BS ISO 10791-6:2014

BSI Standards Publication

Test conditions for machining centres

Part 6: Accuracy of speeds and interpolations

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National foreword

This British Standard is the UK implementation of ISO 10791-6:2014. It supersedes BS ISO 10791-6:1998 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee MTE/1/2, Machine tools - Accuracy.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Test conditions for machining centres —

Part 6:
Accuracy of speeds and interpolations

Conditions d'essai pour centres d'usinage —

Partie 6: Précision des vitesses et interpolations

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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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This second edition cancels and replaces the first edition (ISO 10791-6:1998), which has been technically revised. It also incorporates Technical Corrigendum ISO 10791-6:1998/Cor 1:2004.

ISO 10791 consists of the following parts, under the general title *Test conditions for machining centres*:

— *Part 1: Geometric tests for machines with horizontal spindle (horizontal Z-axis)*

— *Part 2: Geometric tests for machines with vertical spindle or universal heads with vertical primary rotary axis (vertical Z-axis)*

— *Part 3: Geometric tests for machines with integral indexable or continuous universal heads (vertical Z-axis)*

— *Part 4: Accuracy and repeatability of positioning of linear and rotary axes*

— *Part 5: Accuracy and repeatability of positioning of work-holding pallets*

— *Part 6: Accuracy of speeds and interpolations*

— *Part 7: Accuracy of finished test pieces*

— *Part 8: Evaluation of contouring performance in the three coordinate planes*

— *Part 9: Evaluation of the operating times of tool change and pallet change*

— *Part 10: Evaluation of thermal distortions*

Introduction

ISO 10791 is concerned with methods of testing machining centres.

A machining centre is a numerically controlled machine tool capable of performing multiple machining operations, including milling, boring, and tapping, as well as automatic tool changing from a magazine or similar storage unit in accordance with a machining programme.

The object of ISO 10791 is to supply information as wide and comprehensive as possible on tests which can be carried out for comparison, acceptance, maintenance, or any other purpose deemed necessary by the user or the manufacturer.

ISO 10791 specifies, with reference to the relevant parts of ISO 230, several families of tests for machining centres. ISO 10791 also establishes the tolerances or maximum acceptable values for the test results corresponding to general purpose and normal accuracy machining centres.

ISO 10791 is also applicable, totally or partially, to numerically controlled milling and boring machines, when their configuration, components, and movements are compatible with the tests described herein.

In five-axis machining centres having three orthogonal linear axes and two rotary axes, there are such types as machines with two rotary axes in the spindle head (see Annex A), machines with two rotary axes in the workpiece side (see Annex B), and machines with a swivel head and/or a rotary table (see Annex C).

The annexes of this part of ISO 10791 specify the kinematic tests for five-axis machining centres.

Test conditions for machining centres —

Part 6: **Accuracy of speeds and interpolations**

1 Scope

This part of ISO 10791 specifies, with reference to ISO 230-1 and ISO 230-4, certain kinematic tests for machining centres, concerning spindle speeds, feed and the accuracy of the paths described by the simultaneous movement of two or more numerically controlled (NC) linear and/or rotary axes.

This part of ISO 10791 applies to machining centres having three linear axes (X, Y, and Z) and additionally one or two rotary axes (A, B, or C). Movements other than those mentioned are considered as special features and the relevant tests are not included in this part of ISO 10791.

This part of ISO 10791 deals only with the verification of kinematic accuracy of the machine and does not apply to the testing of the machine operation, e.g. vibrations, abnormal noises, etc., which should generally be checked separately.

The tests described in this part of ISO 10791 are also applicable, totally or partially, subject to specific agreement between the manufacturer/supplier and the user, to numerically controlled milling and boring machines, when their configuration, components, and movements are compatible with the tests described herein.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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*

ISO 230-4:2005, *Test code for machine tools — Part 4: Circular tests for numerically controlled machine tools*

ISO 230-7, *Machine tools — Test code for machine tools — Part 7: Geometric accuracy of axes of rotation*

ISO 841:2001, *Industrial automation systems and integration — Numerical control of machines — Coordinate system and motion nomenclature*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 230-1, ISO 230-4, ISO 230-7, and ISO 841 and the following apply.

3.1
linear interpolation
interpolation where relative motion between the tool side and the workpiece side of the machine tool is a straight line obtained by controlling multiple axes simultaneously

3.2
circular interpolation
interpolation where relative motion between the tool side and the workpiece side of the machine tool is a circular arc in a specific plane obtained by controlling multiple axes simultaneously

3.3
tool centre point control function
TCP control function
advanced CNC control function that drives the linear axes of a numerically controlled machine tool, in order to maintain constant tool centre point coordinates, in the workpiece coordinate system, in response to instantaneous position variation of rotary axes

4 Preliminary remarks

4.1 Measurement units

In this part of ISO 10791, all linear dimensions, deviations, and corresponding tolerances are expressed in millimetres. Angular dimensions are expressed in degrees. In some cases microradians or arcseconds may be used for clarification purposes. The equivalence of the following expressions should always be kept in mind:

$$0{,}010/1\,000 = 10\times10^{-6} = 10\ \mu rad \cong 2''$$

4.2 Reference to ISO 230-1 and ISO 230-4

To apply this part of ISO 10791, reference shall be made to ISO 230-1, especially for the installation of the machine before testing, warming up of the spindle and other moving components, description of measuring methods, and recommended accuracy of testing equipment. For tests of circular interpolation motion, reference shall be made to ISO 230-4.

4.3 Testing sequence

The sequence in which the tests are presented in this part of ISO 10791 in no way defines the practical order of testing. In order to make the mounting of instruments or gauging easier, tests can be performed in any order.

4.4 Tests to be performed

When testing a machine, it is not always necessary or possible to carry out all the tests described in this part of ISO 10791. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the manufacturer/supplier, those tests relating to the components and/or the properties of the machine which are of interest. These tests shall be clearly stated when ordering a machine. The mere reference to this part of ISO 10791 for the acceptance tests, without specifying the tests to be carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

4.5 Measuring instruments

The measuring instruments indicated in the tests described in Clause 5 and in Annex A, Annex B, and Annex C are examples only. Other instruments measuring the same quantities and having the same or smaller measurement uncertainty can be used.

In each test, the number of sampled points (or sampling frequency) shall be reported.

4.6 Diagrams

For simplicity, the diagrams in this part of ISO 10791 illustrate only one type of machines in each Annex.

4.7 Position of axes not under test

Linear and/or rotary axes not under test should be located nearest to the middle of their working travel, or in the position that minimizes deflections of the machine components affecting the measurement.

4.8 Software compensation

When built-in software facilities are available for compensating geometric, positioning, contouring, and thermal deviations, their use during these tests for acceptance purposes shall be based on agreement between the manufacturer/supplier and the user, with due consideration to the machine tool's intended use. When the software compensation is used, this shall be stated in the test report.

