MACHINE METROLOGY FOR OPTIMAL PERFORMANCE

The machining time for complex workpieces such as turbine blades, impellors, medical protheses and complex machine frames, as manufactured on 5-axis machine tools, can be very long, typically many hours. The machine's thermal stability is critical for meeting geometrical tolerances and must remain below a certain value. This article presents a fast and accurate method for the dynamic 3D measurement of thermal stability and features a case study describing the use of a non-contact wireless probe.

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Set-up of a classic thermal distortion test using three capacitance sensors.

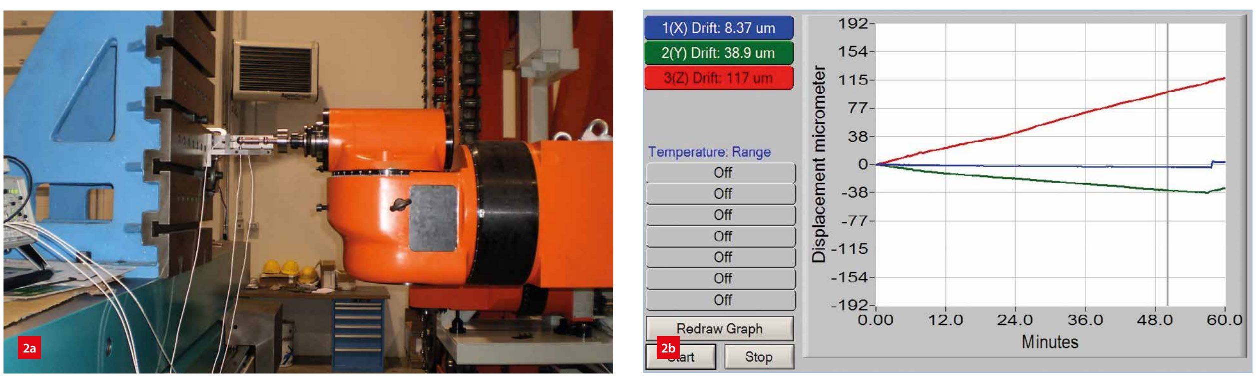
A machine tool contains many heat sources and the spindle is commonly the largest. Spindle power can be 40 kW or even more. Linear motors can also heat up significantly and these are found in fast moving machine tools. Other heat sources are hydraulic pumps, friction in gears and drive trains, electronics, and the cutting process – the environmental air temperature is also of concern; conditioned workshops are rare but do exist.

Machine tools are available in many sizes and configurations and their thermal stability can vary largely: from 'poor' to 'nearly perfect'. Thermal machine behaviour can be improved by using:
- smart design (i.e. low-expansion materials, symmetry);
- temperature control of vital machine components (e.g. the spindle unit, hydrostatic axes);
- air conditioning in the workshop;
- correction models employing integrated temperature sensors (e.g. analytical, empirical or hybrid machine thermal error models).

Temperature control can be very effective, but requires a large amount of energy.

Classic thermal test

In ISO 230-3, "Test code for machine tools – Part 3: Determination of thermal effects", [1] advised tests are described. To measure the thermal stability of a machine



Thermal distortion test on a 'poor' example of a large machine tool.
(a) Set-up, showing dual masterball and probe nest; X-as is perpendicular to drawing plane, Y-axis is vertical, Z-axis runs into the spindle.
(b) Thermal distortion (displacement between spindle and table) in X (blue line), Y (green) and Z (red) versus time. Drift (within one hour) in X, Y and Z is 8.37, 38.9 and 117 μm, respectively.

