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Test code for machine tools —

Part 4:
Circular tests for numerically controlled machine tools

Code d'essai des machines-outils —

Partie 4: Essais de circularité des machines-outils à commande numérique

Reference number
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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This third edition cancels and replaces the second edition (ISO 230-4:2005), which has been technically revised.

The main changes are as follows:

— introduction of circular tests with rotary axes;

— application of definitions from ISO 230-1;

— inclusion of precautions when measuring rotary axes in Annex C.

A list of all parts in the ISO 230 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Test code for machine tools —

Part 4:
Circular tests for numerically controlled machine tools

1 Scope

This document provides methods for the determination of the contouring performance of numerically controlled machine tools.

This document specifies methods of testing and evaluating the bi-directional circular error, the mean bi-directional radial error, the circular error and the radial error of circular paths that are produced by the simultaneous movements of two linear axes.

This document also specifies methods of testing the deviations of the circular or constant radius trajectories generated by any combination of simultaneously controlled (coordinated) linear and rotary axes. The basic principle of these tests is to coordinate the multiple axes of motion (combination of rotary and linear axes) to keep the relative position between the tool and the workpiece constant.

This document describes differences between circular errors and radial errors (Annex A), influences of typical machine errors on circular paths executed with two linear axes (Annex B), precautions for test set-ups for circular tests with rotary axes (Annex C), an example of adjustment of diameter and contouring speed for circular tests (Annex D), and circular tests using feedback signal (Annex E).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 230-1:2012, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

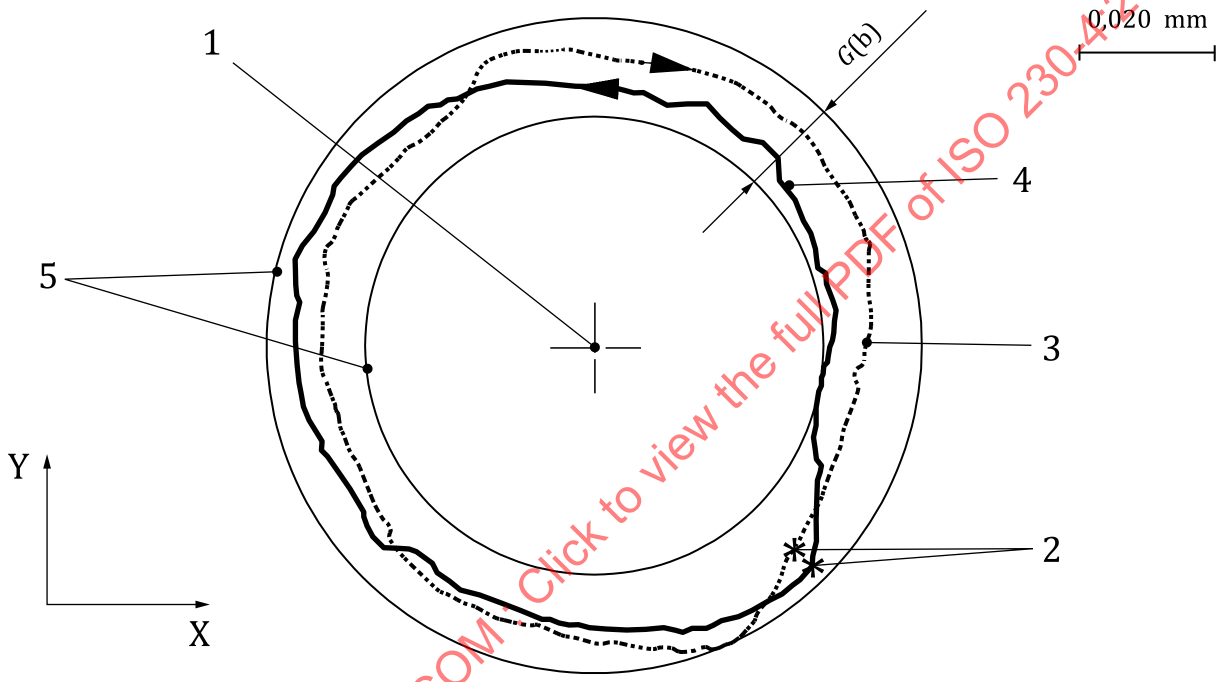
3.1
nominal path
<circular interpolation> numerically controlled and programmed circular path defined by its diameter (or radius), the position of its centre and its orientation in the working zone of the machine tool and which may be either a full circle or a partial circle of at least 90°

Note 1 to entry: Linear interpolation (G01) or circular interpolation (G02 or G03) or other types of interpolation may be used to generate nominal circular path.

3.2
actual path
path produced by the machine tool when programmed to move on the *nominal path* (3.1)

3.3
bi-directional circular error
bi-directional circular deviation
G(b)
minimum radial separation of two concentric circles (minimum zone circles) enveloping two *actual paths* (3.2), where one path is carried out by a clockwise contouring motion and the other one by an anticlockwise (counter-clockwise) contouring motion

Note 1 to entry: See Figure 1, where bi-directional circular error $G(b)_{XY}$ = 0,015 mm. The indices identify the axes moved during the circular test (see 3.7).



Key
1 centre of least squares circle of the two actual paths according to Note 2 to entry
2 starting points
3 actual path, clockwise
4 actual path, anticlockwise (counter-clockwise)
5 concentric circles enveloping the actual paths

Figure 1 — Evaluation of bi-directional error *G*(b) using least squares circle

Note 2 to entry: The bi-directional circular error *G*(b) can be evaluated as the maximum radial range of deviations around the least squares circle. The least squares circle is calculated from two paths, i.e. the clockwise and the anticlockwise (counter-clockwise) paths.

Note 3 to entry: Bi-directional circular error *G*(b) does not include set-up errors, i.e. centring errors of the measuring instrument.

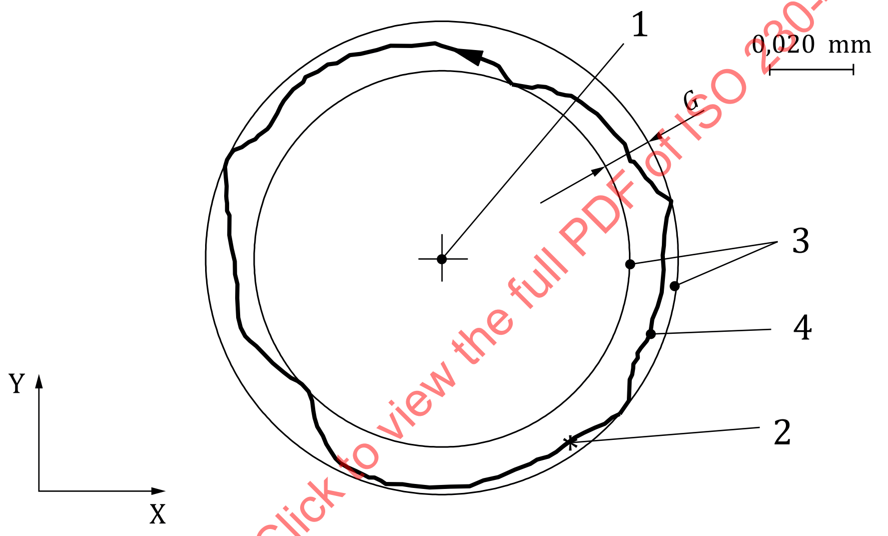
Note 4 to entry: Bi-directional circular error *G*(b) measurement requires the use of test equipment only with calibrated displacement measurements (no need for calibrated length measurements for path diameter). The measurements of *radial error F* (3.5) and *mean bi-directional radial error value D* (3.6) require test equipment with both calibrated length and calibrated displacement (see Annex A).