It shall be noted that when software compensation is used, axes cannot be locked for test purposes.

5 Kinematic tests

5.1 General

The scope of spindle speed tests (K1) and feed speed tests (K2) is to check the overall accuracy of all the electric, electronic, and kinematic chain in the control system between the command and the physical movement of the component.

The purpose of linear interpolation motion tests (K3) is to check the coordinated motion of two linear axes in either of the following two conditions:

— while these axes are moving either at the same speed (45°); or

— while one of these axes is moving at a significantly lower speed than the other (small angles).

The purpose of circular interpolation motion tests (K4) is to check the coordinated motion of two linear axes along a circular path, including points in which the motion of one axis slows down to zero and the direction of movement is reversed. During these tests, axes move with variable speeds.

The tests for checking circular interpolation involving more than two linear axes, including rotary axes, are described in Annex A, Annex B, and Annex C.

5.1.1 Tests described in Annexes A to C

In Annex A, AK1 measures the deviations of the tool centre point trajectory with the rotation of the B-axis. AK2 measures them with the rotation of the C-axis. AK3 and AK4 measure them with the simultaneous interpolation with both B- and C-axes. Similarly, in all of Annexes A to C, each test describes a test for each rotary axis or the combination of two rotary axes.

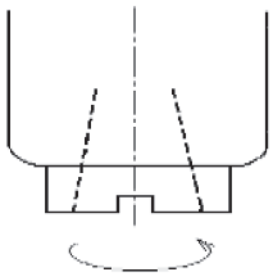
5.1.2 Alternative tests in Annexes A and C

In Annex A, AK1, AK2, and AK4 measure the deviations of the tool centre point trajectory in the workpiece coordinate system (the coordinate system attached to the work table). On the other hand, their alternative tests [AK1 (alternative), AK2 (alternative), and AK4 (alternative)] measure them in radial, parallel, and tangential directions of the rotary axis of interest. In other words, these alternative tests measure the deviations in the coordinate system attached to the rotary axis of interest. Tests CK1 and CK1 (alternative) follow the same principle.

5.2 Spindle speeds and feed speeds

Object and test conditions	**K1**
Checking the deviations in the spindle speed at the midpoint and at the maximum of each speed range for clockwise and counter-clockwise (anticlockwise) directions of rotation. This test shall be carried out for each speed range, where applicable.	

Diagram



Tolerance

±5 %

Measured deviations

Speed range		**Direction of rotation**	**Programmed speed**	**Measured speed**	**Deviation** %
	Mid	counter-clockwise			
		clockwise			
	Max	counter-clockwise			
		clockwise			
	Mid	counter-clockwise			
		clockwise			
	Max	counter-clockwise			
		clockwise			

Measuring instruments

Revolutions counter or stroboscope or others.

Observations

A dummy tool can be clamped in the spindle.

If the instantaneous speed is read, five readings shall be taken and the average calculated. Readings shall be taken at constant speed, avoiding the acceleration/deceleration at start and stop. The override control shall be set at 100 %.

The spindle speed deviation shall be calculated using the following formula:

$$D = \frac{A_s - P_s}{P_s} \times 100$$

where

D is the deviation in percentage;

A_s is the measured speed;

P_s is the programmed speed.

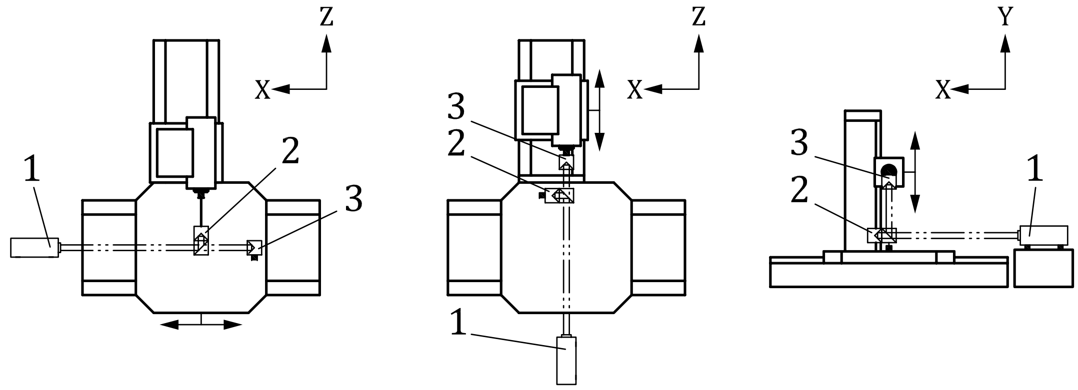
Object and test conditions — **K2**

Checking the accuracy of the speed in the positive and negative directions of all the linear axes at the following speeds:

a) 100 mm/min; b) 1 000 mm/min; c) maximum feed speed; d) rapid traverse.

Diagram

The diagram shows setups for a horizontal machining centre. The setups shall be accordingly for vertical machining centres.



X-axis setup Z-axis setup Y-axis setup

Key

1 laser head

2 interferometer

3 reflector

Tolerance

±5 %

Measured deviations

Programmed feed speed	**Direction**	**Axis**					
		X		**Y**		**Z**	
		Measured avg feed speed	**Deviation** %	**Measured avg feed speed**	**Deviation** %	**Measured avg feed speed**	**Deviation** %
a) 100 mm/min	Positive						
	Negative						
b) 1 000 mm/min	Positive						
	Negative						
c) Max. feed speed ....mm/min	Positive						
	Negative						
d) Rapid traverse ....mm/min	Positive						
	Negative						

Measuring instruments

Laser interferometer.

Observations

Align the laser interferometer (setup for positioning deviation) with the motion of the axis under test. Axis shall be commanded to execute a simple motion between two end points specified. Travel distance of about half the axis travel range (or 500 mm whichever is shorter) to allow the axis to accelerate, then move at constant speed, and then to decelerate to stop shall be selected. Same travel distance shall be used for all feed speeds. The tests shall be carried out for both directions of travel (positive and negative). Speed data should be sampled with a minimum frequency of 100 Hz, no smoothing or averaging shall be allowed. The override control shall be set at 100 %. For each direction, calculate the average feed speed as the average of all measured constant feed speed values (minimum 1 000 sampled points) for a given test.

The feed speed deviations shall be calculated using the following formula:

$$D_\mathrm{f} = \frac{A_\mathrm{f} - P_\mathrm{f}}{P_\mathrm{f}} \times 100$$

where

D_f is the deviation in percentage;

A_f is the measured average feed speed;

P_f is the programmed feed speed.

5.3 Linear interpolation motion

Object and test conditions	**K3**

Checking the straightness error of the path described by linear interpolation of two linear axes controlled simultaneously over any measuring length of 100 mm. The approximate slopes of these paths are given below.