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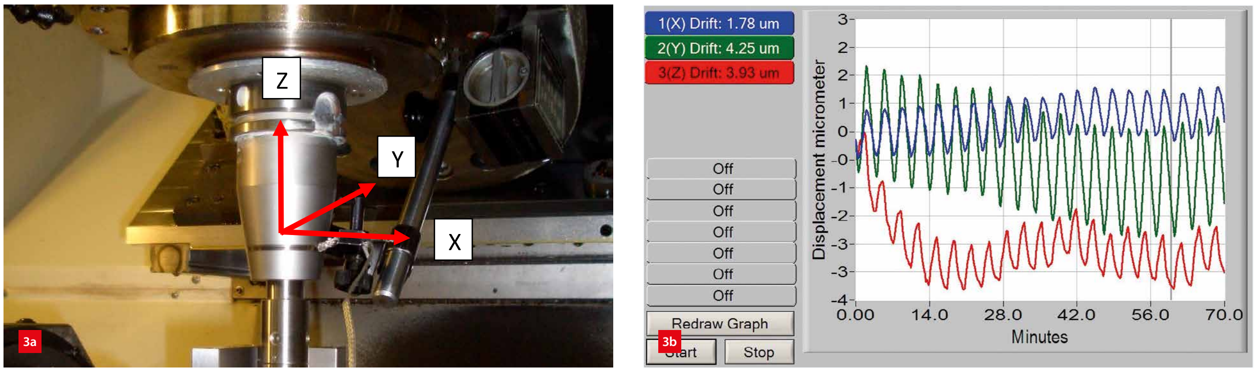


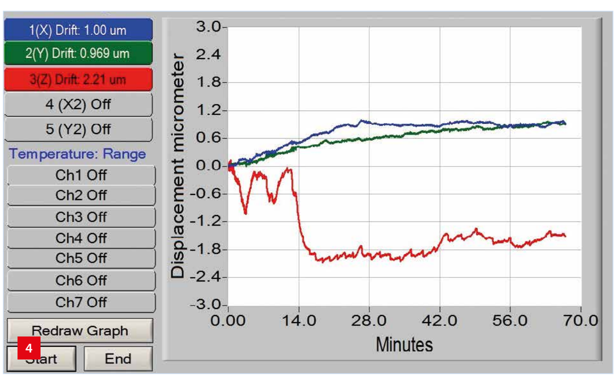
Thermal distortion test for a milling machine with active cooling.
(a) Set-up, showing orientation of the X-, Y- and Z-axis.
(b) Result (displacement between spindle and table) for 70 minutes, with spindle rotating at 10,000 rpm. Thermal drift is less than 4.25 µm.

tool, a high-precision masterball (roundness error < 25 nm) is placed in the spindle and three capacitance sensors are placed in a probe-nest, mounted rigidly on the machine's workpiece table (Figure 1). The spindle is commanded to execute a constant spindle speed (or a spectrum with variations in speed and interval duration) and the relative displacement of the masterball is recorded in X-, Y- and Z-direction. When five sensors are used in combination with a dual masterball or cylinder, the tilt error around X and Y can also be measured. This ISO test assumes that the dominant heat source is the spindle and ignores heat from the cutting process. During finishing, where the precision is required, cutting depths and forces are typically small. When applying such a test, it is best to simulate the machine's normal operation conditions as well as possible.

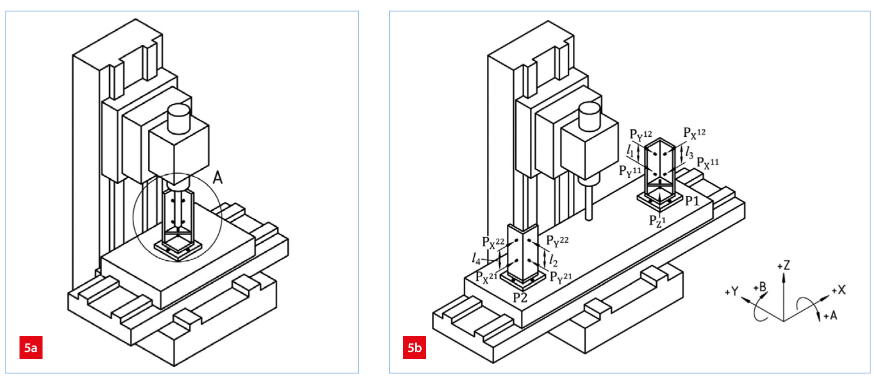
Figure 2 shows a 'poor' example of a large machine tool: the spindle is rotating at its maximum speed of 2,500 rpm and the relative displacement between spindle and table is measured. In this example the thermally induced drift is largest in Z-direction and exceeds 100 µm in less than one hour. This test had even to be stopped to avoid contact between the masterball and the sensor. No thermal correction methods have been used in this machine tool.
Figure 3 displays the measured drift of a milling machine used for cutting turbine blades where the spindle is running at 10,000 rpm for 70 minutes. This machine cools its spindle within 1 °C (wave period is about 3.5 minute) and shows a good thermal stability, with a drift of less than 4.25 µm.
The periodic impact of the cooling is clearly visible.

