Calibrating 5-axis machines to improve part accuracy

5Align™
Productive Process Pyramid™

• Understanding and tracking machine behaviour...

- Process verification
- Thermal compensation
- In-cycle process control
- Process set-up & tool path generation
- Machine geometry calibration
- Probe calibration
- Machine performance optimisation
- Environmental stability & operating disciplines
- FMEA and robust process design
- Design for manufacture
Machine geometry topics

- Sources of geometric error and their impact
- 5Align™ Calibrator and Check-Up cycles for a multi-tasking mill-turn machine
- Case study – impact of machine geometry on part accuracy
- The impact of temperature
Critical geometric relationships

- To machine accurately, you need to know where the tool is relative to the workpiece in all positions:
  - **where the spindle is relative to the machine home**
    - translation in \{X,Y,Z\}, and orientation of spindle zero point (only for spindles with orientation control)
  - **where the rotary axes are relative to the spindle**
    - translation in \{X,Y,Z\} and centre-line orientation \{i,j,k\} and orientation of zero points
  - **where the workpiece is relative to the spindle**
    - offset from machine bed / rotary axis centre-lines - this relationship changes as rotary axes move
  - **tool dimensions**
    - length of tools relative to spindle gauge-line, and diameter of tools when they are spinning (accounting for run-out and pull-up)
Sources of geometric errors

- Error sources...
  - **machine geometry** is not perfect
    - linear axes not orthogonal
    - spindle taper not aligned with machine Z-axis
    - rotary axes not aligned with linear axes
    - rotary axes are not positioned exactly w.r.t. linear axes
    - rotary axis zero points are not aligned with linear axis directions
    - most CNCs are unable to compensate for inter-axis errors

- **thermal distortion** constantly changes inter-axis relationships
  - ambient temperature changes
  - self-generated heat in ball-screws and spindle
    - local heating effects due to friction
    - heat soak from major power sources

**Note:**
Axis linearity / angularity not considered - covered by calibration
Alignment and position errors

• **Alignment errors**
  - Driven by precision of machine construction
  - Vary very slowly (wear and tear) under normal circumstances
  - Machine crashes can cause sudden changes in alignment

• **Position errors**
  - Vary more quickly than alignment errors
  - Susceptible to temperature / heat flows
Impact of alignment errors

• If these errors are not measured and either minimised through maintenance, or accounted for in the program, features will be produced in the **wrong position**!

• A machine with poor geometry will make inaccurate parts, resulting in fruitless efforts to adjust tool and work offsets

• Geometric errors are not constants - mechanical wear and crashes can cause them to change
  – regular assessment of geometry is needed
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5Align™ solutions

- **5Align™ Calibrator…**
  - aimed at the machine builder
  - comprehensive cycles and calibration artefacts that identify individual alignment errors to assist with machine build and installation

- **5Align™ Check-Up…**
  - aimed at the machine user
  - fast check using an artefact to benchmark and monitor machine geometry over time

- **Solutions for…**
  - 5-axis machining centres
  - 5-axis multi-tasking mill-turn machines

Assumes accurate linear systems with no squareness errors
5Align™ test equipment

- Device developed for ease of use
- All items threaded – simple bung
- IMPORTANT – the device does NOT need to run on centre

Pivot point artefact

Spindle alignment artefact
Probe calibration

- Measure position of sphere with mill spindle orientated
- Re-measure sphere with probe rotated through 180 degrees
- Probe tip runout can be calculated and stylus offset loaded to variables

V714-MT-probe-cal.wmv
Check 1 – Main spindle centre line

- Measure sphere at C0 with probe orientation A0
- Measure sphere at C180
- Calculate midpoints in X and Y
Check 2 – Main spindle alignment XZ YZ

- Measure 1st sphere at C0
- Measure 1st sphere at C180
- Calculate midpoints in X and Y
- Measure 2nd sphere / diameter at C0
- Measure 2nd sphere / diameter at C180
- Calculate midpoints in X and Y
- Spindle alignment is difference between midpoints

Main spindle alignment X-Z plane (also X-Y plane)
Check 3 – Mill spindle alignment XZ YZ

• Measure sphere at Spindle 0
• Measure sphere at Spindle 0 using point on shaft of probe
• Measure sphere at Spindle 180 using point on shaft of probe
• Calculate midpoint in X and Y
• Mill Spindle alignment is difference between points
Check 4 – B-axis pivot, head length & pivot to spindle error

- Measure sphere at B0
- Measure sphere at B-90
- Calculate distance moved in X (radial) & Z (X1,Z1)
- Swing radius = (X1+Z1)/2
- Head length = Swing radius – sphere radius – probe length
- Pivot point to mill spindle = Z1 – swing radius

![Diagram showing measurement setup](V718-B-pivot.wmv)
Check 5 – B-axis translation errors

- Measure sphere position XYZ
- Update WCS
- Using dynamic work offsets or custom macro, generate WCS for new B axis position
- Move B-axis
- Measure sphere positional error X,Y,Z
- Repeat through axis movement

V719-B-tracking.wmv
5Align™ Check-Up results

<table>
<thead>
<tr>
<th>Data</th>
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<tbody>
<tr>
<td>A</td>
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</table>

Radius
Best Fit: 8.6083
Max.: 8.6094
Min.: 8.6076
Spread: 0.0020
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Mill-turn test-piece design
Test-piece machining processes

- The face and diameter were rough and finish turned, these become the datums for the CMM check.
- The face slot is machined with the mill spindle horizontal, the side slots with the mill spindle vertical, all features produced using the end of the cutter.
- The face and side holes are spotted (B-axis horizontal / vertical), then drilled and single point bored.
- Two face holes used to align on the CMM.
Test procedure