Horizontal machining centres:

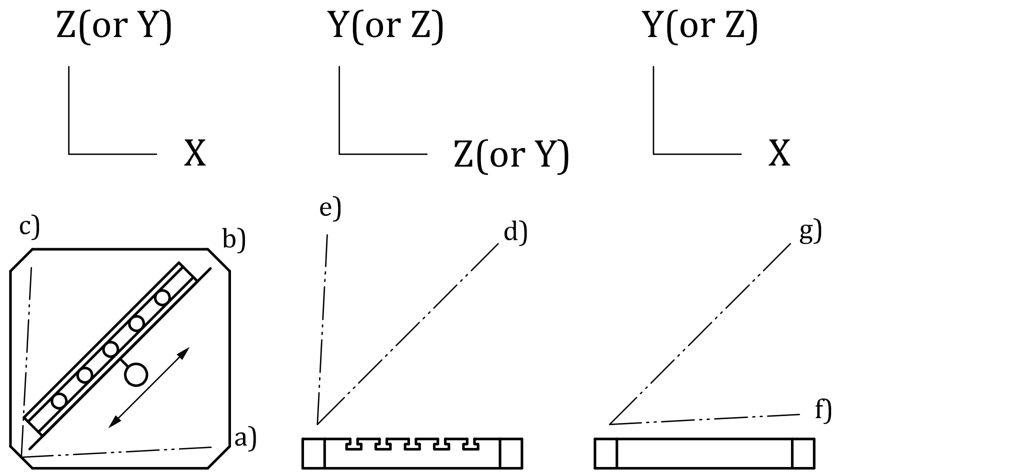
a) dZ/dX = 0,05; b) dZ/dX = 1; c) dX/dZ = 0,05; d) dY/dZ = 1; e) dZ/dY = 0,05; f) dY/dX = 0,05; g) dY/dX = 1.

Vertical machining centres:

a) dY/dX = 0,05; b) dY/dX = 1; c) dX/dY = 0,05; d) dZ/dY = 1; e) dZ/dY = 0,05; f) dZ/dX = 0,05; g) dZ/dX = 1.

Instead of an angle equal to arctan(0,05) [= 2°51’45”], an angle of 3° can be chosen, depending on the programming facilities.

Diagram



Horizontal plane — Vertical YZ plane — Vertical plane parallel to X-axis

NOTE In the coordinate system shown on each diagram, axis names correspond to the horizontal machine configuration, while those in parentheses [e.g. (or Y)] correspond to the vertical machine configuration.

Tolerance

0,020 for any length of 100

Measured deviations

	a)	b)	c)	d)	e)	f)	g)
Measured error							
Length							

Measuring instruments

Straightness reference artefact with appropriate support (e.g. swivelling vise) or sine bar and linear-displacement sensor[a].

[a] The use of a linear-displacement sensor connected with a graphic recorder or a computer is recommended in order to have a measurement result in a graphical form, which is easier to read.

<table>
<tr><th>Object and test conditions</th><th>K3</th></tr>
<tr><td colspan="2">Observations
The measuring length shall be approximately in the middle of the work zone.
After choosing the angle and the length of travel, place a linear-displacement sensor on the tool holding spindle, if it can be locked, otherwise on the spindle head, reasonably perpendicular to the direction of movement.
Place the straightedge or the sine bar on the worktable at the approximate orientation specified in object and test conditions. Move the sensor against the straightedge to read against the reference surface (at the starting position of the measuring length). Record the X-, Y-, Z-positions. Then move the sensor to the end point of the measuring length and adjust the position such that the same linear-displacement sensor reading is obtained against the reference surface of the straightedge. Record the X-, Y-, Z-positions of this location. The programmed path shall be between these two recorded locations.
Then move the axes along the programmed path in both directions, with feed speed of 250 mm/min, reversing the direction outside the measuring length, and record the difference between the maximum and the minimum reading separately for each direction.
The largest deviation in any 100 mm section and its direction shall be recorded.</td></tr>
<tr><td colspan="2">[a] The use of a linear-displacement sensor connected with a graphic recorder or a computer is recommended in order to have a measurement result in a graphical form, which is easier to read.</td></tr>
</table>

5.4 Circular interpolation motion

Object and test conditions — **K4**

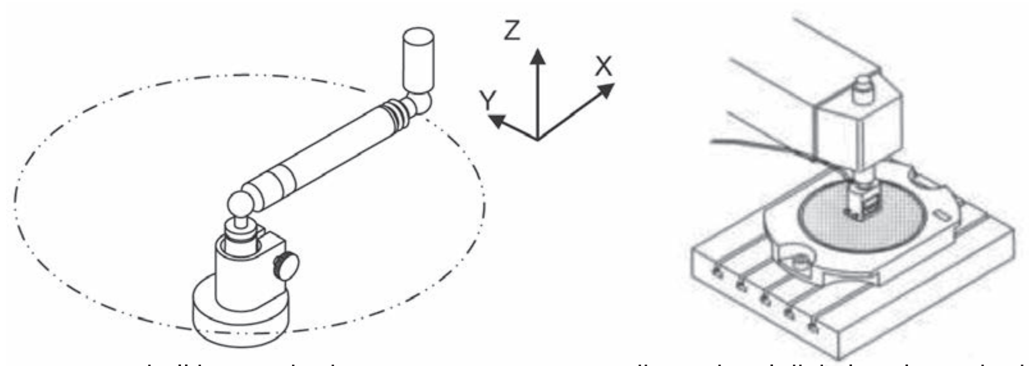
Checking the circular deviation G and the bi-directional circular deviation $G(b)$ of the path generated by circular interpolation of two linear axes over 360°, where applicable, according to ISO 230-4, at one of the following diameters and at two feed speeds, as follows.

1) 20 mm dia.	2) 50 mm dia.	3) 100 mm dia.	4) 200 mm dia.	5) 300 mm dia.
a) 150 mm/min	a) 250 mm/min	a) 350 mm/min	a) 500 mm/min	a) 610 mm/min
b) 630 mm/min	b) 1 000 mm/min	b) 1 400 mm/min	b) 2 000 mm/min	b) 2 440 mm/min

The circular deviation G shall be checked for clockwise and counter-clockwise (anticlockwise) contouring motion.

This test shall be performed in the XY, YZ, and ZX plane, or in the plane composed by other pairs of linear axes (U, V, W, etc.).

Diagram



ball bar method — two dimensional digital scale method

NOTE In the coordinate system shown on each diagram, axis names correspond to the horizontal machine configuration, while those in parentheses [e.g. (or Y)] correspond to the vertical machine configuration.

