Task Specific Error Correction in Coordinate Metrology - The PAMS Method

Mexican CMM Club
21 October 2008
Queretaro, Mexico

Kostadin Doytchinov & Dr. Jim Pekelsky
Institute for National Measurement Standards
National Research Council Canada
Kostadin.Doytchinov@nrc-cnrc.gc.ca
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing
Master Standard Calibration

- Traceability
- Small uncertainties
  - Accurate measuring instrument
  - Proper realization of the measurand
  - Controlled environmental conditions
  - Qualified metrologists
  - Etc.
Comparator Versus a CMM

Comparator

- Simple - designed to measure a specific measurand
- One degree of freedom
- Needs a master standard
- Very low uncertainty
- Easy to use

Typical CMM

- Universal instrument
- Many degrees of freedom
- Different accessories (probes, rotary tables,)
- Absolute measurement
- Uncertainty highly dependent on the task and the operator
CMM Measurement Errors
Sources

• Examples of random error sources:
  - Hysteresis
    - Gaps in mechanics
  - Random probing errors
  - Dirt on part
  - Vibrations
    - In the CMM environment
    - Internal - NC, etc.
  - Part related

• Examples of systematic error sources:
  - Temperature effects
  - CMM geometrical errors
  - Elastic deformation
  - Probe bending
  - Probe lobbing effects
  - Errors due to incorrect calibration
  - Operator related errors
    • Datums
    • Sampling strategy
    • Drawing interpretation
    • Clamping
Measurement Errors

Random errors **cannot** be compensated

Systematic errors **can** be compensated

Repeatability is the limit of the effectiveness of the compensation!

CMM repeatability is the foundation of the machine accuracy
Highest Accuracy Lab CMMs

Typical: \( \text{MPE}_E = 0.3 \text{ to } 0.5 \ \mu \text{m} + L/1000 \ \mu \text{m} \)

Lab conditions: 20 +/-0.2 C°

Experienced and qualified metrologist

On 500 mm the uncertainty as per ISO 10360-2 would be 1 \( \mu \text{m} \) while the task specific uncertainty can be even smaller if special care taken
Shop Floor CMMs

Typical: $\text{MPE}_E = 3\text{ to } 5 \, \mu\text{m} + (3\text{ to } 5)L/1000 \, \mu\text{m}$

Shop floor conditions: $20 +/\!-\! 5 \, ^\circ\text{C}$

CMM Operators often lack metrology and GD&T knowledge

On 500 mm the uncertainty as per ISO 10360-2 would be $6 \, \mu\text{m}$ while the task specific uncertainty can be significantly larger
If we assume that the shop floor CMM has about 2 $\mu$m basic repeatability that leaves 4 $\mu$m available for correction.

Can we take an advantage of this?
CMM as a Comparator

• Previous attempts
  – Mostly with standard artifacts such as rings, plugs, step gauges
  – Complex master parts such as engine block used but for the purpose of uncertainty estimation and lab accreditation
    • DKD master part calibration
  – Russell Shelton’s patent from 1995—US 5,426,861
    • Concentrates on compensation of errors caused by environmental conditions
    • Excellent metrology but fails to offer a complete practical solution
CMM as a Comparator

- ISO 15530-3 Geometrical Product Specifications (GPS) — Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement — Part 3: Use of calibrated workpieces or standards
  - The main goal on uncertainty estimation
  - Secondary goal on the “substitution method”
    - Describes the basic principle but does not offer universal solution
    - Allows a 10% difference in similarity
  - Compensation is on a parameter level — diameter, location, size
    - Cannot be used for free form surfaces

Excellent document, describes the principle but does not offer a complete practical solution
The Lab CMM and the Shop Floor CMM must execute the same CMM program or hit the same points with the same correction vector.
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing

Step 2: Generate PAMSSEC Compensation

From Cal Lab:
- MP Calibration
- Certified CMM Program

Master Part

Production CMM

PAMS Compensation File

Host PC
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing

Step 3: Use the PAMS Compensation File

Production CMM

PAMS Compensation File

Certified CMM Program

Host PC

workpiece

workpiece corrected measurement results
The PAMS Compensation File

- Contains the corrections for each single point measured in the direction of the surface normal (X,Y,Z, i,j,k)
  - Could also carry parameter related information: size, diameter, location, etc.