Note 5 to entry: A line situated in a plane is said to be circular when all its points are contained between two concentric circles whose radial separation does not exceed a given value (see Figure 2).

Note 6 to entry: Designation G(b) is for measurements with external measurement equipment only, for example as described in ISO 230-1:2012, 11.3.4. Results from circular tests using a feedback signal are designated as "bi-directional circular error using feedback signal $G(\text{b})_\text{f}$" (see Annex E).

3.4
circular error
circular deviation
G
minimum radial separation of two concentric circles enveloping the *actual path* (3.2) (minimum zone circles) of a clockwise or anticlockwise (counter-clockwise) contoured path

Note 1 to entry: See Figure 2, where circular error G_{XY} = 0,012 mm. The sequence of indices denotes the direction of contouring (see 3.8).



Key

1 centre of least squares circle of the actual path according to Note 2 to entry
2 starting point
3 concentric circles enveloping the actual path
4 actual path

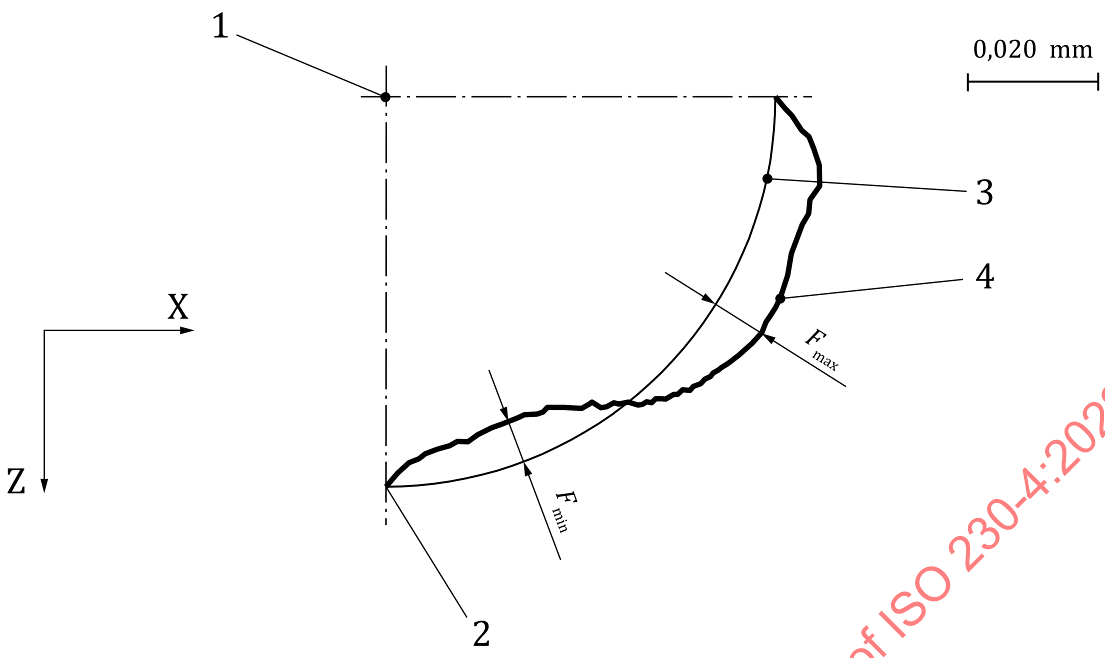
Figure 2 — Evaluation of circular error *G* using least squares circle

Note 2 to entry: Note 2 to entry to Note 6 to entry for *bi-directional circular error G(b)* (3.3) apply for circular error *G*. For differences between the circular error *G* and the *radial error F* (3.5), see Annex A, Table A.1.

Note 3 to entry: Designation *G* is for measurements with external measurement equipment, for example as described in ISO 230-1:2012, 11.3.4, only. Results from circular tests using feedback signal shall be designated circular error using feedback signal G_f, see Annex E.

3.5
radial error
radial deviation
F
deviation between the *actual path* (3.2) and the *nominal path* (3.1), where the centre of the nominal path is obtained either a) from the centring of the measuring instruments on the machine tool or b) from the least squares centring analysis for a full circle only

Note 1 to entry: See Figure 3, where radial error $F_{ZX,\,max}$ = +0,008 mm and radial error $F_{ZX,\,min}$ = −0,006 mm. The sequence of indices denotes the direction of contouring (see 3.8).



Key

1 centre of nominal circle
2 starting point
3 nominal path
4 actual path

Figure 3 — Evaluation of radial error *F*

Note 2 to entry: Positive deviations are measured away from the centre of the circle and negative ones towards the centre of the circle (see Figure 3). The radial error is given by the maximum value, F_{max}, and the minimum value, F_{min}.

Note 3 to entry: Set-up errors can be included in the radial error *F*; this is applicable only where the centre of the nominal path is obtained from the centring of the measuring instrument on the machine tool [option a) of the definition].

Note 4 to entry: For differences between the radial error *F* and the *circular error G* (3.4), see Annex A, Table A.1.

3.6
mean bi-directional radial error
mean bi-directional radial deviation
D
difference between the radius of the least squares circle of two full circle *actual paths* (3.2), where one path is carried out by a clockwise contouring motion and the other one by an anticlockwise (counter-clockwise) contouring motion, and the radius of the *nominal path* (3.1)

Note 1 to entry: For differences between mean bi-directional radial error *D* and *bi-directional circular error G*(b) (3.3), see Annex A, Table A.1.

3.7
identification of axes
designation of the axes which are moved to produce the *actual path* (3.2)

3.8
sense of contouring for circular tests with linear axes
<clockwise/anticlockwise (counter-clockwise) contouring> sequence of indices denoting the direction of contouring

Note 1 to entry: The order of the indices matches the order in which the circular arc crosses the positive extreme of each axis. For example, G_{XY} denotes the anticlockwise (counter-clockwise) *circular error* (3.4), because an anticlockwise (counter-clockwise) arc in the XY plane crosses the X+ axis immediately followed by the Y+ axis. Similarly, G_{YX} denotes the clockwise *circular error* (3.4), because a clockwise arc in the XY plane crosses the Y+ axis immediately followed by the X+ axis. In the case of a bi-directional result, the indices denote the direction of the first arc.