Tolerance

a) G_{ab} = 0,03 mm, G_{ba} = 0,03 mm

$G(b)_{ab}$ = 0,05 mm

b) G_{ab} = 0,05 mm, G_{ba} = 0,05 mm

$G(b)_{ab}$ = 0,09 mm

where ab = XY, YZ, ZX or any pairs of linear axes.

Measured deviations and parameters to be stated

a) feed speed =	Diameter of nominal path Location of measuring instrument	……………………………….
G_{ab} =	— Centre of circle (X/Y/Z)	……………………………….
G_{ba} =	— Offset of tool reference (X/Y/Z)	……………………………….
$G(b)_{ab}$ =	— Offset to workpiece reference (X/Y/Z)	……………………………….
b) feed speed =	Data acquisition parameters	
G_{ab} =	— Starting point	……………………………….
G_{ba} =	— Number of measuring points	……………………………….
$G(b)_{ab}$ =	— Data smoothing process	……………………………….
where ab = XY, YZ, or ZX or any pairs of linear axes	Compensation used Positions of axes not under test	………………………………. ……………………………….

Measuring instruments

Ball bar, or two-dimensional digital scale.

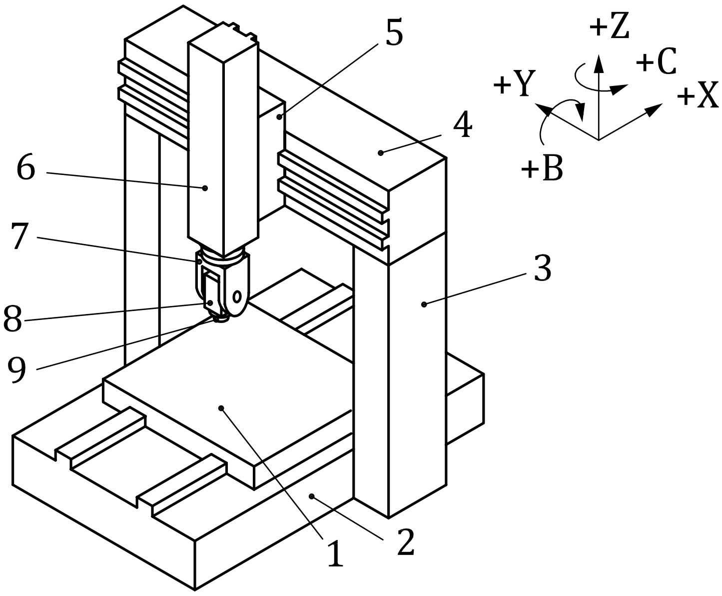
Observations and references to ISO 230-1:2012, 11.3 **and** ISO 230-4:2005 Diameters can differ from the above values in agreement between the manufacturer/supplier and the user. In such cases, the feed speed shall be adjusted according to Annex C of ISO 230-4:2005. Start the interpolation in one of the four quadrants. Ideally measurements should be recorded at a start point other than one of the four reversal points and should have adequate feed in/out motion around the area being inspected; this helps ensure accurate capture of machine performance measurements, including that at the reversal points.

Annex A
(normative)

Kinematic tests for machines with two rotary axes in the spindle head

A.1 Machine configuration and designation

The machines specified in this part of ISO 10791 can be classified based on the structure of the linear axes and the rotary axes. The structural configuration is described by using the structural codes to serially connect the motion axis from the workpiece side to the tool side, and *vice versa*. The name of axes of motion is in accordance with ISO 841:2001. As an example, the structural code of the machine shown in Figure A.1 can be described as [w X' b Y Z C B (C1) t] by connecting the motion axes from the workpiece side to the tool side. In this description, the workpiece side and the tool side are distinguished by naming the workpiece by "w", the tool by "t", and the bed by "b"; (C1) stands for the spindle axis without numerical control for angular positioning.



Key

1 table (X'-axis)
2 bed
3 column
4 cross beam
5 ram saddle (Y-axis)
6 ram (Z-axis)
7 swivelling head (C-axis)
8 tilting head (B-axis)
9 spindle [(C1)-axis]

Figure A.1 — Typical example of a vertical five-axis machining centre with two rotary axes in the spindle head [w X' b Y Z C B (C1) t]

A designation is also supplied in order to define the configuration of a machining centre as a short code; this designation is given by the following four items in order:

— the five-axis machining centre;

— the number of this International Standard, i.e. ISO 10791;

— the letter H for “horizontal” (with a horizontal spindle) or V for “vertical” (with a vertical spindle);

— the structure configuration.

EXAMPLE Designation of a machining centre, vertical spindle, with two rotary axes in the spindle head moving along the Z-axis, the ram saddle moving along the Y-axis, and the worktable moving along the X-axis (refer to Figure A.1):

Five-axis machining centre ISO 10791 V [w X' b Y Z C B (C1) t]

A.2 Kinematic tests

A.2.1 General

Tests specified in this annex refer, for simplicity, to the example of machine configuration depicted in Figure A.1 but they are applicable to all configurations of machining centres equipped with two continuously controlled rotary axes on the spindle head.

AK1, AK2, and AK4 measure the deviations of the tool centre point trajectory in the workpiece coordinate system (i.e. the coordinate system attached to the work table) while their alternatives measure them in radial, parallel, and tangential directions to the rotary axis of interest (i.e. in the coordinate system attached to the rotary axis of interest). In this annex, alternative tests are given to perform the test in different setups of sensitive directions of the measurement.

NOTE 1 Tests specified in this annex are also applicable, where relevant, to machining centre configurations with one single continuously controlled rotary axis on the spindle head.

NOTE 2 These tests provide information about the capability of a machine to simultaneously coordinate the axes. However, these tests might not directly predict the actual workpiece form errors resulting from cutting.

A.2.2 Circular interpolation motion by simultaneous three-axis control (AK1 and AK2)

The purpose of these tests is to check the accuracy of the circular trajectories when the circular interpolation motion of two linear axes is synchronized with the rotation of a rotary axis at a constant speed, except for start/stop phase at the beginning/end of the test.

A.2.3 Circular interpolation motion by simultaneous five-axis control (AK3 and AK4)

The purpose of these tests is to check the accuracy of the trajectories when three linear axes and two rotary axes are controlled simultaneously at constant speed keeping the distance between the point on the table and the point on the spindle constant.

Object and test conditions	**AK1**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous three-axes interpolation of two linear axes (X'- and Z-axes) and the tilting head rotary axis (B-axis).

a) in the x-axis direction, $E_{\text{int,X,XZB}}$

b) in the Z-axis direction, $E_{\text{int,Z,XZB}}$

c) in the y-axis direction, $E_{\text{int,Y,XZB}}$

The offset of the precision sphere to spindle nose (spindle gauge line), *L*, should be approximately 150 mm. The rotational speed of B-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

The rotational angle of the B-axis should be tested over its entire working range, limited by possible interference between the test mandrel and the linear-displacement sensor.

