Metrology for parallel kinematic machine tools (PKM)

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Abstract

In the first part of this paper, the differences between metrology for serial kinematic machine tools (SKM) and parallel kinematic machine tools (PKM) are described, especially for the measurement of geometric deviations. These differences lead to special problems for the calibration of parallel kinematic machine tools, partly comparable to the problems for the calibration of five and multi-axis serial kinematic machine tools. In an initiative of the German NC Gesellschaft, the German association for NC technology, rules for testing PKM were established. A comparison of available test equipment for PKM, organised also by the NC Gesellschaft, resulted in a specification for future test equipment for PKM. The rules and specifications are discussed, also with respect to the applicability to multi-axis serial kinematic machine tools.

1 Machine tool metrology for SKM and PKM

Testing serial kinematic machine tools (SKM) with respect to geometric performance includes testing position and orientation of axes (e.g. squareness, parallelism, position of a rotational axes), testing component errors of single axes (e.g. straightness, pitch movement, angular positioning accuracy) and machining and measuring test pieces with special contours (e.g. straight line, circle, holes).

Typical for machine tool metrology for SKM are small measuring lengths and small angles, like the deviation from a straight line or the deviation from an angle equal to zero for the pitch movement of a linear axis. Large measuring lengths and angles are only needed for linear and angular positioning
measurements. These large lengths are not distances of any components, but lengths of travel of the linear axes, therefore laser interferometers or linear scales can be used easily for these measurements.

The general test procedures according to ISO 230-1 and ISO 230-2 [1,2], the test procedures for machining centres [3-6] and turning centres [7,8] check the performance of the machine tool between the tool and the work-piece. For SKM this automatically gives a simple relation to the error sources, i.e. to the erroneous components of the axes under test.

Therefore the results of the tests can be directly used for compensating the machine tool, e.g. the systematic positional deviation E according to ISO 230-2 [2] is directly used for the so called lead screw compensation provided by most numerical controls. On SKM geometric tests according to ISO [1-8] can be used for testing the performance and for calibrating.

On a six-axis parallel kinematic machine tool (PKM) a platform is moved by six struts that are directly connected to the platform by (spherical) joints. If just one of these six struts is moved, the platform will move in X, Y and Z and rotate around X, Y and Z. Any error observed between the tool and the work-piece might be caused by any erroneous movement of one of the six struts, or by any combination of struts. An erroneous movement of a strut could be caused by a wrong movement of the strut, by a wrong absolute length of the strut, or by a wrong movement in one of the (spherical) joints.

On a PKM the simple relation between the error measured between tool and work-piece and the error source is lost. For PKM the geometric tests according to ISO [1-8] are integral performance tests, like the diagonal displacement test [9] for an SKM. Therefore geometric tests according to ISO can be used for testing the performance of PKM, but not for calibrating PKM.

2 Calibration of a PKM

The calibration of a PKM is different from the calibration of an SKM, because – as shown in the previous paragraph – geometric tests according to ISO and according to common practice do not reveal the error sources of the PKM.

2.1 Influence of geometric errors varies with the position in the working volume

Furthermore, the influence of geometric errors varies significantly with the position in the working volume. Depending on the orientation of the struts, which depends on the position in the working volume, a particular amount of error might have a significant or a non-significant contribution to the error between tool and work-piece.
Figure 1: Influence of position in working volume to influence of error movements. Right strut is shortened by same amount for left and right figure. The resulting configuration (dotted line) in the left figure is mainly shifted horizontally, in the right figure mainly vertically.

Figure 1 shows a simple example: from a horizontal base line two struts reach to the working point. The position of the working point is changed by changing the lengths of the struts. The left and the right figures show two possible nominal working points (full lines). In the two positions the same amount of error, an erroneous movement of the right strut, is introduced. The dotted lines show the situation with the erroneous right strut. The resulting changed position of the working point is quite different, depending on the nominal position in the working volume.