3.9
contouring interpolation error
contouring interpolation deviation
E_{int}
range of deviations of the tool centre point trajectory from the fixed point in the *workpiece coordinate system* (3.11), when a rotary axis (or axes) is (are) driven, synchronously with interpolated circular motion with linear axes, such that the tool centre point nominally stays at this fixed point in the *workpiece coordinate system* (3.11)

Note 1 to entry: Typical test methods are described in ISO 230-1:2012, 11.3.5. Typical measuring instruments are described in ISO/TR 230-11:2018, 12.2.1, 12.3.3 and 12.3.4.

Note 2 to entry: If the length-measuring device (ball bar, linear displacement sensor or nest of three linear displacement sensors) is rotated with a rotary axis, the measurements are taken in the coordinate system attached to the rotary axis, i.e. in radial, tangential and/or axial direction. This is specified by $E_{\mathrm{int,radial}}$, $E_{\mathrm{int,tangential}}$ and $E_{\mathrm{int,axial}}$.

Note 3 to entry: If the length-measuring device (ball bar, linear displacement sensor or nest of three linear displacement sensors) is not rotated with a rotary axis, the measurements are taken in X, Y and Z directions of the *machine coordinate system* (3.10). This is specified by $E_{\mathrm{int,X}}$, $E_{\mathrm{int,Y}}$ and $E_{\mathrm{int,Z}}$.

Note 4 to entry: The axes moved are specified by giving the nomenclature of the axes. For example, a measurement with linear axes X and Y and rotary axis C in radial direction is specified by $E_{\mathrm{int,radial,XYC}}$. A measurement with three linear axes X, Y, Z and two rotary axes A, C in radial direction corresponds to a spherical test according to ISO 230-1:2012, 11.5 and is specified by $E_{\mathrm{int,radial,XYZAC}}$.

Note 5 to entry: Clockwise or anticlockwise (counter-clockwise) movement is defined by the rotary axes if there is just one rotary axis moved. If two rotary axes are moved, clockwise and anticlockwise (counter-clockwise) are defined by the axis that moves over a larger range, generally the axis that moves over 360°. Clockwise is specified by CW, anticlockwise (counter-clockwise) is specified by CCW. For a clockwise measurement with the axes X, Y and C in radial direction the specification is $E_{\mathrm{int,radial,XYC(CW)}}$.

Note 6 to entry: Precautions for test set-ups for circular tests with rotary axes are given in Annex C.

3.10
machine coordinate system
MCS
right-hand rectangular system with the three principal axes labelled X, Y and Z, with rotary axes about each of these axes labelled A, B and C, respectively

Note 1 to entry: The machine coordinate system is prescribed by ISO 841 for many machine tools.

[SOURCE: ISO 230-1:2012, 3.2.1, modified — figure deleted and Note 1 to entry added.]

3.11
workpiece coordinate system
WCS
Cartesian coordinates fixed on the workpiece

Note 1 to entry: When a machine tool has the rotary axis (axes) on the workpiece side, the workpiece coordinate system is rotated with the rotary axis (axes).

[SOURCE: ISO 2806:1994, 2.7.3, modified — Note 1 to entry added.]

4 Test conditions

4.1 Test environment

Where the temperature of the environment can be controlled, it shall be set at 20 °C or at the specified reference temperature. If the environment is at a temperature other than 20 °C or other than the specified reference temperature, nominal differential thermal expansion (NDE) correction between the measurement system and the measured object (machine tool) shall be made to correct the results to correspond to 20 °C or to the specified reference temperature (for radial error measurements only).

The machine and, if relevant, the measuring instrument shall have been in the test environment long enough to have reached a thermally stable condition before testing. They shall be protected from draughts and external radiation, such as sunlight and overhead heaters.

4.2 Machine to be tested

The machine shall be completely assembled and fully operational. All necessary levelling operations and functional checks shall be completed before starting the tests.

Unless otherwise agreed between the manufacturer or supplier and the user, the circular tests shall be carried out with the machine in the unloaded condition, i.e. without a workpiece.

4.3 Machine warm-up

The tests shall be preceded by an appropriate warm-up procedure, as specified by the manufacturer of the machine and/or agreed between the supplier or manufacturer and the user.

If no other conditions are specified, the preliminary movements shall be restricted to only those necessary to set up the measuring instrument.

4.4 Test parameters

The parameters of the test are:

a) diameter (or radius) of the nominal path and – for tests with rotary axis (axes) – radial offset(s) from rotary axis(axes);

b) contouring speed (information on adjustment of diameter and contouring speed for circular tests to keep the axes' acceleration constant, see Annex D);

c) sense of contouring for circular tests with linear axes, and with rotary axes clockwise or anticlockwise (counter-clockwise) according to 3.8 and 3.9;

d) identification of axes, i.e. machine axes moved to produce the actual path;

e) location of the measuring instrument in the machine tool working zone;

f) temperature (environment temperature, measuring instrument temperature, machine temperature) and expansion coefficient (of machine tool, of measuring instrument) used for compensation for mean bi-directional radial error D and radial error F measurement only;

g) data acquisition method (data capture range if different from 360°, starting and stop points of the actual movement, number of measuring points taken for digital data acquisition and information about filtering, as applicable);

h) any machine compensation routines used during the test cycle;

i) positions of slides or moving elements on the axes which are not being tested.

4.5 Test instrument calibration

For the checking of the mean bi-directional radial error *D* and the radial error *F*, the reference dimension of the test instrument (e.g. reference length L_B of the ball bar) shall be known.

NOTE For circular tests using a feedback signal, see Annex E.

4.6 Measurement uncertainty

The main contributors to the measurement uncertainty for the bi-directional circular error *G*(b), the circular error *G* and the contouring interpolation error E_{int} are:

— measurement uncertainty of the test equipment;

— repeatability of measurement;

— influence of temperature on the machine tool and/or the test equipment, checked, for example, by an environmental temperature variation (ETV) test according to ISO/TR 16015.

The main contributors to the measurement uncertainty for the mean bi-directional radial error *D* and the radial error *F* are:

— contributors for the errors *G*(b) and *G* (see first list in 4.6);

— uncertainty of the temperature measurement of the machine tool and the test equipment [caused by the uncertainty of the temperature sensor(s) and the uncertainty due to the location of the temperature sensor(s)];

— uncertainty of the thermal expansion coefficients of the machine tool and the test equipment (used for the compensation to 20 °C or to the specified reference temperature).

5 Test procedure

To determine bi-directional circular error *G*(b), mean bi-directional radial error *D,* two actual paths shall be measured consecutively: one in a clockwise sense of contouring and the other in an anticlockwise (counter-clockwise) sense of contouring.