Figure 4 presents an even better example. This can be classified as representative of 'best-in-class' machines on the market. Here a milling machine, used for manufacturing 'smooth-surface moulds', is commanded to execute 42,000 rpm and the measured thermal distortions are recorded. The measured displacement is less than 2.2 µm in Z-direction, and in X- and Y-direction the thermally induced drift is even less than 1 µm. Machines with such good stability are rare and very expensive (> 1 M€) and typically employ multiple thermal correction techniques combined.

In the tests above, only the spindle is active and the axes do not move. In ISO 10791-10 ,"Test conditions for machining centres – Part 10: Evaluation of thermal distortions", [2] additional tests are implemented to include moving axes, see Figure 5.
The ISO 230 series covers the test conditions for accuracy measurement of (conventional) machine tools where the ISO 10791 series apply to machining centres, which can execute multiple machining operations; 5-axis machine tools would typically class as machining centres. The approach to thermal tests is the same in both standards.



Thermal distortion test result (displacement between spindle and table) for a 'best-in-class' milling machine at 42,000 rpm.
Drift in X (blue), Y (green) and Z (red) is shown over 70 minutes.



Schematic drawings of ISO 10791-10.
(a) Classic test set-up.
(b) New set-up for which a linear axis is moved between P1 and P2 for a period of time.

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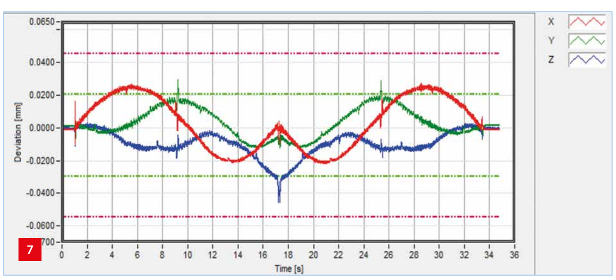
Rotary Inspector set-up: 3D probe in spindle, masterball on the table.

Using the Rotary Inspector

5-Axis machine tools incorporate linear X-, Y- and Z-drives combined with two rotary tables to allow rotation about two of these axes. Classic thermal distortion tests cannot determine changes in pivot line position and squareness of the rotary axes, relevant for all 5-axis machine tools. IBS Precision Engineering has developed a measurement system dedicated for 5-axis machine tools named Rotary Inspector. The measurement system consists of a Trinity wireless measuring head, comprising three displacement sensors for non-contact measurement, and a precision masterball. The measuring head (probe) is mounted in the spindle and the masterball is placed in a fixed position on the table (Figure 6).

A measurement protocol is implemented which contains three kinematic tests, in line with the ISO 10791-6 requirements for total machine tool accuracy [3]. The machine is first commanded to rotate the first rotary axis (e.g. B-axis) while two linear axes follow (i.e. X and Z), then the same for the second rotary axis (e.g. C-axis) while X and Y follow, and finally all five axes are activated. For this last 5-axis test, the C-axis rotates twice as fast as the B-axis, as prescribed in ISO 10791-6. These tests are executed in approximately 1 minute; where the speed is usually chosen to replicate typical speeds applied during machine operation for production. The kinematic tests capture a snapshot of the machine's accuracy.



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Displacement (deviation) in X, Y and Z between Trinity measuring head (representing cutting tool) and masterball (representing workpiece) during synchronised 5-axis motion of linear axes and rotation table (see Table 1).

Table 1
Pivot line position and squareness errors of machine A and B rotation axes derived from 3-axis tests.

