Software based accuracy improvement of 5-axis machine tools by compensation of rotary axis errors

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1 INTRODUCTION

Complex workpieces such as turbine blades, impellors, medical protheses and complex machine frames, are typically manufactured today on 5-axis machine tools. The 5-axis continuous movements are realized by a combination of the machine's 3 linear and 2 rotary axes. The stability of the location of these axes is critical for meeting geometrical tolerances. This article presents an analysis on the stability of the pivot line of rotary axes using a fast and accurate 3D measuring method to determine the dynamic 5-axis performance of the machine [1,2,3,6,7].

Figure 1. Photo of measurement setup of Rotary Inspector, combining a 3D wireless probe with a precision master ball on a 5-axis machine tool.

2 EXPERIMENTAL PROCEDURE

During 5-axis machining, continuous movements between the spindle and the table are realized by a synchronized combination of the machine's three linear axes and two rotary axes. The correct relative location of these rotary axes to the other axes is critical for meeting geometrical tolerances. Location errors can occur due to:

1. Geometrical misalignment (For example at machine build, after a collision or work piece load) or
2. Distortion during thermal heat up.

The impact of these distortions can be highly machine or workpiece dependent.

If the errors in the pivot line location and orientation can be measured, they can be compensated in the controller for further optimization to improve the accuracy of the machine. This improvement in accuracy may then be validated with a 5-axis test.

To determine the location and orientation of the pivot line of a rotary axis, the Rotary Inspector (RI) is used, see Figure 1. A 3D wireless non-contact probe is placed in the spindle and represents the cutting tool. A precision master ball, placed on the table, represents the workpiece. Measurement sequences are applied according to ISO10791-6 to determine the kinematic accuracy of the machine [8].

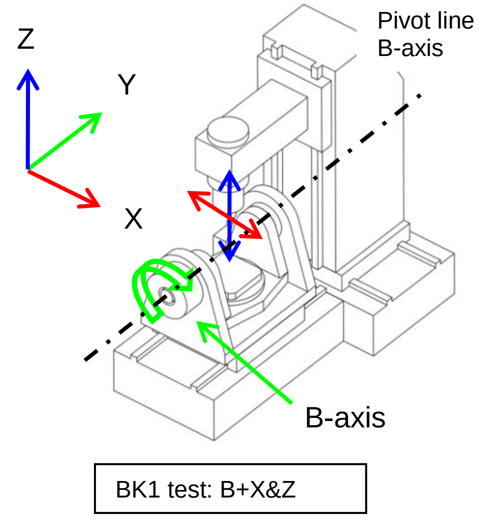

Figure 2. Schematic drawing of BK1 test.

For a trunnion table machine having two rotary axes at the table, three kinematic tests are performed named BK1, BK2 and BK4. In the BK1 test, see Figure 2, the B-axis is commanded to move +/- 90° degrees while the linear axes X and Z follow. Typically, this is executed in less than 30 seconds. In a perfect machine, the rotary and linear axes would follow each other perfectly. In practice errors occur and the deviations in relative position observed in the 3-axis test is used to determine the relative offset in the pivot line of the B-axis.

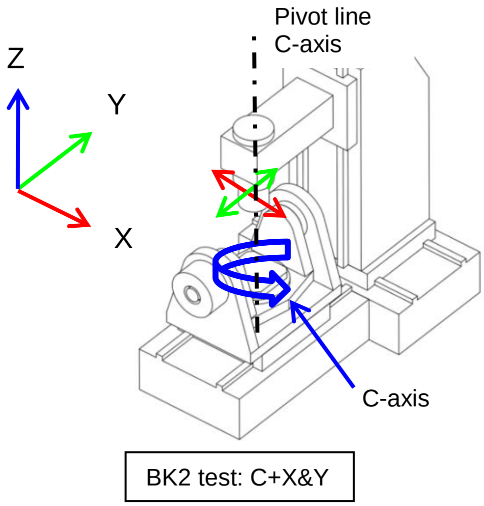

Figure 3. Schematic drawing of BK2 test.

For the BK2 test the C-axis executes a full circle clockwise and counterclockwise while the X- and Y-axis follow, see Figure 3. This is used to determine the C-axis pivot line location and orientation.

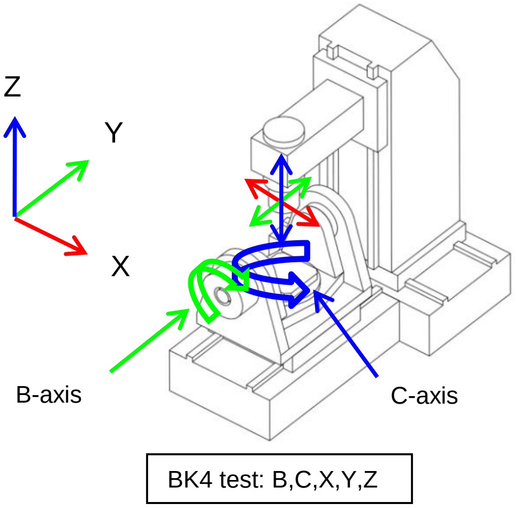

Figure 4. Schematic drawing of BK4 test.