To determine circular error *G*, radial error *F* and contouring interpolation error E_{int}, the measurement shall be once for clockwise contouring and once for anticlockwise (counter-clockwise) contouring. Clockwise and anticlockwise (counter-clockwise) for contouring interpolation error are defined by the rotary axis. If two rotary axes are moved, clockwise and anticlockwise (counter-clockwise) for contouring interpolation error are defined by the rotary axes with the larger range of movement, generally the rotary axis moving over 360° (see 3.9, Note 5 to entry).

All measured data corresponding to the actual path (including any peaks at reversal points) shall be used in the evaluation.

For radial error, *F*, of a partial circle, set-up errors should be minimized.

Typical measuring methods for circular test with two linear axes are rotating one-dimensional linear displacement sensor, circular master and two-dimensional displacement sensor, telescoping ball bar, two-dimensional digital scale and two linear displacement sensors and a reference square artefact (as described in ISO 230-1:2012, 11.3.4). Measuring instruments are described in ISO/TR 230-11:2018, 12.2.1 (telescoping ball bar) and 12.3.1 (two-dimensional digital scale).

Typical measuring methods for circular tests with rotary axis(axes) are linear displacement sensor and spherical artefact, three linear displacement sensors and spherical artefact (radial test), telescoping ball bar (as described in ISO 230-1:2012, 11.3.5 and 11.5). Measuring instruments are described in

ISO/TR 230-11:2018, 12.2.1 (telescoping ball bar), 12.3.3 (3D-probe for spheres, contact type), and 12.3.4 (3D-probe head, non-contact type).

For influences of typical machine errors on circular paths executed with two linear axes, see Annex B and References [7] to [12].

Annex C summarizes precautions for test set-ups for circular tests with rotary axes.

6 Presentation of results

A graphical method of presenting results is recommended with the following test result data specified numerically:

a) for circular tests with linear axes

1) bi-directional circular error $G(\mathrm{b})$;

2) mean bi-directional radial error D, corrected to 20 °C or to the specified reference temperature;

3) circular errors G, for clockwise and/or anticlockwise (counter-clockwise) contouring;

4) radial errors, F_{max} and F_{min}, for clockwise and anticlockwise (counter-clockwise) contouring, corrected to 20 °C or to the specified reference temperature;

b) for circular tests including rotary axes

contouring interpolation error E_{int} for clockwise and for anticlockwise (counter-clockwise) movements.

Typical examples of presentation of test results are shown in Table 1, Table 2 and Table 3, which also apply for contouring interpolation error E_{int} (see Figure C.5). When a polar plot is not available for contouring interpolation error, an X-Y plot with the nominal angular position of the rotary axis of interest is acceptable (see Figure C.6).

NOTE For better clarity, the presentation of results is shown in three tables (Table 1, Table 2 and Table 3) in this document. In a test report, the three tables can be combined into one table.

The test report shall include the following:

— date of test;

— name of machine tool;

— measuring equipment;

— test parameters (see 4.4).

Magnification scale of the graphical presentation shall be stated.

The test uncertainty shall be stated.

7 Points to be agreed between supplier or manufacturer and user

The points to be agreed between the supplier or manufacturer and the user are as follows:

a) warm-up procedure prior to testing the machine (see 4.3);

b) test parameters (see 4.4);

c) for circular tests with linear axes, which test result data for the bi-directional circular error $G(\mathrm{b})$, the mean bi-directional radial error D, the circular error G, the radial error F [from 6 a) 1) to 6 a) 4)] are required and to be presented; and for circular tests with rotary axis (axes), which contouring interpolation errors E_{int} are required and are to be presented.

Table 1 — Example of data presentation for bi-directional circular error G(b) and mean bi-directional radial error D

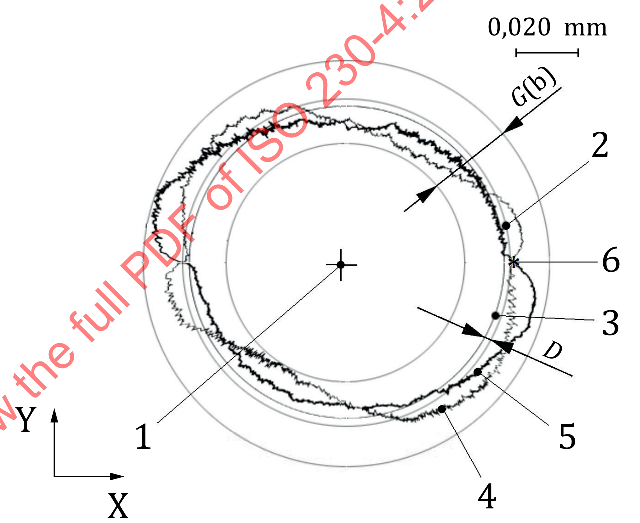
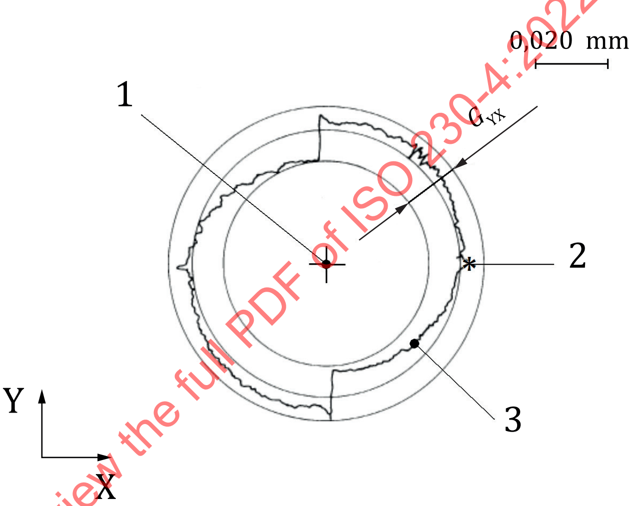
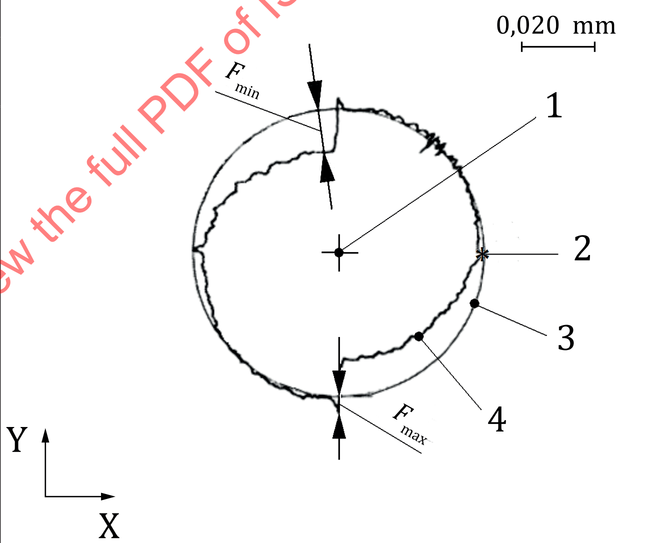
<table>
<tr><td>Date of test</td><td>yy/mm/dd</td><td>Name of machine</td><td>xyz</td></tr>
<tr><td>Measuring instrument</td><td>abc</td><td colspan="2">Location of measuring instrument</td></tr>
<tr><td colspan="2">Test parameters</td><td>centre of circle (X/Y/Z)</td><td>250 mm/250 mm/100 mm</td></tr>
<tr><td>diameter of nominal path</td><td>40 mm</td><td>offset to tool reference (X/Y/Z)</td><td>0 mm/0 mm/−80 mm</td></tr>
<tr><td>contouring speed</td><td>500 mm/min</td><td>offset to workpiece reference (X/Y/Z)</td><td>0 mm/0 mm/30 mm</td></tr>
<tr><td>contouring direction</td><td>—</td><td colspan="2" rowspan="5">
</td></tr>
<tr><td>machine axes under test
(X, Y, Z)</td><td>XY</td></tr>
<tr><td colspan="2">Data acquisition method</td></tr>
<tr><td>starting point</td><td>0°</td></tr>
<tr><td>stop point</td><td>0°</td></tr>
<tr><td>number of measuring points (digital only)</td><td>1 500</td><td colspan="2" rowspan="5">Key
1 centre of least squares circle of the two actual paths
2 nominal path
3 least squares circle of two actual paths
4 actual path, anticlockwise (counter-clockwise)
5 actual path, clockwise
6 starting point</td></tr>
<tr><td>data smoothing process</td><td>none</td></tr>
<tr><td>Compensation used</td><td>none</td></tr>
<tr><td>Positions of axes not under test</td><td>Z = 150 mm</td></tr>
<tr><td colspan="2">NOTE
bi-directional circular error $G(b)_{XY}$ = 0,028 mm
mean bi-directional radial error D_{XY} = −0,001 mm</td></tr>
</table>

