L x 1.3</td>
<td>19.73 ± 0.09</td>
<td>X-axis</td>
<td>Pavel Skalnik</td>
<td>Yes</td>
</tr>
<tr>
<td>UM</td>
<td>Carl Zeiss UMC 850</td>
<td>1200 x 850 x 600</td>
<td>2.1 + L x 3.3</td>
<td>20.39 ± 0.03</td>
<td>Y-axis</td>
<td>Mitja Mlakar</td>
<td>Designated by MIRS</td>
</tr>
<tr>
<td>PTB</td>
<td>UPMC 850 CARAT</td>
<td>850 x 1200 x 600</td>
<td>0.8 + L x 3.5</td>
<td>20.18 ± 0.04</td>
<td>X-axis</td>
<td>Norbert Gerwien</td>
<td>Yes</td>
</tr>
<tr>
<td>LNE</td>
<td>Renault Automotion 251310</td>
<td>2500 x 1300 x 1000</td>
<td>4.5 + L x 4.0</td>
<td>20.04 ± 0.03</td>
<td>Z-axis</td>
<td>Fabien Viprey</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Results:
Linear positioning error along $X_{HB}$

\[ \forall i \in [1; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix} + E_{xx_{HB}}(i)_{R_{HB}} + E_{yx_{HB}}(i)_{R_{HB}} + E_{zx_{HB}}(i)_{R_{HB}} \]

Point of interest number $i$
Results:
Straightness error along \( Y_{HB} \)

\[
\forall i \in [1; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix} + E_{x_{HB}}(i)_{R_{HB}} + E_{y_{HB}}(i)_{R_{HB}} + E_{z_{HB}}(i)_{R_{HB}}
\]
Results: Straightness error along $Z_{HB}$

$\forall i \in [1, N]$, \[
\begin{pmatrix}
  \bar{x}_i \\
  \bar{y}_i \\
  \bar{z}_i
\end{pmatrix}_{R_{HB}} = \begin{pmatrix}
  (i - 1) \times L + E_{x_{HB}}(i) \\
  0 \\
  0 + E_{z_{HB}}(i)
\end{pmatrix}_{R_{HB}}$

Graph showing straightness error $E_{z_{HB}}$ across various points of interest.
Results:
Straightness error along $Z_{HB}$

\[ \forall i \in [1; N], \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}_{R_{HB}} = \begin{pmatrix} (i - 1) \times L \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} E_{xx_{HB}}(i) \\ E_{yy_{HB}}(i) \\ E_{zz_{HB}}(i) \end{pmatrix}_{R_{HB}} \]
Real time platform for Identification of geometric errors

Developed end user interface

\[ F = 33.33 \, \text{kHz} \]
\[ T = 30 \, \mu\text{s} \]

Resolution = 10 nm

\[ U_{(k=2)} \text{RMP600} = 0.25 \, \mu\text{m} \]

\[ U_{\text{delay max at 240mm/min}} = 0.47 \, \mu\text{m} \]
Geometric model of 3-axis chain of the investigated machine tools

\[
\delta X = -E_{XX}(X) - E_{XY}(Y) - E_{XZ}(Z) \\
-(E_{B0Z} + E_{BX}(X) + E_{BY}(Y)) \times G(x, y, z) \\
+(E_{C0Y} + E_{CX}(X)) \times F(x, y, z) \\
+E_{BZ}(Z) \times J_Z \\
-(E_{CY}(Y) + E_{CZ}(Z)) \times J_Y
\]

\[
\delta Y = -E_{YX}(X) - E_{YY}(Y) - E_{YZ}(Z) \\
+(E_{A0Z} + E_{AX}(X) + E_{AY}(Y)) \times G(x, y, z) \\
-E_{AZ}(Z) \times J_Z \\
+(E_{C0Y} + E_{CX}(X) + E_{CY}(Y) + E_{CZ}(Z)) \times J_X
\]

\[
\delta Z = -E_{ZX}(X) - E_{ZY}(Y) - E_{ZZ}(Z) \\
-E_{AX}(X) \times F(x, y, z) \\
+(E_{A0Z} + E_{AY}(Y) + E_{AZ}(Z)) \times J_Y \\
-(E_{B0Z} + E_{BX}(X) + E_{BY}(Y) + E_{BZ}(Z)) \times J_X
\]

Geometric errors effects on the joint parameters
Identification procedure of motion errors of X-axis

Application on Mikron UCP710 5-axis machine tool:

$E_{XX}$, $E_{YX}$, $E_{ZX}$, $E_{AX}$, $E_{BX}$ and $E_{CX}$ along the X-axis identified on the points of interest $O_i$ of the Hole-Bar:
Results of identification in the shop floor

$T = 27 \pm 1 ^\circ C$

$T = 20 \pm 1 ^\circ C$

$E_{XX}$ in July

$E_{XX}$ in December

$E_{YX}$, and $E_{ZX}$ in July

$E_{YX}$, and $E_{ZX}$ in December

$E_{AX}$, $E_{BX}$, and $E_{CX}$ in July

$E_{AX}$, $E_{BX}$, and $E_{CX}$ in December
Results of identification in the shop floor

Identified geometric errors depend on the environmental conditions

$T = 27 \pm 1 ^\circ C$

$T = 20 \pm 1 ^\circ C$
Results of identification in the shop floor

 Identified geometric errors depend on the environmental conditions

\[ T = 27 \pm 1 ^\circ C \]
\[ T = 20 \pm 1 ^\circ C \]

\[ E_{XX} \text{ in July} \]
\[ E_{XX} \text{ in December} \]

\[ E_{YX}, \text{ and } E_{ZX} \text{ in July} \]
\[ E_{YX}, \text{ and } E_{ZX} \text{ in December} \]

\[ E_{AX}, \text{ and } E_{BX}, \text{ and } E_{CX} \text{ in July} \]
\[ E_{AX}, \text{ and } E_{BX}, \text{ and } E_{CX} \text{ in December} \]

Solutions:

\( \Rightarrow \) use of climate chamber
\( \Rightarrow \) compensation of boundary conditions: several geometric models which depend on boundary conditions
Calibration using a Laser Tracer

![Graphs showing calibration results using a Laser Tracer.](image)

Fabien VIPREY  JRP-TIM: Final Workshop at PTB, May 18th, 2016
A variation between the results can be observed ➔ definition of end-point reference straight line (end-points), effects of the angular errors and boundary conditions
• Novel Hole-Bar made of thermo-invariant material (Invar) was defined and developed to calibrate machine tool
• The design of the Hole-Bar involves several patterns, including cylindrical and plane geometric entities, useful to extract 12 points of interests ➔ providing 3 geometric errors (linear positioning error and 2 straightnesses) for each selected position
• The developed Hole-Bar was carefully calibrated on an accurate CMM, traceable to the SI meter definition at LNE
• The reversal technique was applied to calibrate the Hole-Bar in order to separate the motion errors of the CMM and the true intrinsic parameters of the Hole-Bar
• An intercomparison was shuttled between 4 european NMIs (PTB, CMI, UM, LNE)
• The Hole-Bar was used for the calibration of the Mikron UCP710 machine tool to evaluate the efficiency
Further works

- Submission of a journal paper about the intercomparison
- Identification of the motion errors of the rotary axes using the Hole-Bar
- Application of a compensation

Dissemination

- 2nd MacroScale International Conference, Wien (Austria), October 2014
- Article submitted for publication in the journal: Precision Engineering

Novel multi-feature bar design for machine tools geometric errors identification
Thank you for your attention!

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