2.2 Number of possible geometric errors

If we look at the possible number of geometric errors, we have to realise, that SKM represent an optimum design in this aspect. A five axes SKM has 52 possible geometric errors, whereas a PKM has 57 or 81 possible geometric errors.

Hexapods, PKM with struts, that change their lengths, have 57 possible geometric errors. Hexaglides, PKM with fixed struts and footpoints gliding on guideways, have 81 possible geometric errors (see Table 1). The advantage of hexaglides is the possibility of measuring more geometric features with common test methods already known from SKM (see following two sections).

2.3 Different types of geometric tests

The joints for the struts provide nominally a spherical movement, therefore a sphericity check is needed, not for a mechanical component, but for a movement.
The absolute lengths of the struts have to be known, because the movement of
the platform changes, if the length of a strut differs from the nominal length. A
test equipment for a direct measurement of the effective length of a mounted
strut is not available today.

The distances between the joints on the platform and on the machine bed,
respectively on the guideways have to be known, because again the movement
of the platform changes, if these distances differ from the nominal values. For
these distance measurements no equipment is available today.

The spherical movement of the joints could be checked on the machine tool if
the joints provided surfaces, that can be touched with probes, and if the PKM
can be moved around single joints.

The lengths of the struts and the distances between the joints can be pre-
calibrated on a coordinate measuring machine if the joints provide surfaces,
that can be touched with a probe.

2.4 Indirect calibration

Geometric features of a PKM that can be checked directly, like throw of the
spindle or straightness of guideways for hexaglides, are calibrated directly
using the same test equipment as for SKM.

Table 1: Number of geometric errors of SKM and PKM

<table>
<thead>
<tr>
<th>Component</th>
<th>Component Errors</th>
<th>Location Errors</th>
<th>Number of Geometric Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear axis</td>
<td>6</td>
<td>3</td>
<td>XYZ 27</td>
</tr>
<tr>
<td>Rotational axis</td>
<td>6</td>
<td>5</td>
<td>AB 22</td>
</tr>
<tr>
<td>Spindle</td>
<td>5</td>
<td>4</td>
<td>S 9</td>
</tr>
<tr>
<td>Spherical joint</td>
<td>1</td>
<td>3</td>
<td>S 9</td>
</tr>
<tr>
<td>- Fixed joint</td>
<td>1</td>
<td>-</td>
<td>J1-12 48</td>
</tr>
<tr>
<td>- Moveable joint</td>
<td>1</td>
<td>-</td>
<td>J1-6 24</td>
</tr>
<tr>
<td>Strut</td>
<td>1</td>
<td>1</td>
<td>J1-6 6</td>
</tr>
<tr>
<td>Variable length</td>
<td>1</td>
<td>1</td>
<td>L1-6 12</td>
</tr>
<tr>
<td>Fixed length</td>
<td>-</td>
<td>1</td>
<td>L1-6 6</td>
</tr>
<tr>
<td>Linear axis with spherical</td>
<td>3</td>
<td>5</td>
<td>X1-6 48</td>
</tr>
<tr>
<td>Joint coordinate system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine tool</td>
<td></td>
<td></td>
<td>-6</td>
</tr>
<tr>
<td>Platform</td>
<td></td>
<td></td>
<td>-6</td>
</tr>
</tbody>
</table>

| Total                         | 52               | 57              | 81                         |
Geometric features that cannot be checked directly, like lengths of struts and distances between joints, have to be calibrated indirectly. Here any movements in the working volume are measured, and the errors of such movements are used to calibrate (or optimise) geometric parameters.

The problem of the indirect calibration is, that any geometric deviation in the relative movement between tool and work-piece can be caused by many geometric errors, as shown in section 1.