Table 2 — Example of data presentation for circular error *G*

<table>
<tr><td>Date of test</td><td>yy/mm/dd</td><td>Name of machine</td><td>xyz</td></tr>
<tr><td>Measuring instrument</td><td>abc</td><td colspan="2">Location of measuring instrument</td></tr>
<tr><td colspan="2">Test parameters</td><td>centre of circle (X/Y/Z)</td><td>250 mm/250 mm/300 mm</td></tr>
<tr><td>diameter of nominal path</td><td>250 mm</td><td>offset to tool reference (X/Y/Z)</td><td>0 mm/0 mm/−80 mm</td></tr>
<tr><td>contouring speed</td><td>1 000 mm/min</td><td>offset to workpiece reference (X/Y/Z)</td><td>0 mm/0 mm/230 mm</td></tr>
<tr><td>contouring direction</td><td>+Y to +X</td><td colspan="2" rowspan="10">


Key
1 centre of least squares circle
2 starting point
3 actual path, clockwise</td></tr>
<tr><td>machine axes under test (X, Y, Z)</td><td>XY</td></tr>
<tr><td colspan="2">Data acquisition method</td></tr>
<tr><td>starting point</td><td>0°</td></tr>
<tr><td>stop point</td><td>0°</td></tr>
<tr><td>number of measuring points (digital only)</td><td>1 800</td></tr>
<tr><td>data smoothing process</td><td>none</td></tr>
<tr><td>Compensation used</td><td>none</td></tr>
<tr><td>Positions of axes not under test</td><td>Z = 350 mm</td></tr>
<tr><td colspan="2">NOTE
circular error G_{YX} = 0,018 mm</td></tr>
</table>

Table 3 — Example of data presentation for radial error *F*

Date of test	yy/mm/dd	**Name of machine**	xyz
Measuring instrument	abc	**Location of measuring instrument**	
Test parameters		centre of circle (X/Y/Z)	250 mm/250 mm/100 mm
diameter of nominal path	150 mm	offset to tool reference (X/Y/Z)	0 mm/0 mm/−80 mm
contouring speed	300 mm/min	offset to workpiece reference (X/Y/Z)	0 mm/0 mm/30 mm
contouring direction	+Y to +X	**Temperature**	
machine axes under test (X, Y, Z)	XY	environment temperature	22 °C
Data acquisition method		temperature of the measuring instrument	22 °C
starting point	0°	machine temperature	22 °C
stop point	0°		
number of measuring points (digital only)	1 800		
data smoothing process	none		
Compensation used	none	**Key** 1 centre of least squares circle 2 starting point 3 nominal path 4 actual path, clockwise	
Positions of axes not under test	Z = 150 mm		
NOTE radial error: $F_{YX,max}$ = +0,005 mm $F_{YX,min}$ = −0,013 mm			

Annex A
(informative)

Differences between circular errors *G* and *G*(b) and radial errors *F* and *D*

Table A.1 — Differences between circular errors *G* and *G*(b) and radial errors *F* and *D*

Influences	Circular errors *G* and *G*(b)	Radial error *F* and *D*
Deviation of form[a]	Included	Included
Deviation of diameter[b]	Not included, as the diameters of the minimum zone circles are not evaluated	Included
Deviation of position[c]	Not included, as the position of the minimum zone circles is defined by the actual path only	Included in *F* for a partial circle, not included in *F* for a full circle and not included in *D*

[a] Deviation between the shape of the actual path (e.g. elliptical form deviation) and a circle.

[b] Deviation between the diameter of the actual path and the diameter of the nominal path.

[c] Deviation between the position of the centre of the actual path and the centre of the nominal path (e.g. errors in the X and Y positions).

Annex B
(informative)

Influences of typical machine errors on circular paths executed with two linear axes

B.1 General

This annex points to the principal influences of typical machine errors on circular motion. In general, these individual errors show a combined influence on actual paths. Therefore, the information in this annex alone is not sufficient for a detailed analysis of circular measurements. Detailed analysis of circular measurements is described in References [10] and [11].

Circular paths that are produced by two linear axes on numerically controlled machines are influenced by geometric errors of the two axes and by errors caused by the numerical control and its drives.

B.2 Influence of geometric errors

B.2.1 Influence of a progressive linear positioning error

When the X-axis movement is long, for example, due to a scale error, the actual path is changed to an ellipse with its major diameter parallel to the X-axis. If the Y-axis is assumed to be error free, the diameter of the path parallel to Y-axis is not changed, i.e. the diameter is equal to the nominal diameter [see Figure B.1 a)].