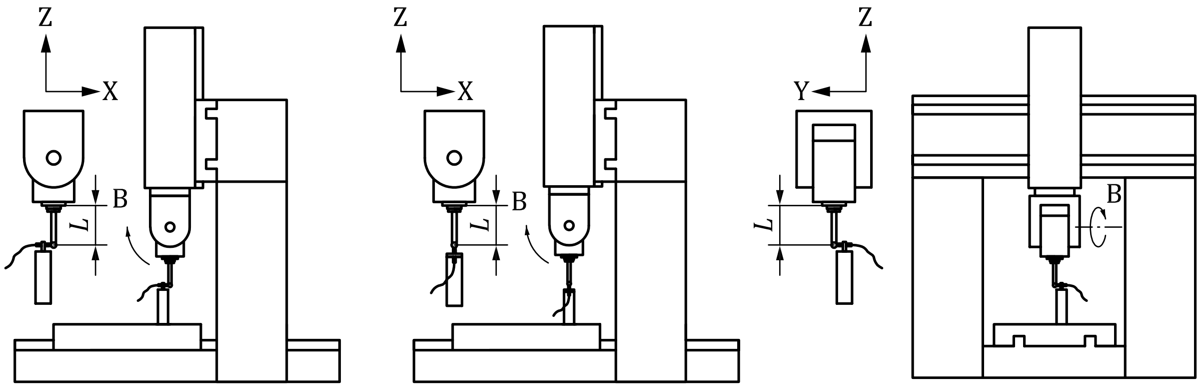
Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of the B-axis motion.

NOTE 1 Test c) can be performed as a possible alternative to the test of squareness between the B-axis of rotation and the ZX plane, described by the corresponding geometrical test in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

NOTE 2 This test refers to the example of machine configuration with B- and C-axes in the spindle head. It is applicable to other configurations (e.g. A- and C-axes in the spindle head).

NOTE 3 For machines with non-orthogonal swivelling heads, attention should be paid to avoid interference of the fixture and the measuring instruments.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{\text{int,X,XZB}}$ (CW, CCW)	a) $E_{\text{int,X,XZB}}$ (CW, CCW)
b) $E_{\text{int,Z,XZB}}$(CW, CCW)	b) $E_{\text{int,Z,XZB}}$(CW, CCW)
c) $E_{\text{int,Y,XZB}}$(CW, CCW)	c) $E_{\text{int,Y,XZB}}$(CW, CCW)
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

Precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations and reference to ISO 230-1:2012, 11.3.5 Y-axis at mid travel. Set the TCP control function to ON. Move the B-axis and the C-axis to 0°. When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used: — bring the linear-displacement sensor to sense the precision sphere attached to the spindle and rotate the spindle to find the mean run-out position; — move the B-axis to −90° and zero the displacement sensor against the sphere; — rotate the B-axis at a constant speed to the maximum positive angle allowed without interference and record the readings of the linear-displacement sensor; — rotate the B-axis back to −90° and record the readings of the linear-displacement sensor; — report the difference between the maximum and minimum recorded values. The offset of the precision sphere to the spindle nose, *L*, shall be calibrated and reported. The centre of the precision sphere shall be aligned on the spindle axis average line. Any misalignment influences the test result. For ball bar setup and additional precautions, see Annex D. Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on the machine table. It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**AK1** **(alternative)**

Checking of the deviations of the tool centre point trajectory [ideally a circular path in a) and c), a fixed point in b)] during the simultaneous three-axis interpolation of two linear axes (X'- and Z-axes) and the tilting head rotary axis (B-axis).

The sensitive direction of the measurement shall be set as follows:

a) radial to the tilting head rotary axis (B-axis), $E_{\text{int,radialB,XZB}}$;

b) parallel to the tilting head rotary axis (B-axis), $E_{\text{int,axialB,XZB}}$ ($E_{\text{int,Y,XZB}}$);

c) tangential to the rotation of the tilting head rotary axis (B-axis), $E_{\text{int,tangentialB,XZB}}$.

The reference length of the ball bar L_B is 100 mm, and the rotational speed of the B-axis should be 360°/min or agreed between the manufacturer/supplier and the user. The offset of the ball on the spindle side to the spindle nose (spindle gauge line), L, should be approximately 150 mm.

The rotational angle of the B-axis should be tested over its entire working range, limited by possible interference.

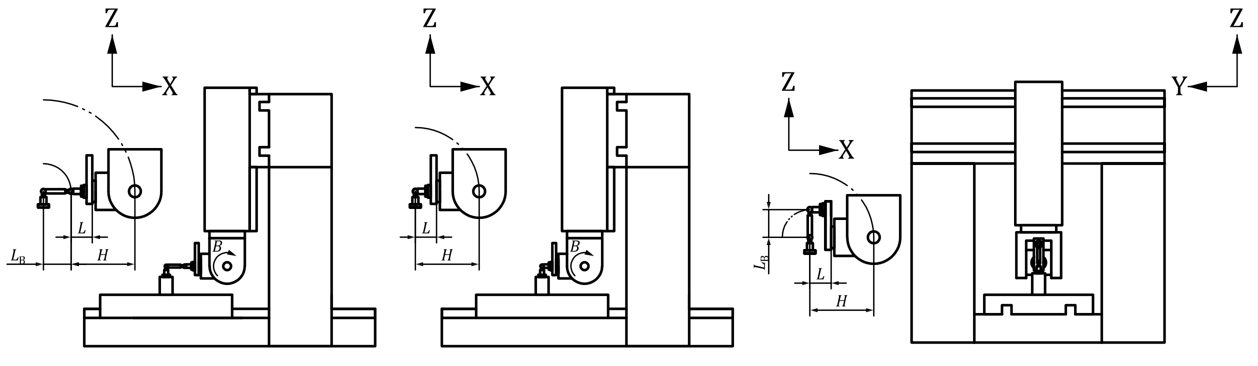
Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of B-axis motion.

NOTE 1 Test b) can be performed as a possible alternative to the test of squareness between the B-axis of rotation and the ZX plane, described by the corresponding geometrical test in ISO 10791-1, ISO 10791-2 or ISO 10791-3.

NOTE 2 This test refers to the example of machine configuration with B- and C-axes in the spindle head. It is applicable to other configurations (e.g. A- and C-axes in the spindle head).

NOTE 3 For machines with non-orthogonal swivelling heads, attention should be paid to avoid interference of the fixture and the measuring instruments.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)

a) $E_{\text{int,radialB,XZB}}$ (CW, CCW)

b) $E_{\text{int,axialB,XZB}}$ (CW, CCW)

c) $E_{\text{int,tangentialB,XZB}}$ (CW, CCW)

Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.