- Customizable on the shop floor
  - Compensation files for different lab temperatures: 18 °C, 20 °C, 22 °C, etc.
  - Compensation files for different probe/stylus combinations, different measuring speed, etc.

The PAMS measuring program can pick up the right comp. file based on temperature, probe configuration, etc.
The PAMS Master Part

- The Master Part can be just one of the parts from the manufacturing line
  - It is just a workpiece, an object we use to transfer the accuracy of the lab CMM, lab environmental conditions, the knowledge of the lab metrologist to the shop floor
  - It does not even need to be in tolerance
- If the parts are with free form surfaces only and no suitable datums there are several possibilities
  - Reverse engineering of the master part and using best-fitting to make the alignment
The CMM Program

- The CMM program must be written in a CMM software compatible with both, the calibration CMM and the production CMM
  - Common CMM software platforms
    - Cosmos (Mitutoyo), PCDMIS (Hexagon), DMIS translators
    - I++ opportunity
- The PAMS Lab must certify the CMM program for compliance with the GD&T callouts on the drawing
  - Point density must adequately reflect the form error of the part. The lab may explore with a large number of points and the based on the result decide to reduce it

Certified CMM Program
• Uncertainties of the Master Part calibration – coming from the PAMS lab
• Uncertainties of the method implementation
  – Depends on the stability of the shop floor environmental conditions
  – Dirt on part, etc.
• Uncertainties from the shop floor CMM – mostly random uncertainties
  – Repeatability of the machine
• ISO 15530-3 and the rest of the ISO 15530 series can be used to determine the uncertainties of the PAMS
Ideal Conditions for PAMS

• Repeatable Shop floor CMM
• The Lab CMM and the shop floor CMM run the same software
• Slow changing conditions on the shop floor
• Prismatic parts with well defined datums
Example 1 – Machined part with well defined datums, regular features, small tolerances

- Perfect candidate for the PAMS
  - Very reproducible individual measured points
    - Within the CNC vectoring accuracy
  - Very reliable point correction
Example 2 – Machined part with well defined datums, free form surfaces

- Good candidate for the PAMS
  - Reproducible individual measured points
    - Within the CNC vectoring accuracy
    - The individual parts must not be significantly different
  - Care must be taken when correcting on high curvature
Example 3 – Free form surfaces, no repeatable datums

Good fixture and temporary datums on the Master Part are feasible solution
Example 3 – Free form surfaces, no repeatable datums

- PAMS implementation possible but special tools required
  - Difficult or impossible to reproduce individual measured points
  - The calibrated master part have to be reverse engineered and then modified to include the correction
  - Best fitting required
Examples of Corrected Influences

- **Temperature effects**
  - If temperature varies significantly the PAMS compensation file needs to be updated or multiple files are created

- **Fixturing Problems**
  - If part distorted on the production CMM the effects are removed by the method.

- **Uncorrected systematic geometrical errors (mapping errors)**
- **Systematic dynamic errors**
- **Systematic probe effects**
  - Non-sphericity of stylus tip

- **Reduces calculation uncertainties by supplying better quality input raw data (points)**
- **Removes the decision making of the CMM operator at the factory level**
The Benefits of PAMS

- **Increased accuracy** of the production CMMs
  - Most of the systematic effects removed
  - The repeatability of the CMM is the limit of the method
- Can be fully integrated and invisible to operators
- **Direct traceability** to the measurands instead of relying on indirect measurements – gauge blocks, ball plates, step gauges, etc.
- CMM program written by a qualified metrologist with knowledge of GD&T standards and software capabilities
- **Accredited**: Will satisfy any quality auditor
• Reduces tremendously the influence of the CMM operator

• **Flexibility:** Allows easy switch to different measurement parameters (measuring speed, approach distance, etc.) or even different hardware (probes, extensions) simply by re-measuring the master part and storing multiple compensation files.
The Limitations of PAMS