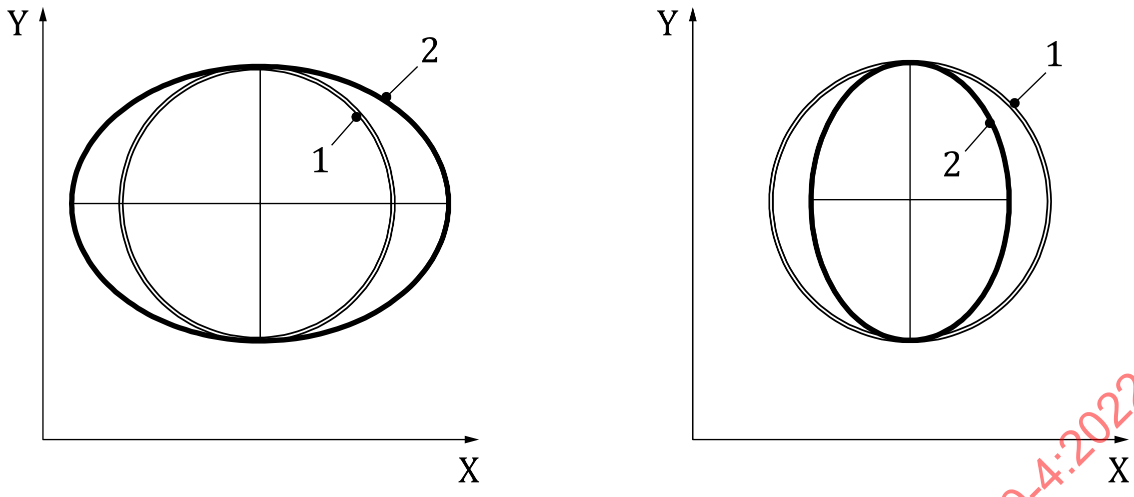
When the X-axis movement is short and the Y-axis is still assumed to be without errors, the actual path is changed to an ellipse with its major diameter parallel to Y-axis. That diameter is again equal to the nominal diameter [see Figure B.1 b)].

Figure B.1 can be evaluated as described if a measuring system is used that measures deviations from the nominal path (e.g. 2D grid scale, telescoping ball bar calibrated for radius). If the measuring device measures changes of the radius only (e.g. telescoping ball bar not calibrated for radius), the scales of the two machine tool axes moved cannot be evaluated, only any mismatch between the two machine tool axes, generally stated as “scale mismatch”.

B.2.2 Influence of squareness error of axes

When axes X and Y are not square and the angle between the two axes is larger than 90°, the actual path is changed to an ellipse with its principal axes at ± 45°. The major diameter of the ellipse is at −45° (+135°) [see Figure B.2 a)]. In addition, it is assumed that the squareness error is the only error in the XY plane.

When the angle between the two axes is smaller than 90°, the actual path is again changed to an ellipse with its principal axes at ±45°, but with the major diameter at +45° (+225°) [see Figure B.2 b)].



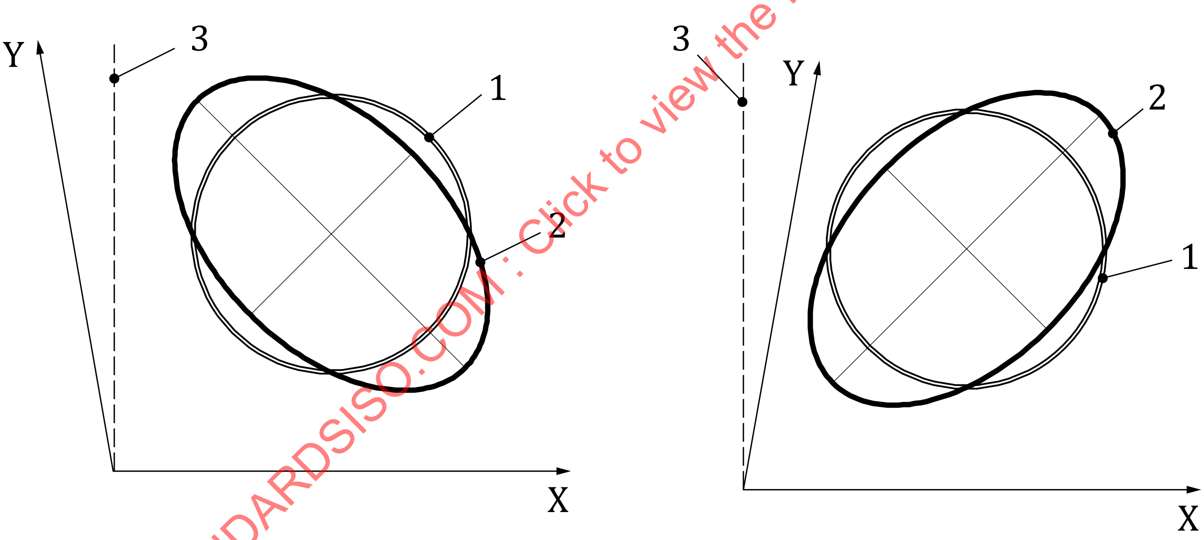
a) X-axis movement long **b) X-axis movement short**

Key

1 nominal path

2 actual path

Figure B.1 — Influence of short and long movements of an axis on actual paths



a) Angle larger than 90° **b) Angle less than 90°**

Key

1 nominal path

2 actual path

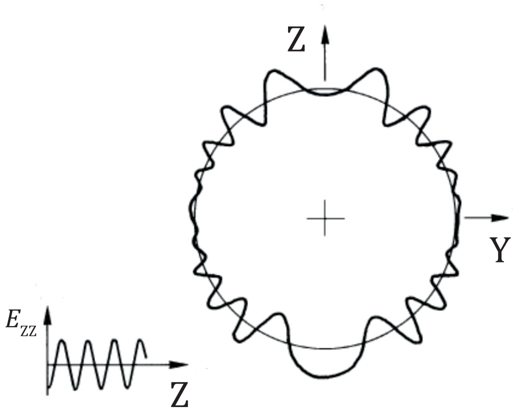
3 nominal Y-axis (square to X-axis)

Figure B.2 — Influence of squareness error of axes on actual paths

B.2.3 Influence of periodic errors

Periodic errors also influence actual paths. The deviation from the circular path is non-elliptic. Figure B.3 shows changes to the path if a periodic positioning error of Z-axis is assumed.

Other periodic errors (e.g. straightness error and angular error motion) can produce non-elliptic deviations from the circular path.



Key

E_{ZZ} positioning error of Z

Figure B.3 — Influence of periodic positioning errors of Z-axis

B.3 Influence of the numerical control and its drives

B.3.1 General

A circular path that is produced by two linear and numerically controlled axes gives information on the behaviour of the numerical control and its drives. The movement for each axis is quite complicated, with travel, velocity and acceleration of each axis changing, according to a sine or to a cosine if the feed speed on the circular path is kept constant.

B.3.2 Influence of reversal error

When axial reversal error is present, “steps” occur at the points of reversal. Figure B.4 shows typical reversal error occurring at the four quadrature points (from both axes) giving four quadrants with different centres. For uncompensated reversal error, the figure shows the typical shape produced by anticlockwise (counter-clockwise) contouring.