• The Renishaw 5Align™ Calibrator tests carried out without parameter update
• The machine ‘tool eye’ calibrated using a setting tool
• All cutting tools datumed against the tool eye
• First test piece machined
• Machine parameters updated as prescribed by the 5Align™ Calibrator tests
• Second test piece machined
• Both parts inspected on a Mitutoyo DCC CMM
## CMM measurement results

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Drawing reference</th>
<th>Deviation</th>
<th>Influencing parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.000 turned diameter</td>
<td>B4</td>
<td>0.212</td>
<td>Machine centreline X-axis</td>
</tr>
<tr>
<td>1.0 deep milled slot front face</td>
<td>D3</td>
<td>0.019</td>
<td>Demonstrates relationship to turned face - offset correct</td>
</tr>
<tr>
<td>Centre Hole X0</td>
<td>B5</td>
<td>0.12</td>
<td>Machine centreline X-axis</td>
</tr>
<tr>
<td>Centre Hole Y0</td>
<td>B5</td>
<td>0.003</td>
<td>Machine centreline Y-axis</td>
</tr>
<tr>
<td>29.5 milled flat (1)</td>
<td>C4</td>
<td>0.535</td>
<td>Machine centreline X-axis, Head length, Alpha error</td>
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<tr>
<td>29.5 milled flat (2)</td>
<td>C5</td>
<td>0.541</td>
<td>Machine centreline X-axis, Head length, Alpha error</td>
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<tr>
<td>Side bored hole (1) position Z-</td>
<td>C3</td>
<td>-0.329</td>
<td>Head length, Alpha error</td>
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<tr>
<td>axis</td>
<td></td>
<td>-0.003</td>
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<tr>
<td>Side bored hole (1) position Y-</td>
<td>C3</td>
<td>0.019</td>
<td>Y-axis Yaw error</td>
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<tr>
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<td>0.014</td>
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<tr>
<td>Side bored hole (2) position Z-</td>
<td>D3</td>
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<td>Head length, Alpha error</td>
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<tr>
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<td>D3</td>
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<td>Y-axis Yaw error</td>
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<tr>
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<td>0.006</td>
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</table>
Conclusions

- The effects of the correct calibration were significant and improved the accuracy of the machined part to an acceptable level.

- **No tool offsets were altered to achieve the change in results**

- Without using 5Align™, an operator would try altering tool offsets to achieve nominal dimensions and undoubtedly become frustrated due to the limited effect across all errors.

- Following correct machine calibration however, any residual errors can confidently be attributed to tool wear and deflection, enabling tool offsets to be used to control the machining process.
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Thermal errors - ‘C frame’ VMC

Spindle motor

Internal heat sources

X

Y

Z

FRONT VIEW

SIDE VIEW
Thermal errors - ‘C frame’ VMC

HEAT FLOWS

FRONT VIEW

SIDE VIEW
Thermal errors - ‘C frame’ VMC

- Small drift in X direction due to ball-screw heating
- Larger drift in Y due to local ball-screw heating and heat soak into casting
- C frame opens up and grows, due to Z-axis ball-screw heating and heat soak from spindle motor. Big effect in Z. Also affects the Y-axis.
Thermal errors - ambient temperature

- Changes in temperature in the machine shop during the day will affect the thermal condition of machines...
  - higher / lower temperatures will cause machines to expand / contract
  - temperature gradients in the shop may create differential expansions, especially on large, unguarded machines
  - rapidly changing ambient temperatures can cause unpredictable changes in machine geometry
    - different materials
    - constrained growth
Check 6 – spindle position tracking

• An in-process check that quickly identifies how the relative positions of the main and milling spindles has moved since it was last calibrated
  – Use for tracking impact of temperature

• If possible, measure the position of a small, recently turned diameter…
  – Either use error in position to update system parameters
  – Or update a primary work co-ordinate to use for subsequent milling operations

• If it is not possible to measure a diameter…
  – Use a datum point on the chuck to track the centre-line (note: this is subject to axis growth errors)
Check 7 – B-axis error tracking

• An in-process check that quickly identifies where the pivot point, head length and pivot to spindle error have moved since they were last calibrated
  – Use for tracking impact of temperature

• Measure a corner on either the part or the chuck at B0 and B-90
  – Analyse as per check 4
  – Either update system parameters (if possible)
  – Or establish a work co-ordinate in each spindle orientation to be used
## Suggested calibration regime

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Calibration Activities</th>
</tr>
</thead>
</table>
| YEARLY:    | • Full laser check on linear & rotary axes  
             • QC10 Ballbar check to benchmark linear axis performance  
             • 5Align™ Calibrator cycles to optimise & benchmark machine alignments  
             • Establish limits of acceptance |
| MONTHLY:   | • Ballbar check to monitor linear axis performance  
             • 5Align™ Check-Up cycle to monitor machine alignments  
             • Compare with acceptance limits |
| DAILY:     | • Establish calibration trail between tools and spindle probe  
             • Probe calibration |
| IN-PROCESS:| • In-process reaffirmation of spindle alignment and pivot point  
             • Establish position of part relative to spindle |
Machine geometry summary

- The alignment of 5-axis machines is critical to machining accuracy
- Alignments can be affected by wear & tear, crashes and temperature
- 5Align™ Calibrator cycles measure each component of machine alignment in an automated, repeatable manner
- 5Align™ Check-Up cycles provide a benchmark for machine geometry condition monitoring
- In-process checks can track the hour-by-hour impact of heat flows and temperature
- Solutions for various 5-axis machine configurations