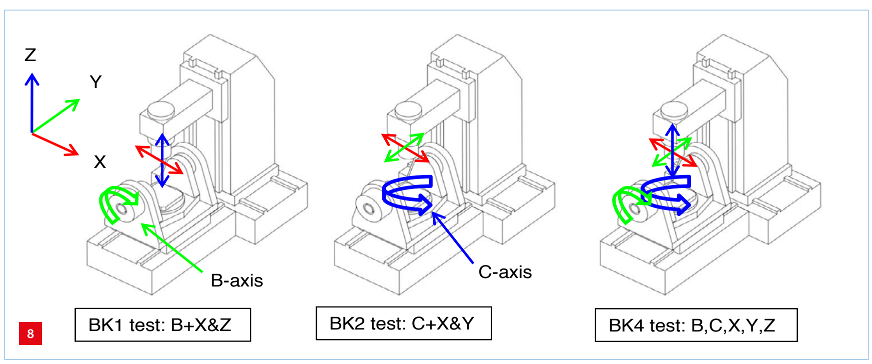
BK1 test (A-axis)		BK2 test (B-axis)	
Pivot line position error	**Value (mm)**	**Pivot line position error**	**Value (m)**
YOA	–0.0037	XOB	–0.0023
ZOA	–0.0157	ZOB	–0.0159
Pivot line squareness error	**Value (°)**	**Pivot line squareness error**	**Value (°)**
COA	0.0002	COB	0.0006
BOA	0.0005	AOB	0.0001

Figure 7 and Table 1 present the results of an example measurement. The 5-axis test result (Figure 7) shows the amplitude of the X-, Y- and Z-direction displacement between the masterball and the probe during the test motion. Where the position of the masterball is determined by the rotary axes and that of the probe by the linear axes. As the masterball represents the contact point of the work-piece and the probe the end of the cutting tool, the smaller these deviations are, the better the machine's precision.

The pivot line position error (or displacement) and the pivot line squareness error of each rotary axis (Table 1) are derived from the 3-axis tests. For the A-axis, the position error of its pivot line in Y-direction is denoted by YOA and in Z-direction by ZOA. The squareness error of the pivot line of the A-axis is described by COA (i.e. rotation around Z-axis) and BOA represents the other squareness error (i.e. rotation around Y-axis). For the B-axis, these parameters are XOB (i.e. pivot line position error in X-direction) and ZOB (i.e. pivot line position error in Z-direction), whereas COB (i.e. rotation around Z-axis) and AOB (i.e. rotation around X-axis) represent the squareness errors of the pivot line. Errors can be corrected directly in the kinematic chain; the results of the 5-axis test can thus be improved.

Case study DMU machine

The Rotary Inspector system was mounted on a 5-axis machine tool having a B- and a C-axis present at the table. The machine was commanded to continuously execute the corresponding NC file in a loop, moving all axes, see



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Schematics of kinematic tests on a 5-axis machine tool with B- and C-axis at the table (see Table 2).

Table 2
Programmed motions to heat up a 5-axis machine tool, set in a loop (see Figure 8).

Test name	B-axis angle	C-axis angle	Linear axes
BK1 test	0° › 90° › 0°	0° (idle)	X and Z follow, Y idle
BK2 test	0° (idle)	0° › 360° › 0°	X and Y follow, Z idle
BK4 test	0° › 90° 90° › 0° 0° › 90° 90° › 0°	0° › 180° 180° › 360° 360° › 180° 180° › 0°	X, Y and Z follow X, Y and Z follow X, Y and Z follow X, Y and Z follow

Table 3
Pivot line position error of the B-axis during heat-up.

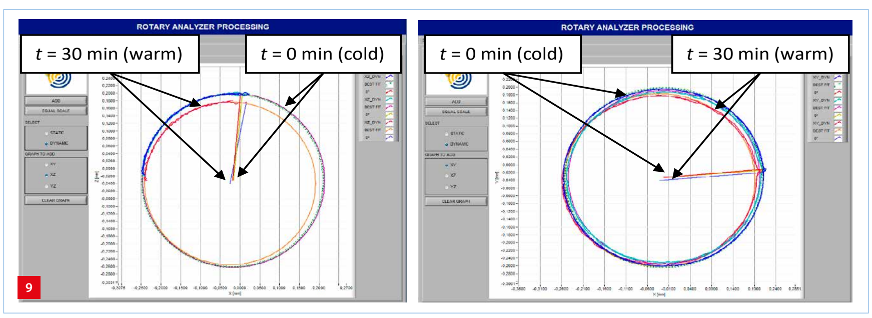
B-axis	XOB		ZOB	
Time *t* (min)	Value [mm]	Change [µm]	Value [mm]	Change [µm]
0	–0.0177	-	–0.0298	-
5	–0.0186	–0.9	–0.0309	–1.1
30	–0.0227	–4.1	–0.0410	–10.1
Cumulative		**–5.0**		**–11.2**