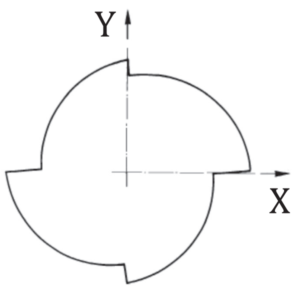


Figure B.4 — Quadrature reversal steps

When recovery of the reversal error occurs [whether by the use of scales for the feedback or by use of reversal compensation in the computerized numerical control (CNC)], time delay effects cause peaks or “spikes” at the reversal points (see Figure B.5). The magnitude of these “spikes” will depend on the mechanical backlash, elastic deformation due to friction and the time delay.

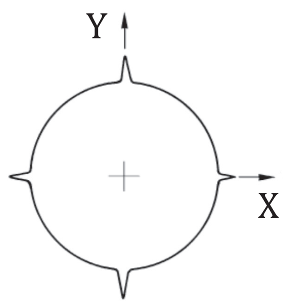


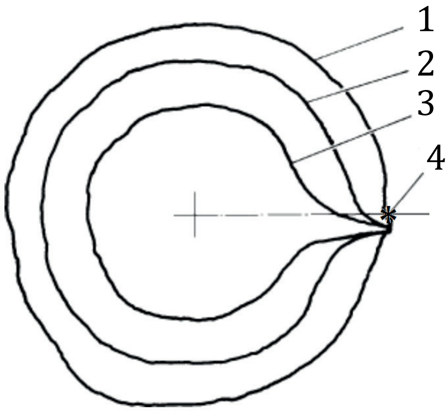
Figure B.5 — Quadrature reversal spikes

Note that the “steps” and “spikes” at reversal points are actually distorted “flats” and show up on machined circles, but do not appear on standard checks of the accuracy and repeatability of positioning of linear axis (e.g. according to ISO 230-2), because the measurements are taken only after the machine movement has stopped, in accordance with these standard checks.

In practice, both “spikes” and “steps” can occur together by different amounts. If, in addition, reversal error compensation and/or friction compensation is applied that does not exactly match the existing error, then quite complex shapes can occur at quadrature, including “negative spikes” and “negative steps.”

B.3.3 Influence of acceleration of axes

If the feed speed for the circular path is increased, the acceleration of the axes increases accordingly. The drive of an axis can behave in such a way that the amplitude of the movement decreases at a higher frequency at higher feed speeds. This results in paths that are smaller in diameter than the nominal circular path (see Figure B.6). A smoothing filter, applied to positional command to the axis, behaves in the same way as the response delay of the drive.



Key

1 actual path of circular movements with low contouring speed

2 actual path of circular movements with medium contouring speed

3 actual path of circular movements with high contouring speed

4 starting and stop points

Figure B.6 — Influence of acceleration of axes

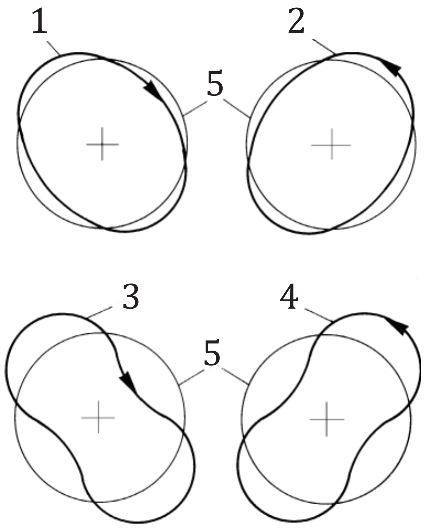
Special control algorithms in the numerical control of the machine tool (e.g. feed forward control) can compensate the influence of the acceleration of respective axes. A smoothing filter can have similar effects to the actual path.

B.3.4 Influence of different following errors (mismatch of position loop gain)

If the following errors of the two axes involved are different, the actual path is changed to an elliptical one. The principal axes of the ellipse are at ±45°.

Depending on the contouring direction [clockwise or anticlockwise (counter-clockwise)], the major diameter is at +45° or −45° (see Figure B.7).

When the feed speed is increased, the elliptical error from the circle increases accordingly.



Key

1 actual paths with low contouring speed clockwise
2 actual paths with low contouring speed anticlockwise (counter-clockwise)
3 actual paths with high contouring speed clockwise
4 actual paths with high contouring speed anticlockwise (counter-clockwise)
5 nominal path

Figure B.7 — Influence of different following errors

Annex C
(informative)

Precautions for test set-ups for circular tests with rotary axes

C.1 General

Test results for circular tests on metal-cutting machine tools using either a ball bar; a sphere-ended test mandrel and flat-ended linear displacement sensor(s); or three linear displacement sensors and a spherical artefact (radial test) can be affected by the set-up of measuring instruments. This annex gives precautions for test procedures to minimize the influence of set-up errors.

C.2 Tests with ball bar

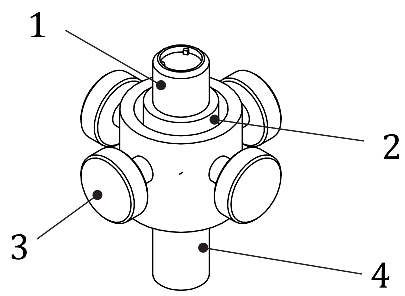
C.2.1 Alignment of precision spheres

In general, the precision sphere of the ball bar on the spindle side is aligned to the axis average line of the spindle. Any misalignment can influence the test result.

This alignment can be done by using a fixture attached to the spindle to minutely adjust the sphere position. See Figure C.1 for an example of such a fixture.

In some cases, for example when the rotary axis under test is not on the spindle side, the position of the sphere centre relative to the axis average line of the spindle can be measured, and then the machine coordinate system is shifted to cancel it. The position of the sphere centre can be measured by measuring the run-out in the radial direction of spindle rotation using a linear displacement sensor.

The precision sphere of the ball bar not on the spindle side is located at a position such that the ball bar is directed to the measurement's sensitive direction specified in each test, i.e. radial, tangential, axial, X, Y or Z. For example, when a rotary axis is on the workpiece side and the measured direction is fixed in the workpiece coordinate system, i.e. in radial, tangential and axial directions, then the precision sphere of the ball bar on the workpiece side is not required to be precisely located. It does not affect the test result (effect of second order).



