Thermal Displacements of Rotary Axes

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Overview

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Introduction

IWF/inspire research on 5-axis machine tools
- geometric testing
- compensation
- dynamic testing
- thermal testing

since begin of 2010 new
5-axis machining center
- with swiveling rotary table
- vertical machining center
t-(C)-Z-X-Y-b-B-C-w
Introduction

Thermal testing on machine tools, standard tests (ISO 230-3)
- warm-up
- linear axes reciprocating movement
- spindle drift

Thermal research activities (of 5 axis machine tools)
- typical thermal displacements of various rotary axes
- analysis of different measurement setups
- proposal for standardization of thermal testing of rotary axes
- compensation
  - phenomenological
  - model-based
Measurement Setups, Continuous R-Test

synchronous circular movement of linear and rotary axes, analysis of relative displacement between precision ball and linear probes, continuous movement during one rotation

circle and plane fit into measurement data, center and radius of the circle, orientation of the plane, no angular position error (A0A, B0B, C0C)

uncertainty influences, influence of measurement device and positioning uncertainty decrease with number of measurement points, thermal distortion during measurement cycle, thermal distortion of linear axes
synchronous circular movement of linear and rotary axes, analysis of relative displacement between precision ball and linear probes, discrete measurement points, usually $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$

circle and plane fit into measurement data, center and radius of the circle, orientation and angular error

uncertainty influences, influence of measurement device and positioning uncertainty increase due to the limited number of measurement points, thermal distortion during measurement cycle, thermal distortion of linear axes
mandrel and incremental probes, mandrel and six incremental probes to measure the thermal displacements, with retractable probes no lateral movement of linear axes necessary → only short time for positioning required, number of incremental probes and size of measurement setup

eccentric gauge block, measurement of the angular error C0C / B0B, small movement of linear axes (or larger retraction of probes) to allow rotation of gauge block

uncertainty influences, influence of measurement device, positioning uncertainty only Z axis direction, thermal distortion during measurement cycle
comparison, measurable thermal errors and uncertainties
- R-Test slightly higher uncertainty due to movement of linear axes
- discrete R-Test uncertainty higher than continuous, due to less measurement points
- B0B / C0C for continuous R-Test needs information of current angle
- \( \Delta R \) with “enhanced ISO 230-3” requires additional incremental probe

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Warm-Up (1)

5-axis machine tool
- t-(C)-Z-Y-b-X-B-C-w (t...tool, b...bed, w...work piece)
- cold before start, thermal displacements measured during warm-up

measuring process
- continuous R-Test
- measurement cycle every 20min
- 360° rotation of C
- 180° rotation of B
- Measurement cycle duration ≈1min
- stand-still in between measurement cycles
Warm-Up (2)

- significant temperature increase of rotary-turning unit
- infrared images after t=1h and t=4h of switch on
- temperature increase of spindle
displacements
- small location errors in X direction due to symmetry (<5μm)
- large location errors in Y and Z direction (<25μm)
- influence in Z by spindle elongation and rotary-turning unit displacement
- angular errors move back to zero after 2.5h
Reciprocating Movement, C (1)

5-axis machine tool, C axis reciprocating movement
- axis configuration: t-(C)-Z-X-Y-b-B-C-w
- movement between C=180° and C=-180° with F=4500° /min

measuring process, C axis
- discrete R-Test
- measurement cycle every 9min
- measurement at four positions, additional one for repeatability of measurement cycle
- duration ≈1min
- reciprocating movement in between two measurement cycles
- stop after 5h, then measurement cycle used to measure cooling down

Figure: Location of the temperature probes
Reciprocating Movement, C (2)

temperatures, C axis reciprocating movement
- temperature changes due to movement small (<1°C)
- biggest influence due to change in environmental temperature (<2.5°C)

displacement, C axis reciprocating movement
- displacements small as temperature changes are low (<2μm)
- influence of environmental temperature variation

C Reciprocating Movement, F=4500 °/min
Reciprocating Movement, B (1)