Measured deviations

a) $E_{\text{int,radialB,XZB}}$ (CW, CCW)

b) $E_{\text{int,axialB,XZB}}$ (CW, CCW)

($E_{\text{int,Y,XZB}}$ (CW, CCW)

c) $E_{\text{int,tangentialB,XZB}}$ (CW, CCW)

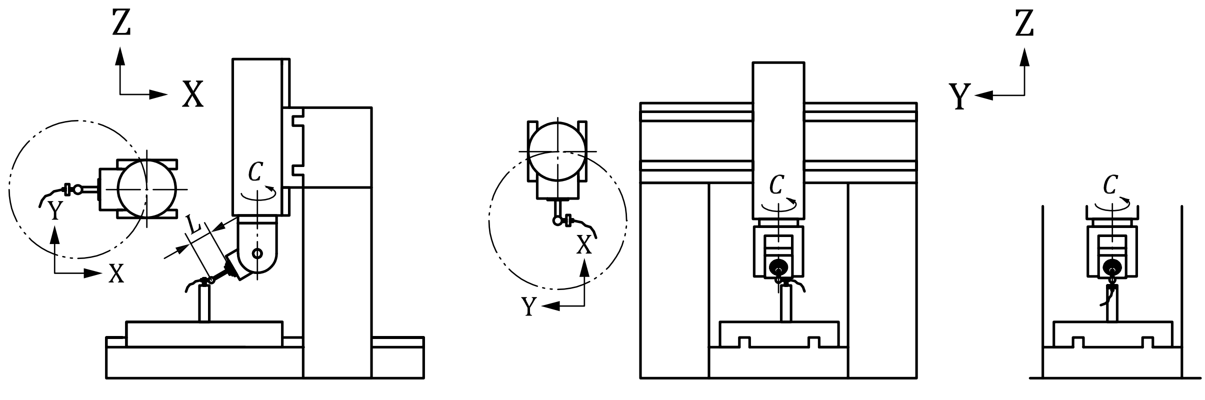
Measuring instruments

Ball bar, or precision sphere with stem and flat-ended linear-displacement sensor(s) or a sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012**, 11.3.5**
One of the balls of the ball bar is mounted on the machine table. In a) and b), the ball of the spindle side is mounted on the spindle axis average line. In c), it is mounted at the distance L_B from spindle axis average line (see Annex D). The axis of ball bar is kept radial to B-axis in a), parallel to B-axis in b), and tangential to B-axis in c). The circular interpolation motion is conducted by the X'- and Z-axes while rotating the tilting axis (B-axis) of the spindle head. Set the TCP control function to ON. In the machine coordinate system, the radius of the trajectory of B-axis average line is H+LB in a), and H in b) and c), where H is L added by the distance between the spindle gauge line and B-axis. For each test, continuously record the readings of the ball bar (changes of its length) during the interpolated motion. Report the difference between the maximum and minimum recorded values for a), b), and c). The offset of the ball on the spindle side to the spindle nose (spindle gauge line), L, shall be calibrated and reported. In a) and c), the table-side ball of the ball bar shall be aligned at the centre of the trajectory of the spindle-side ball in the work-piece coordinate system. Any misalignment influences the test result. A precision sphere with stem and a sensor's nest (e.g. R-test) can be also used when the sensor's nest can be mounted in the spindle side. See Annex D for additional precautions. It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**AK2**
Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous three-axes interpolation of two linear axes (X'- and Y-axes) and the swivelling head rotary axis (C-axis). a) in the X-axis direction, $E_{int,X,XYC}$ b) in the Y-axis direction, $E_{int,Y,XYC}$ c) in the Z-axis direction, $E_{int,Z,XYC}$ The offset of the precision sphere to spindle nose (spindle gauge line), *L*, should be approximately 150 mm and the rotational speed of C-axis should be 360°/min or agreed between the manufacturer/supplier and the user. The rotational angle of the C-axis should be over 360°, where applicable. Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of the C-axis motion. NOTE Test c) can be performed as a possible alternative to the test of squareness between the C-axis of rotation and the XY plane, described by the corresponding geometrical test in ISO 10791-1, ISO 10791-2, or ISO 10791-3.	

Diagram



Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{int,X,XYC\ (CW,\ CCW)}$ b) $E_{int,Y,XYC\ (CW,\ CCW)}$ c) $E_{int,Z,XYC\ (CW,\ CCW)}$ Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	a) $E_{int,X,XYC\ (CW,\ CCW)}$ b) $E_{int,Y,XYC\ (CW,\ CCW)}$ c) $E_{int,Z,XYC\ (CW,\ CCW)}$

Measuring instruments

Precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations and reference to ISO 230-1:2012**, 11.3.5**
X- and Y-axis at mid travel. Set the TCP control function to ON.
When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:
— move the B-axis and the C-axis to 0°;
— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position;
— move the B-axis to 60° and the C-axis to 180°; zero the linear-displacement sensor against the sphere;
— rotate the C-axis at constant speed to −180° and record the readings of the linear-displacement sensor;
— rotate the C-axis to 180° and record the readings of the linear-displacement sensor;
— report the difference between the maximum and minimum recorded values for a), b), and c).
The offset of the precision sphere to the spindle nose, *L*, shall be calibrated and reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.
Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.
For ball bar setup and additional precautions, see Annex D.
It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**AK2 (alternative)**

Checking of the deviation of the tool centre point trajectory [ideally a circular path in a) and c), a fixed point in b)] during the simultaneous three-axis interpolation of two linear axes (X'- and Y-axes) and the swivelling head rotary axis (C-axis).

The sensitive direction of the measurement shall be set as follows:

a) radial to the rotary axis (C-axis), $E_{\mathrm{int,radialC,XYC}}$;

b) parallel to the rotary axis (C-axis), $E_{\mathrm{int,axialC,XYC}}$ ($E_{\mathrm{int,Z,XYC}}$);

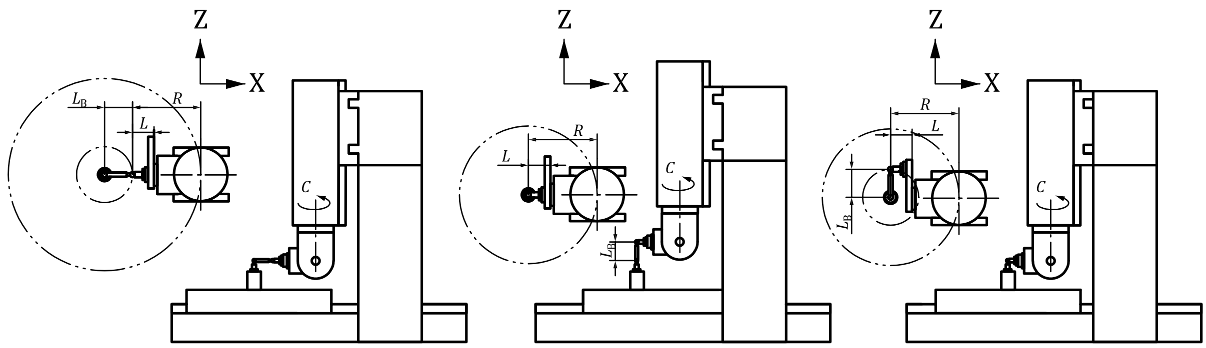
c) tangential to the rotation of the rotary axis (C-axis), $E_{\mathrm{int,tangentialC,XYC}}$.