Key

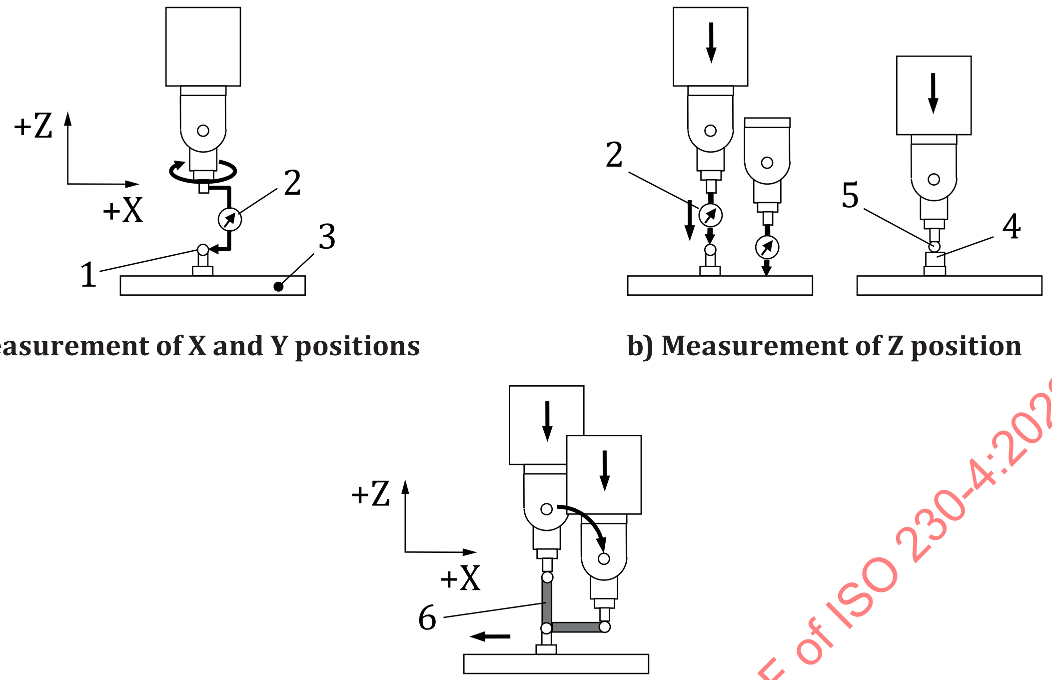
1 magnetic socket

2 magnet holder

3 screw

4 stem to chuck

Figure C.1 — Example of a fixture to align the sphere in the spindle side



a) Measurement of X and Y positions

b) Measurement of Z position

c) Alternative way to measure X and Z positions using a ball bar

Key

1 precision sphere not on spindle side
2 linear displacement sensor
3 table
4 tool length setting system
5 spindle-side precision sphere
6 ball bar

Figure C.2 — Procedure to measure the location of precision sphere not on spindle side

When the influence is not of second order, the precision sphere of the ball bar not on the spindle side is aligned at the centre of the circular path of the spindle-side sphere in the machine coordinate system. When the precision sphere not on the spindle side is placed, its position in the machine coordinate system is measured using a linear displacement sensor and a tool length setting system [see Figure C.2 a) and b) for a machining centre] or a ball bar [see Figure C.2 c)].

For example, the Z-position of the precision sphere not on the spindle side is typically measured as follows [Figure C.2 b) for a machining centre]: first, the Z-direction distance of the precision sphere centre to the table surface is measured using a linear displacement sensor attached to the spindle. Then the spindle-side sphere is installed on the spindle and its Z-position is measured using a tool length setting system installed on the table. Assuming that the height of the tool length setting system (the distance of the spindle-side sphere to the table surface) is known, the Z-position of the table-side sphere relative to the spindle-side sphere can be calculated.

C.2.2 Programming

The rotary axis (axes) is (are) driven as specified in each test. The motion of linear axes is programmed such that the ball bar is directed as specified in each test throughout the test cycle.

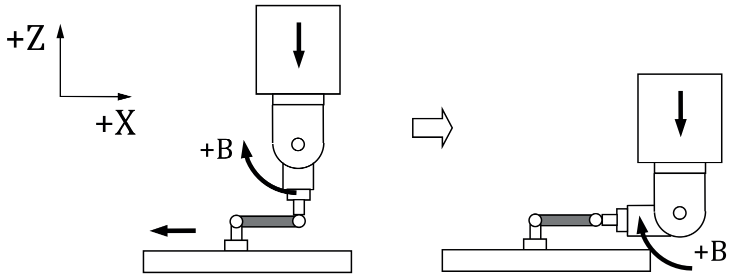


Figure C.3 — Ball bar test for circular test of X, Z and B axes in X-direction

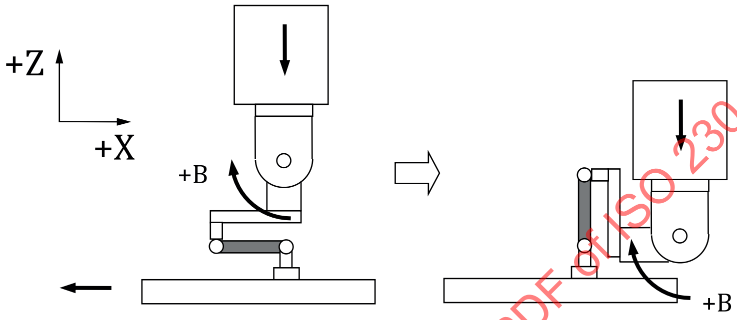


Figure C.4 — Ball bar test for circular test of X, Z and B axes in tangential direction

For example, for a circular test of X, Z and B axes in X-direction, X and Z trajectories are given such that the ball bar is always directed approximately in the X-axis direction. The nominal path for linear axes is exactly the same as in the case with the sphere-ended mandrel and linear displacement sensor(s). An example of ball bar test set-up for this test is shown in Figure C.3.

For example, for a circular test of X, Z and B axes in tangential direction (see Figure C.4), the precision sphere not on the spindle side is located at the centre of the circular path (i.e. on the spindle axis average line). A fixture, such as the one depicted in Figure C.4, is needed to put the spindle-side sphere away from the spindle axis average line. This set-up measures the error tangential to the rotation of the swivel axis (B-axis) at the position of the precision sphere not on the spindle side. The two tests in Figures C.3 and C.4 can be thus seen as kinematically equivalent.

For the convenience of programming, set the tool centre point (TCP) control function to ON. The TCP function enables automatic coordination of linear axes with respect to the programmed motion of rotary axis (axes).

Contouring speeds and travels of linear axes in the machine coordinate system are changed according to the distance of the sphere centre to the rotary axis. Sensitivity to angular error motions and to orientation errors of the axis of rotation increases (as well as the sensitivity to linear axes error motions and orientation errors) if this distance becomes larger.

C.2.3 Test procedure

The reference length L_B of the ball bar should be known, and the offset of the precision sphere centre on the spindle side to the spindle nose (spindle gauge line) shall be calibrated. The offset of the precision sphere to the spindle nose (spindle gauge line) can be typically calibrated by using a tool length setting system. For a machining centre, first a reference tool of the pre-calibrated length [the distance from the spindle nose (spindle gauge line) to the tool tip] is attached to the spindle and its Z-position at the tool tip is calibrated by using a tool length setting system installed on the table. Then, the precision sphere is attached to the spindle and its Z-position is measured by using the same set-up. The offset of the precision sphere to the spindle nose (spindle gauge line) can be calculated from the measured Z-position difference, the pre-calibrated length of the reference tool and the pre-calibrated radius of the precision sphere.