The overall 5-axis accuracy is measured with the BK4 test, see Figure 4. For this test the C-axis moves twice as fast as the B-axis over its entire range while the X-, Y- and Z-axis follow, covering most of the machine's working space. The Rotary Inspector system executes the BK1, BK2 and BK4 test in an automated sequence in approximately 1 – 1,5 minutes, allowing the user to make a "snap-shot" of the machine's accuracy.

Table 1 B-axis errors derived from Rotary Inspector BK1 measurement.

	Nomenclature (ISO 10791-6)
XOB	Location error B-axis in X-direction (µm)
ZOB	Location error B-axis in Z-direction (µm)
AOB	Squareness error B-axis around X-axis (deg)
COB	Squareness error B-axis around Z-axis (deg)

After performing the BK1 and BK2 test, the errors in the axes pivot-lines can be compensated in the controller. In Table 1 are listed, as example, the errors derived for the BK1 test. The full BK4 5-axis test can be used to measure the accuracy before and after compensation.

In this paper 2 case studies are presented, in section 3 on geometrical misalignment; in section 4 on thermal stability.

3 EFFECT OF GEOMETRICAL ALIGNMENT

A Rotary Inspector measurement was carried out on a DMU50 5-axis machine and the data was used to compensate for the geometric errors. In Figure 5 the measurement result is displayed showing the deviations in X,Y and Z between the rotary table and linear axis positions during the 5-axis BK4 measurement. The span of these deviations indicates the 5-axis accuracy at 69 µm.

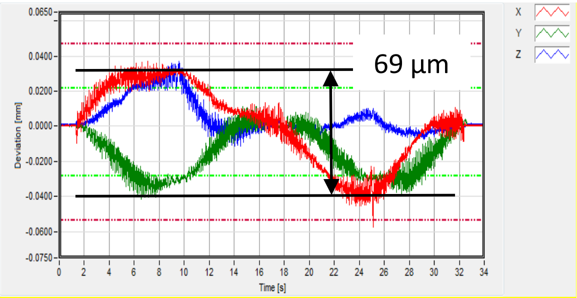

Figure 5. Result of BK4 test before compensation.

First the pivot position of the B- and C-axis was compensated, using the result from the BK1 and

BK2 measurement. Then the squareness errors of the rotary axes were compensated. It was observed that the resulting total 5-axis error was 0.0382 mm (figure 6), slightly larger than when the squarenesses were not compensated (0.019 mm), figure 7. This occurred despite that the individual 3-axis error measurements (BK1 and BK2) indicated an improvement after compensation for the pivot line location.

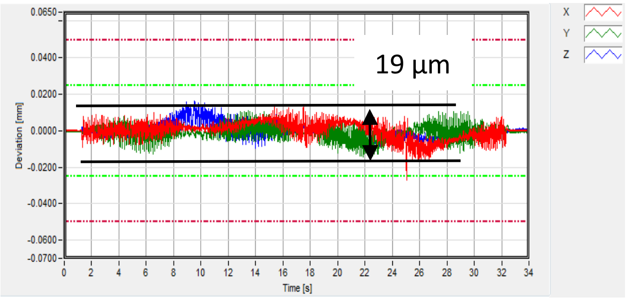

Figure 6. Result of BK4 test with pivot point compensation (no squareness).

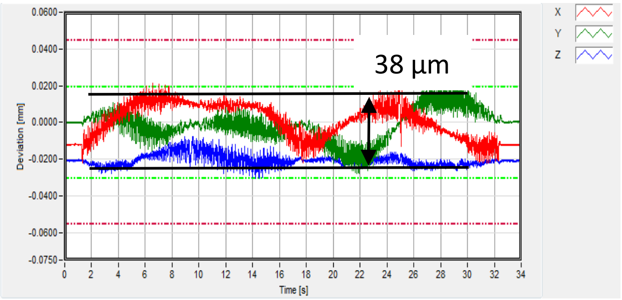

Figure 7. Result of BK4 test with pivot point and squareness compensation.

To address this, further measurements were carried out. In the standard BK1 measurement, the B-axis was measured with the C axis in zero position and the ball 177 mm in +Y direction. To investigate this issue, the B axis measurement was repeated with the C-axis at 180° and thus the 177 in –Y direction (see Figure 5).

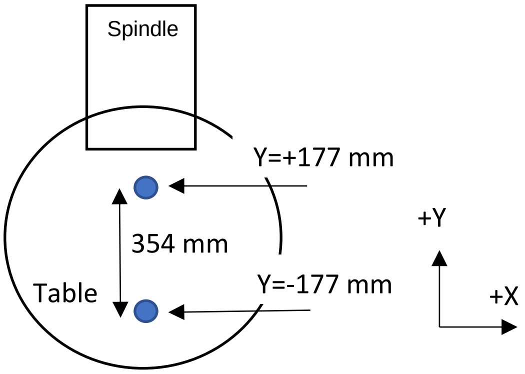

Figure 8. Schematic drawing of top-view, showing two master ball positions used for BK1 tests.