The reference length of the ball bar L_B is 100 mm, and the rotational speed of the C-axis should be 360°/min or agreed between the manufacturer/supplier and the user. The offset between the sphere in the spindle side and the spindle nose (spindle gauge line), L, should be approximately 150 mm.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) of C-axis motion.

NOTE Test b) can be performed as a possible alternative to the test of squareness between the C-axis of rotation and the XY plane, described by the corresponding geometrical test in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)

a) $E_{\mathrm{int,radialC,XYC}}$ (CW, CCW)

b) $E_{\mathrm{int,axialC}}$ (CW, CCW) [$E_{\mathrm{int,Z,XYC}}$ (CW, CCW)]

c) $E_{\mathrm{int,tangentialC,XYC}}$ (CW, CCW)

Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.

Measured deviations

a) $E_{\mathrm{int,radialC,XYC}}$ (CW, CCW)

b) $E_{\mathrm{int,axialC}}$ (CW, CCW)

[$E_{\mathrm{int,Z,XYC}}$ (CW, CCW)]

c) $E_{\mathrm{int,tangentialC,XYC}}$ (CW, CCW)

Measuring instruments

Ball bar, or a precision sphere with stem and flat-ended linear-displacement sensor(s), or a sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012, 11.3.5

In a) and b), the ball of the ball bar of the spindle side is mounted on the spindle axis average line. In c), it is mounted at the distance LB from spindle axis average line (see Annex D). The ball of the table side is mounted on the table. The axis of ball bar is kept radial to C-axis in a), parallel to C-axis in b), and tangential to C-axis in c).

The circular interpolation motion is conducted by the X'- and Y-axes while rotating the rotary axis (C-axis) of the swivelling head. Set the TCP control function to ON.

For each test, continuously record the readings of the ball bar (changes of its length) during the interpolated motion. Report the difference between the maximum and minimum recorded values for a), b), and c).

The offset of the spindle-side ball to spindle nose, L, shall be calibrated and reported. In a) and c), the table-side ball shall be aligned at the centre of the trajectory of the spindle-side ball in the workpiece coordinate system. Any misalignment influences the test result.

A precision sphere with stem and a sensor's nest (e.g. R-test) can also be used when the sensor's nest can be mounted at the spindle side. See Annex D for test procedure and for additional precautions.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**AK3**

Checking of the deviation of the tool centre point trajectory along a conical circular path during simultaneous five-axis interpolation of three linear axes and two rotary axes.

The angle between the axis of the programmed cone and the Z-axis, and the apex angle of the programmed cone, shall be respectively either 10° and 30°, or 30°, and 90°.

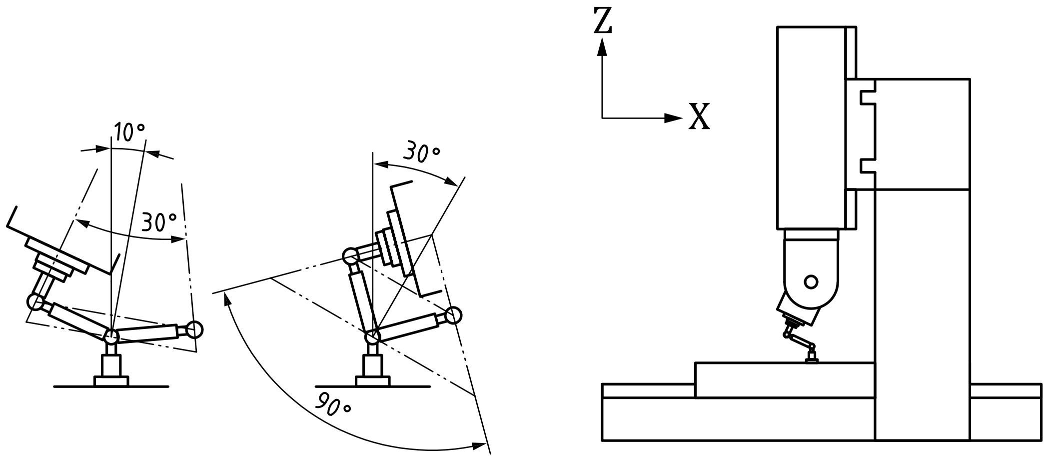
The ball of the ball bar of the spindle side shall be mounted and centred on the spindle axis average line.

The ball bar shall be set perpendicular to the cone surface.

The diameter of the circular path should be approximately 200 mm, and the peripheral feed speed should be 1 000 mm/min.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C-axis motion.

Diagram



Tolerance (to be agreed between the manufacturer/supplier and the user)

— $E_{\text{int,cone30°,XYZBC (CW, CCW)}}$ or $E_{\text{int,cone90°,XYZBC (CW, CCW)}}$

Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.

Measured deviations

— $E_{\text{int,cone30°,XYZBC (CW, CCW)}}$, or

— $E_{\text{int,cone90°,XYZBC (CW, CCW)}}$

Measuring instruments

Ball bar.

Observations and reference to ISO 230-1:2012**, 11.4**

If the diameter differs from the above value, the feed speed shall be adjusted according to Annex C of ISO 230-4:2005.

The offset of the ball on the spindle side to the spindle nose (spindle gauge line) shall be calibrated and reported. The spindle-side ball of the ball bar shall be aligned at the spindle axis average line. Any misalignment influences the test result. The table-side ball of the ball bar shall be aligned at the cone axis (for this alignment procedure, see Figure D.2). See Annex D for further precaution for this test.

For each test, record the readings of the ball bar (changes of its length) during the interpolated motion.

Report the difference between the maximum and minimum recorded values. The nominal diameter of the circular path shall be noted.