3 Rules for calibration of PKM

The working group “parallel kinematic machine tools (PKM)” of the German NC Gesellschaft has set up rules for testing PKMs, that have been discussed with industry [10]. The rules are:

3.1 Acceptance tests for PKM shall be the same as for SKM

- ISO 10791-1/2/3/4/6/7/8 [3-6,12-14] are used as reference for machining centres.
- ISO 13041-1/4/7/8/10 [7,8,15-17] are used as reference for turning centres.
- Test results depend on the location of the measurement line within the working volume. This is true for SKM, as well as for PKM.
- On an SKM pitch and yaw movements influence the positioning accuracy, roll movements influence the out-of-straightness and the squareness. The influences are quite simple (Abbe offset).
- On a PKM the influence of geometric deviations (e.g. distances between joints, strut length, positioning accuracy) depends strongly on the location of the measurement line in the working volume.
- Testing nominal rotational movements of the platform of a PKM shall correspond to testing 45° split indexable or continuous heads, swivel heads or rotary heads of an SKM.
- PKM platforms, that can be rotated by 90°, shall be tested according to ISO 10791-1/2/3 annex A, B, C, geometric tests for machining centres [3-5].
- PKM platforms, that can be rotated, shall be tested according to ISO 10791-4, accuracy and repeatability of positioning of linear and rotary axes of machining centres [6], or according to ISO/DIS 13041-4, accuracy and repeatability of positioning of linear and rotary axes of turning centres [8], and according to ISO 10791-6, tests K5 and K6, flatness of the spindle movement and spherical interpolation accuracy for a machining centre [12].

3.2 The calibration of a PKM with 6 possible movements (X, Y, Z, A, B, C) shall be compared with the calibration of a 5-axis SKM

- The time needed to calibrate a swivel axis of an SKM can be significant.
- The measurement uncertainty for measurements on a swivel axis of an SKM shall be determined in detail.
The calibration of rotary tables and swivel axes of an SKM needs much more effort than the calibration of 3 linear axes.

3.3 Calibration shall be, if possible, a direct calibration. Indirect calibration differs for each type of PKM

- It is the know-how of the machine tool manufacturer, how to calibrate the machine tool. This is true for an SKM, as well as for a PKM.
- For an SKM the calibration is quite similar to the acceptance test.
- For a PKM common acceptance tests cannot be used for calibration.
- Most acceptance tests according to ISO are integral tests, if applied on a PKM, because many geometric deviations influence any acceptance test.
- Testing the positioning accuracy on a space diagonal according to ISO 230-6 [9] is an integral test for an SKM and a PKM. Testing the positioning accuracy parallel to X, Y, and Z on an SKM is a direct calibration of the measuring system of X, Y and Z respectively. Testing the positioning accuracy parallel to X, Y, and Z on a PKM is just an integral test.

3.4 Indirect and direct calibration become easier if more parameters are measured simultaneously

- X, Y, Z are measured simultaneously, instead of just one length or one angle.
- As a maximum, parameters X, Y, Z, A, B, C can be measured simultaneously.
- Testing a linear axis of an SKM becomes easier if one test equipment measures the positioning accuracy, as well as the out-of-straightness.
- It is assumed, that the indirect calibration of a PKM is easier if X, Y, Z, or if X, Y, Z, A, B, C are measured simultaneously (hypothesis).

3.5 Simultaneous measurement of the translations X, Y, Z simplifies the calibration of PKM, SKM and hybrid machine tools

- The simultaneous measurement of all six degrees of freedom (X, Y, Z, A, B, C) is so demanding, that it seems not realisable today.
- The simultaneous measurement of X, Y, Z seems to be realisable today.
- X, Y, Z should be measurable in the whole working volume of the machine tool.
- Such a test equipment would simplify and shorten acceptance tests and calibration of SKM.

4 Comparison of test equipment

The working group PKM of the German NC Gesellschaft also compared existing test instruments for PKM [11] based on the following specification for future test equipment:
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**mandatory requirements**
- measurement of X, Y, Z in working volume in the work-piece coordinate system
- measurement uncertainty 25-30% of ISO tolerances [3-8,12-16]
- resolution 10% of measurement uncertainty
- usability in workshop like a laser interferometer with respect to required operator experience and portability
- interface to numerical control available for major NC systems