The pivot line error parameters in the Z-X plane are expect to be constant with Y. Thus this second measurement should have yielded the same results, but this was not the case, see Table 2. The B-axis pivot line was measured as displaced 18.6 µm in the Z-direction between these two measurements.

Table 2 B-axis parameters for BK1 measurement at Y= -177 mm and for Y= +177 mm.

Location [mm]	XOB [µm]	ZOB [µm]	AOB [°]	COB [°]
Y= -177	4.1	-18.9	0.0005°	-0.0002°
Y= +177	0.6	-0.3	0.0002°	0.0001°
Max-min	**3.5**	**18.6**	**0.0003°**	**0.0003°**

This result indicates a squareness error between the Y- and Z-axis (the Y-axis is sagging in Z whilst moving out in Y). This can be calculated at 3 millidegree (arctan(0.019/354)=0.0031°). The pivot line difference in X is 3.5 µm only and not considered further.

To correct this Y-Z squareness error, the B-axis parameter for AOB has been adjusted by 0.003° and the BK4 test is repeated once more. Figure 9 shows the result after compensation, a large improvement is observed; here an amplitude of only 15 µm is detected.

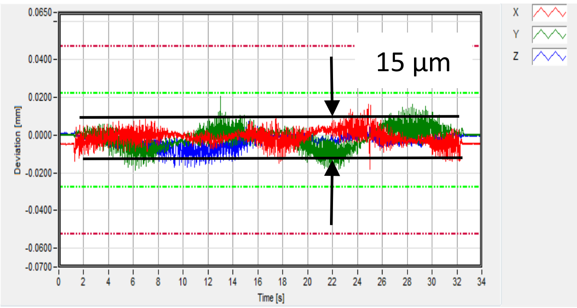

Figure 9. Result of BK4 measurement after adjustment of 0.003° to AOB.

When compensating 5-axis machine tools, the 5-axis test proved to be critical as a final check.

4 THERMAL STABILITY

Even after a machine's accuracy has been optimized, the accuracy can be influenced by error sources like thermal distortion. The influence of a machine warming up on the 5-axis accuracy has been studied in this section. Measurements in this case were on a second DMG machine. To heat-up the machine tool, its axes are moved continuously [4,5]. The measurement sequence containing the BK1, BK2 and BK4 tests were put in a loop and the location and orientation error of the pivot line of both rotary axes repeatedly determined.

In Table 3 the results show that the B-axis squareness did not change significantly (less than 1 millidegree) during a 30min thermal cycle. However, the pivot line position displaced -5.0 µm in X and -11.2 µm in Z-direction.

Table 3 *Location error and squareness error of pivot line B-axis during heat-up.*

B-axis	XOB [µm]	ZOB [µm]	AOB [°]	COB [°]
Time	Value	Value	Value	Value
t=0	-17.7	-29.8	-0.0073	-0.0091
t=5 min	-18.6	-30.9	-0.0071	-0.0091
t=30 min	-22.7	-41.0	-0.0071	-0.0100
Max-min	**-5.0**	**-11.2**	**0.0002**	**0.0009**

The results for the C-axis during this heat-up cycle are shown in Table 4. The pivot line of the C-axis shows a similar effect with a drift of -9.5 µm in X and -7.1 µm in Y-direction while the squareness error changed less than 0.3 millidegree.

Table 4 Location error and squareness error of pivot line C-axis during heat-up.

C-axis	XOC [µm]	YOC [µm]	AOC [°]	BOC [°]
Time	Value	Value	Value	Value
t=0	-17.9	-31.9	-0.0005	0.0002
t=5 min	-21.1	-32.6	-0.0006	0.0003
t=30 min	-27.4	-39.0	-0.0008	0.0002
Max-min	**-9.5**	**-7.1**	**-0.0003**	**-0.0001**

A relatively short warm up cycle does already show significant errors in the pivot line location which will have a significant effect on the part accuracy. With systems like the Rotary Inspector, these errors could be compensated, as shown in the previous paragraph. And as the measurement can be done during production within 1-1,5 minutes, allowing a continuous improvement of the accuracy of the machine.

5 SUMMARY

A 3D wireless probe and masterball are used to measure and compensate 5-axis machine tools in approximately 1-1,5 minute.

The system was used to not only identify the errors of the rotary axes, but as the BK4 test includes all machine's axis it was possible to identify and correct the squareness error of the linear axes.

Running the three ISO kinematic tests BK1, BK2, BK4 continuously, machine thermal stability can be assessed.

Compensation is a successful way to improve a machine's accuracy but this should always be checked with 5-axis tests as 3-axis tests alone can lead to misleading results or disappointing machine accuracy.

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