- Not Applicable to manual CMMs
- Not applicable to single parts
- Time consuming and expensive for small series of parts
- Improves the CMM accuracy only for the specific part at the specific volume location.
- Effectiveness reduced if environmental conditions are fast changing
- More difficult to implement with parts with no datums and only free form surfaces
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing

• Why wasn’t it done before?
  – CMM software incompatibilities
    • High accuracy lab CMMs often use CMM software different from production CMMs – Quindos, SIP Concerto, etc.
  – Concentrating on parameter compensation instead of correcting the fundamental bit of information – the measured point
Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing

• Why it is possible now?
  – Common CMM software platforms
    • Cosmos (Mitutoyo), PCDMIS (Hexagon)
    • DMIS translators
    • I++ opportunity
  – Can be driven by the National Metrology Institutes, the standards community, CMM users and the CMM international community
Possible PAMS Accreditation System

PAMS Labs Subject to an Accreditation System

- PAMS Lab 1
- PAMS Lab N
- Company 1
- Company 2
- Company n
- Company n+1
The PAMS labs will be subject to ISO 17025.

In addition, the Lab will need to have a metrologist with a knowledge of GD&T and measurement standards such as ISO 1101, Y14.5, ISO 10360 series, ISO 15530 series.

Existing certification programs could be adapted and used:
- Aukom for example ([http://www.aukom-ev.de](http://www.aukom-ev.de))
- ASME - Geometric Dimensioning and Tolerancing Professional Certification
- IIDGT ([www.iidgt.com](http://www.iidgt.com))
– Save money by avoiding buying an expensive CMM by improving the accuracy of the existing one
– Achieve good accuracy even with the not so good environmental conditions
– Possibility to use less qualified operators on these CMMs.
– Instead of interim checks make interim PAMS compensation file update – not only checking but improving as well
– Pay for the qualified PAMS lab metrologists only when they write the program and calibrate your master part – don’t employ them
Software manufacturers implement special PAMS compensation tools – the best way!

- Ability to store the calibration file which goes together with the master part and the PAMS script (the CMM program).
- Ability to create the compensation file
- Ability to use the compensation file when running the PAMS script (the CMM program)
- Fully automated and invisible to the user

Correction done outside the CMM software

- Data evaluation package
  - Smartfit, SmartProfile, etc.
PAMS is the BEST Possible CMM Calibration for Measuring THE PART!
Mazak Canada Master Part
## Calibrated Points

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>I</th>
<th>J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128.29980</td>
<td>-128.30095</td>
<td>0.00461</td>
<td>0.000000</td>
<td>0.000000</td>
<td>1.00000</td>
</tr>
<tr>
<td>2</td>
<td>128.29990</td>
<td>128.29851</td>
<td>-0.00476</td>
<td>0.000000</td>
<td>0.000000</td>
<td>1.00000</td>
</tr>
<tr>
<td>3</td>
<td>-128.29930</td>
<td>128.29847</td>
<td>0.00506</td>
<td>0.000000</td>
<td>0.000000</td>
<td>1.00000</td>
</tr>
</tbody>
</table>
Mazak Canada Master Part
Shop floor CMM **uncompensated**

Shop floor CMM **compensated**
References

• Doytchinov, K., Pekelsky, J., “Part & Method-Specific (PAMS) Compensation for CMMs in Serial Manufacturing”, Provisional patent application, Apr 2004
• Shelton, Russell, Advanced Metrological Development. Method and apparatus for inspecting parts for dimensional accuracy outside a laboratory environment, US patent US05426861A
• Nielsen, Henrik, CMMs and Proficiency Testing, IDW 2002
• ISO 10360-2:2001; Geometrical Product Specifications (GPS) - Acceptance and re-verification tests for coordinate measuring machines - Part 2: CMMs used for measuring size.
• Trapet E., Waldele F., Wiegand, Coordinate Measuring Machines in the Calibration Chain, PTB - Germany
Thank You!