Shop Floor Calibration of Machine Tools

L. Buchner,
G. Günther,
Dr. Johannes Heidenhain GmbH, Germany
Shop floor calibration of machine tools

Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
Advantages of Five Axis Machining

Technological:
Flexibility of the tool orientation
- Enables enhanced part complexity (complex shapes, undercuts, difficult angles)
⇒ Functionality at minimum weight and dimensions
- Enables optimal tool orientation relative to the workpiece contour
- Enables shorter tools
⇒ Better quality of complex free form surfaces

Economical:
Machining complex shapes in one setup
- Setup times reduced
- Increase repeatable accuracy in series
- Reduced number of machines to finish part
- Reduced tooling costs
⇒ Reduced cost per part

But:
Five axis machine tools need higher efforts to achieve high accuracy:
⇒ Larger number of mechanical parts define machine coordinate system
⇒ Number of error sources increases significantly
Shop floor calibration of machine tools

Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
The Influence of the Kinematic Model

NC-data of the workpiece → Kinematic model of the machine in the controller → Physical machine

Effect:
Finished part with manufacturing errors

- (Nominal) Geometry of the machine
- Idealizations (e.g. axis positions)
- Manufacturing and assembly errors
- Thermal deviations
- Deviations due to gravity load
Accuracy of Machine Tools – Error Classification

Geometric (static) errors
- (Non-linear) deviations between coordinate systems of machine and CNC
- Encoder accuracy
- Rectangularity, straightness
- Kinematic model accuracy
- Axis offsets
- Abbe distance, friction, backlash

Thermal (quasi-static) errors
- Unbalanced ratio between power losses and cooling
- Spindle design
- Feed drive design
- Cooling design
- Machine frame symmetry

Dynamic errors
- Interaction of structural mechanics and controller dynamics
- Resonant frequencies
- Structural damping
- Control loop amplification
- Friction, backlash
- Acceleration, Jerk
Schematic exposure of a rotary axis (table axis)

Centre of rotary axis in the kinematic model of the control

Real centre of rotary axis
Differences between the kinematic model and the real machine leads to errors in the workpiece contour
Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
Demands on a calibration method

We are searching for a procedure which can identify and compensate kinematic errors.

Due to the fact that the machine kinematic alters during the production process, a readjustment under shop floor conditions is necessary.

Demands on the procedure:

- Reliable measurement under harsh shop floor conditions
- Easy to handle
- Lead time for the process must be short
- Fully automated process must be possible
- Should work on every machine type
Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
3D-touch probe is used for measuring

• Well proven measuring equipment under harsh shop floor conditions
• Automatic measuring procedure with a toolchanger
• Automatic cleaning of the measuring point
• Standard probes offer an accuracy which is sufficient for most applications
• Piezoresistive touch probe TS740 (accuracy 1µm) is ideal for high end use
Piezoresistive Touch Probe TS740

Accuracy grade

Probe accuracy grade X, Y-Axis: ±0.02 μm
Probe repeatability X, Y-Axis: ±0.00 μm

Probe velocity: 4 mm/s
Reference temperature: 22°C ± 1°C

Die Messkurve zeigt die Mittelwerte aus 10 An tastungen pro An tastrichtung.

Anzahl der An tastrichtungen: 6

The error curve shows the mean values from ten measurements per probe direction.

Number of probe directions: 6

Prüfer / Inspected by Klück
11.09.2007
A calibration sphere which is mounted on the machine table is used as the measuring point.
• The software is fully integrated into the NC-control
• It is programmed like a normal touch probe cycle
• The dialogue guided cycle is independent to the machine kinematics
Origin of WCS is set to the centre of the calibration sphere

Reduction of the deviations of the first rotary axis

Reduction of the deviations of the second rotary axis

Reduction of the deviations of the … rotary axis

Protocol of the measurement results

The control rotates the WCS around the origin (centre of calibration sphere)

Measurement of the sphere centre

Adjust the position of the rotary axis and correct the kinematic model (optional)
The software creates log-files of all measuring data in a text format.

TNCscope offers different possibilities for a graphical illustration.

The results can also be visualized with other applications.
A least square algorithm is used to minimise the residual errors.
Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
We want to know, whether the measurement with KinematicOpt reflects the real accuracy of a workpiece?
Verification on a workpiece

Following measurement data have been compared with three different parameter sets in the kinematic model:

1. Standard deviation to nominal value of all measured tilting errors on the calibration sphere (with KinematicOpt)

2. Standard deviation to nominal value of all measured errors on the workpiece

<table>
<thead>
<tr>
<th></th>
<th>Deviations measured with KinematicOpt (σ) [mm]</th>
<th>Deviations measured on the workpiece (σ) [mm]</th>
<th>Error-Discrepance between workpiece and KinematicOpt [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece 1</td>
<td>0.146</td>
<td>0.148</td>
<td>0.002</td>
</tr>
<tr>
<td>Workpiece 2</td>
<td>0.024</td>
<td>0.020</td>
<td>0.004</td>
</tr>
<tr>
<td>Workpiece 3</td>
<td>0.018</td>
<td>0.013</td>
<td>0.005</td>
</tr>
</tbody>
</table>
Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
Effects of Thermal Influences

Intention: Detection of the thermal influence on the tilting accuracy

Description of experiment:

1. Adjustment of the kinematic model

2. 5 heating cycles of the machine (15 minutes)
   - Simulated (air cutting) 5 axis machining (18000 rpm – 75% max. rpm)
   - Resetting of the WCS origin (compensation of the thermal drift of the TCP in the untilted workpiece coordinate system)
   - Measurement of the deviations in the tilted workpiece coordinate system

3. 3 cooling cycles of the machine (15 minutes)
   - Standstill of the machine
   - Resetting of the WCS origin and Measurement of the deviations

4. Readjustment of the kinematic model
Effects of Thermal Influences

- Heating under Load
- Cooling (no Load)
- Recalibration

Graph showing the movement of B-Axis and C-Axis with respect to nominal value over time.

- B-Axis Movement (red line)
- C-Axis Movement (green line)

Time [min] vs. Sigma with respect to nominal value [μm]
Effects of Thermal Influences

Max. Displacement: 26.4[µm]

Max. Displacement: 8.7[µm]
Contents

1. Advantages of Five Axes Machining
2. Sources for Manufacturing Deviations
   - The Influence of the Kinematic Model
   - Error Classes
3. Demands on a calibration method
4. Calibration with KinematicOpt
   - Measuring equipment
   - Measurement Procedure
   - User Interface
   - Adjustment of the Kinematic Model
5. Verification on a Test Workpiece
6. Effects of Thermal Influences
7. Conclusions
• Differences between real machine kinematic and the kinematic model in the control leads to form errors of the workpiece

• Environmental and operational influences alter the machine kinematic during the production

• High accuracy demands on five axes machining requires frequent adjustment of the kinematic model

✓ KinematicOpt is a measurement procedure to adjust the kinematic model
✓ It is suitable for shop floor conditions
✓ The procedure does not substitute a thorough calibration of the machine
✓ The measurement cycle gives the user an indication about the accessible accuracy, which could be the basis for the decision to make a more thorough calibration
✓ Calibration can make good machines better but can not make bad machines good
✓ KinematicOpt will be available on Heidenhain iTNC530 from autumn 2007