Table 4
Pivot line squareness error of B-axis during heat-up.

B-axis	AOB		COB	
Time *t* (min)	Value [°]	Change [°]	Value [°]	Change [°]
0	–0.0073	-	–0.0091	-
5	–0.0071	0.0002	–0.0091	-
30	–0.0071	-	–0.0100	–0.0009
Cumulative		**0.0002**		**–0.0009**

Figure 8 and Table 1. Feed rate was set to 1,500 mm/min. In Table 3 the results are compared between 'cold start', and after 5 and 30 minutes of 'heat-up by moving axes'. During the 30 minutes heat-up the B-axis has moved –5.0 µm in X-direction and –11.2 µm in Z-direction. The squareness of the B-axis pivot line to the linear axis was also determined, see Table 4. The rotation of the B-axis pivot line can be neglected as this is less than 1 millidegree.

The Rotary Inspector measurement data obtained can also be analysed using Rotary Analyzer software, showing best-fit circles in the XZ-plane for the B-axis (see Figure 9a) and in the XY-plane for the C-axis (see Figure 9b). As the machine was commanded to execute a relative circle with 0.2 mm radius (between a rotary axis and the circular path of two linear axes), measurement data is distributed on a circle.



Analysis results for the DMU machine.
(a) B-axis (XZ-plane).
(b) C-axis (XY-plane).

A perfect machine would show a concentric circle with 0.2 mm radius. Any deviations are representative of errors in the alignment of the rotary axis path to the linear axes or vice versa. The B-axis was measured with the BK1 test (see Table 2 and Figure 8); the measurement was performed twice, at $t = 0$ and $t = 30$ min. The C-axis was measured with the BK2 test (also at $t = 0$ and $t = 30$ min). Due to the drift of the total machine, the centre point of both the B- and C-axis in Figure 9 has moved. This has resulted in a different circular path as shown in both graphs; blue is the circular path for $t = 0$ (cold machine) and red is the path for $t = 30$ min (warm machine).

With the thermal errors measured, these can be automatically compensated. Such automation has been implemented at IBS for Siemens and Heidenhein machine controllers. With Siemens, for example, errors are corrected using the Siemens VCS (Volumetric Compensation System) application. For the Taiwanese market, a compensation module has been implemented that links to their smart machine platform, Productivity 4.0.

Summary

Thermal tests are considered as rather expensive because of the considerable machine down time. The thermal stability of 5-axis machine tools can vary a lot; from a few micrometres to more than one hundred micrometres. Besides the spindle also the machine's axes are moved in the latest standardised thermal machine tool tests to heat-up a machine. Measures to control and limit the machine's thermal distortion are applied more and more in industry and this trend is expected to continue in the next decade as it improves the machine's accuracy and stability significantly.

When calibrating a machine tool, its thermal behaviour should be considered for best accuracy. This means that heat-up cycles should be applied when testing a machine tool, representing its normal use better. Upon implementation of the fast and accurate 3D thermal test procedure presented in this article, high-precision machines should be able to achieve sub-micron thermal stability whereas the large, general-purpose machines may be expected to have a thermal stability in the order of 20 µm.

REFENCES
[1] ISO 230-3, "Test code for machine tools – Part 3: Determination of thermal effects", second edition, 2007.
[2] ISO 10791-10, "Test conditions for machining centres - Part 10: Evaluation of thermal distortions", first edition, 2007.
[3] ISO 10791-6, "Test conditions for machining centres – Part 6: Accuracy of speeds and interpolations", second edition, 2014.