**non-mandatory requirements**
- minimum working volume 200 mm x 200 mm x 200 mm
- maximum working volume 2000 mm x 2000 mm x 2000 mm
- measurement of X, Y, Z, A, B, C in working volume in the work-piece coordinate system
- time needed for acceptance test 1 week
- time needed for calibration ½ day – 1 day
- price < €50,000
- dynamic tests frequency of 100 Hz minimum

Test instruments compared are:

- **test piece** sphere plate measured in different spatial arrangements, probed with 3D probe system, use of electronic level
- **flexible test piece** tetrahedron, made of six struts and four spheres, special probe for machine tool
- **long range ball bar** long range ball bar as one redundant strut, or three long range ball bars in a tetrahedron arrangement to measure X, Y, Z simultaneously
- **serial linkage arm** like a SCARA robot with three joints, hold on the tool side by a sphere in a magnetic socket
- **laser tracker** laser interferometer following a cat’s eye, measuring travelled distance and the two angles of orientation of the beam
- **6D straight edge** straightedge with linear scale and five mechanical probes square to the linear scale
- **opto-mechanical 6D straight edge** linear scale with cross-grid, 2 optical probes on the cross grid, 3 mechanical probes square to the straight edge
- **µ-GPS of Zeiss** measurement of X, Y, Z in space with three laser distances
- **6D laser interferometer** measurement of travel with laser-interferometer, laser beam as basis for straightness and pitch measurement, roll measurement with electronic level
The results of the comparison are:

- **test piece**
  good for small machine tools, good for static tests, not applicable for dynamic tests

- **flexible test piece**
  measurement uncertainty for straightness might be too large, probe system has to be developed, time for acceptance test and calibration is unknown, price of equipment is unknown, not applicable for dynamic tests

- **long range ball bar**
  good equipment, not applicable for testing angular movements, like tilting platform

- **serial linkage arm**
  hardly usable, because of measurement uncertainty

- **laser tracker**
  measurement uncertainty for squareness might be too large, price of equipment is high, question to the measurement of the relative movement between tool and work-piece on smaller machine tools (laser tracker should be mounted on the work-piece side, optics on the tool side)

- **6D straight edge**
  good equipment, not applicable for testing angular positioning errors

- **opto-mechanical 6D straight edge**
  measurement uncertainty for roll, pitch, yaw might be too large, not applicable for testing angular positioning errors, possibly good equipment as a opto-mechanical 3D straight edge

- **μ-GPS of Zeiss**
  hardly usable, because of measurement uncertainty and small working volume

- **6D laser interferometer**
  the manufacturer’s statements to the measurement uncertainties have to be cross-checked first

Summarising, the test piece for small PKM, the long range ball bar, the 6D straight edge and the opto-mechanical 3D straight edge are potential test instruments for PKM calibration. Those instruments, except the test piece, are not commercially available today, and they are in the status of experimental set-ups.

### 5 Calibration of multi-axis SKM

The calibration of multi-axis, serial kinematic machine tools is not a simple task, as mentioned already in section 3.2. In particular, the calibration of the position and orientation of rotary and swivel axes is a demanding task. Also thermal influences on the location of rotary axes is subject of latest research.
In order to speed up the calibration procedure and to reduce the measurement uncertainty, new test instruments are searched for. Simultaneous measurement of X, Y and Z – as for PKM calibration – could simplify and improve the calibration of rotary axes. So any improvement for the calibration of PKM will also improve the calibration of multi-axis SKM.

6 Summary

SKM are an optimum with respect to the number of possible geometric errors. The geometric tests according to ISO can be used for acceptance as well as for calibration.

PKM have more geometric errors than SKM, the influences of geometric errors depend significantly on the position in the working volume, and geometric tests need new procedures, because special features like sphericity and absolute distances have to be calibrated. Geometric tests according to ISO are integral tests that cannot be used for direct calibration.

Testing PKM should be the same as for SKM. PKM calibration should be compared with the calibration of 5-axis SKM. Calibration of PKM can be simplified if three or more features are measured simultaneously.

Recommended test instruments are still in the experimental stage and need further development. Such instruments will also improve multi-axis SKM calibration.

References