5-axis machine tool, B axis reciprocating movement
- movement between B=60° and B=-60° with F=4500° /min, stop after 5h

measuring process, B axis
- similar to C axis, discrete R-Test
- measurement at four positions (0, -45, 45 and 0°), duration ≈1min
displacements, B axis reciprocating movement
- symmetry in X responsible for small displacement in X0B (<3μm)
- heat from B bearing moves into support → displacement in Z0B (<8μm)
- small radial growth (2μm) and displacement in Y direction (range <7μm)
5-axis machine tool, swiveling spindle reciprocating movement
- t-(C)-B-Z-Y-X-b-A-w
- movement between B=90°, B=-45°, F=2000°/min

measuring process, B axis
- measurement at three angles (0°, 45°, 90°)
- standard ISO 230-3 setup
- displacement C0B not visible
- movement of linear axes (X and Z) → error influence on B axis displacements
- measurement: X, Y, Z, B, A at 0°; X, Y, Z at 45°/90°
Displacements, swiveling spindle reciprocating movement
- largest displacement in direction of B-axis (20µm)
- temperature increase in air temperature
  - air temperature affects axis support (+1°C)
  - increase in air temperature leads to Z0B (12µm)
  - uneven air temperature around support leads to B0B (12µm/m)
Quasi-Continuous Rotation, C (1)

5-axis machine tool, C axis quasi-continuous rotation
- S=800 1/min for about 540s
- stop after 5h, then cooling down with same measurement cycle

measuring process, C axis
- discrete R-test
- measurement cycle every 9min
- measurement at five positions, fifth for repeatability, duration ≈ 1min
- rotating movement in between two measurement cycles
temperatures, C axis quasi-continuous rotation
- temperature increase of table (4° C)
- temperature peaks when table stops → no convection
- heat slowly moves towards B bearing
- working envelope air temperature increased (1° C)
displacements, C axis quasi-continuous rotation
- heat from C axis $\rightarrow$ Y0C because of asymmetry (12µm)
- temperature increase of table leads to $\rightarrow$ radial growth of table (5µm)
- $\rightarrow$ Z displacement of table (7µm)
- angular error only in A0C (range of 25µm/m), other small due to symmetry
Conclusions

typical deformations of rotary-swiveling table
- symmetry in X direction $\rightarrow$ almost no location error X0C, X0B
- angular errors rather small
- rather large movement in Y direction (away from thrust bearing)
- movement in Z direction $\rightarrow$ heat on the unit and from bearing into support

typical deformations of swiveling spindles
- rather large movement in axial direction (away from thrust bearing)
- measurement setup not satisfactory $\rightarrow$ influence of linear axes

typical measurement records
- displacement of rotary axes in good agreement with PT1 elements (1st order lag)
- phenomenological compensation for different speeds and loads seems reasonable
Future steps

phenomenological compensation of thermal displacements of rotary axes
- Example: PT1 elements for thermal displacement for different speeds
- Different influence factors on the thermal displacements of rotary axes

→ Phenomenological compensation disturbed by elements 1 to 3
Use of machine tool for education

machine tool used for demonstrations and practical exercises in the following lectures:
practical course ‘from the idea to the workpiece’
  machining examples, machining of Matterhorn on NMV5000
machine tool metrology
  measurement of positioning accuracy with laser interferometer on NMV5000
  measurement of straightness with straightedge on NMV5000
  measurement of tool spindle with spindle analyzer on NMV5000
manufacturing processes 1 and 2
  NC programming, milling
production machines 1 and 2
  design of machine tools, components of machine tools, machine tool performance, modeling of machine tools
bachelor thesis ‘test piece for 5-axis machine tools’
  measurements and manufacture on NMV5000
master thesis ‘thermal behavior of rotating and swiveling axes
  measurements on NMV5000
student focus project ‘sun car’
  manufacturing of key parts on NMV5000
Summary

future activities
- simulation and machining of 5-axis test pieces
- dynamic testing
- thermal testing including rotary axes
- compensation for thermal distortion of rotary axes
- enhancement of machine tools

Acknowledgement

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