If easily available, the range of movement of each axis (three linear axes and two rotary axes) shall be reported.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**AK4**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous five axes interpolation of three linear axes and two rotary axes.

a) in the workpiece coordinate system X-axis direction, $E_{\text{int,X,XYZBC}}$

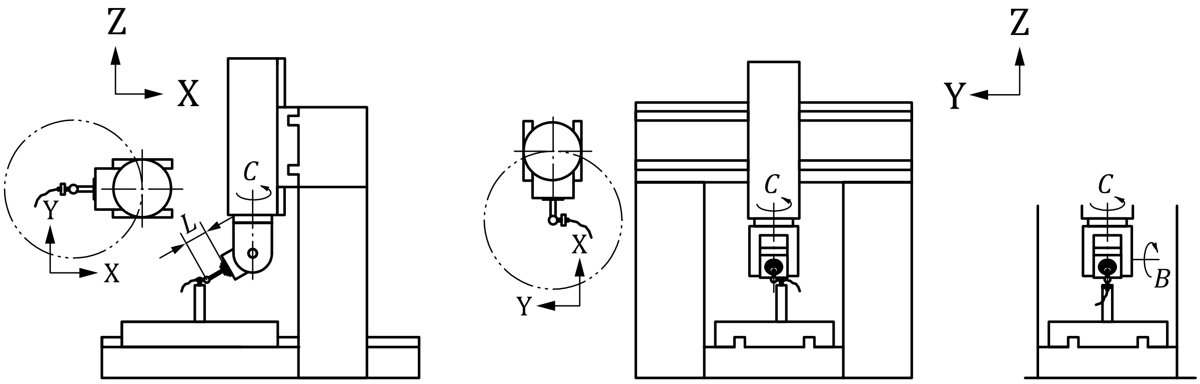
b) in the workpiece coordinate system Y-axis direction, $E_{\text{int,Y,XYZBC}}$

c) in the workpiece coordinate system Z-axis direction, $E_{\text{int,Z,XYZBC}}$

The offset of the precision sphere to spindle nose (spindle gauge line), *L*, should be approximately 150 mm and the rotational speed of C-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) contouring motion of C-axis.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)

a) $E_{\text{int,X,XYZBC (CW,CCW)}}$

b) $E_{\text{int,Y,XYZBC (CW,CCW)}}$

c) $E_{\text{int,Z,XYZBC (CW,CCW)}}$

Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.

Measured deviations

a) $E_{\text{int,X,XYZBC (CW,CCW)}}$

b) $E_{\text{int,Y,XYZBC (CW,CCW)}}$

c) $E_{\text{int,Z,XYZBC (CW,CCW)}}$

Measuring instruments

A precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations

Move the B-axis and the C-axis to 0°. Set the TCP control function to ON.

When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:

— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position. Zero the displacement sensor against the sphere;

— move C-axis from 0° to 180° and simultaneously B-axis from 0° to 90°. Then continuously rotate C-axis from 180° to 360° while rotating B-axis from 90° to 0°. B- and C-axes rotations could be limited due to possible interference with the precision sphere with stem;

— record the linear-displacement sensor readings;

— report the difference between the maximum and minimum recorded values for a), b), and c).

The offset of the precision sphere to spindle nose, *L*, shall be calibrated and reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.

Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.

If easily available, the range of the movements (three linear axes and two rotary axes) shall be reported.

For ball bar setup and additional precautions, see Annex D.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	AK4 (alternative)

Checking of the deviation of the tool centre point trajectory along a spherical path during simultaneous five-axis interpolation of three linear axes and two rotary axes.

The sensitive direction of the measurement shall be set as follows;

a) radial to the tilting axis (B-axis), $E_{int,radialB,XYZBC}$;

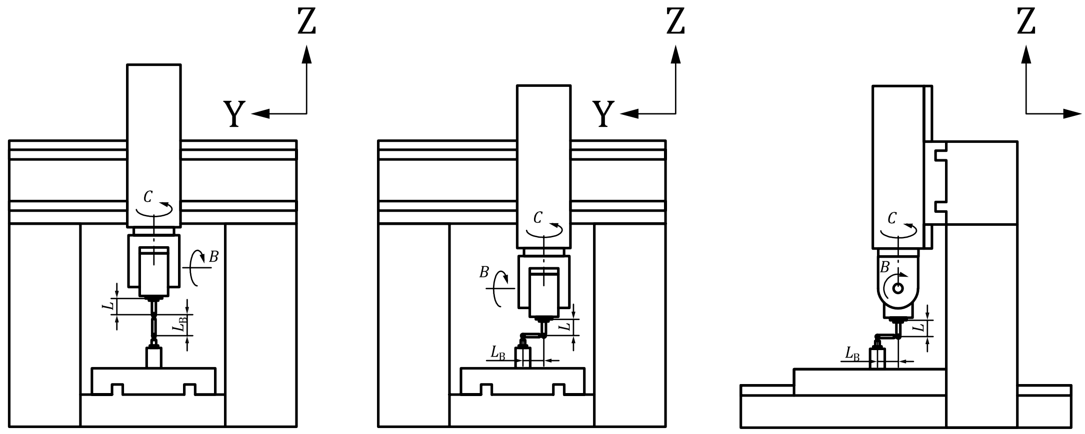
b) parallel to the tilting axis (B-axis), $E_{int,axialB,XYZBC}$;

c) tangential to the rotation of the tilting axis (B-axis), $E_{int,tangentialB,XYZBC}$.

The reference length of the ball bar, L_B, is 100 mm, and the rotational speed of the C-axis is 360°/min or agreed between the manufacturer/supplier and the user. The offset of the precision sphere to the spindle nose (spindle gauge line), L, should be approximately 150 mm.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C-axis motion.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	Measured deviations
a) $E_{int,radialB,XYZBC(CW,CCW)}$	a) $E_{int,radialB,XYZBC\ (CW,CCW)}$
b) $E_{int,axialB,XYZBC(CW,CCW)}$	b) $E_{int,axialB,XYZBC\ (CW,CCW)}$
c) $E_{int,tangentialB,XYZBC(CW,CCW)}$	c) $E_{int,tangentialB,XYZBC(CW,CCW)}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

Ball bar, or a precision sphere with stem and flat-ended linear displacement sensor(s), or a sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012, **11.3.5**

The offset of the ball on the spindle side to the spindle nose (spindle gauge line), L, shall be calibrated and reported. The centre of the ball on the spindle side shall be aligned on the spindle average line. Any misalignment influences the test result.

The axis of the ball bar is set radial to B-axis in a), parallel to B-axis in b), and tangential to B-axis in c).

Move the X-, Y-, and Z-axes simultaneously so as to keep the distance between the two balls constant while rotating C-axis from 0° to 180° and, simultaneously, B-axis from 0° to 90°. Then continuously rotate C-axis from 180° to 360° while rotating B-axis from 90° to 0°. Set the TCP control function to ON. B- and C-axes rotations could be limited due to possible interferences with the precision sphere with stem.

For each test, record the readings of the ball bar (changes of its length) during the interpolated motion. Report the difference between the maximum and minimum recorded values for a), b), and c).

A precision sphere with stem and a sensor's nest (e.g. R-test) can be also used when the sensor's nest can be mounted at the spindle side. See Annex D for precautions for test procedure and for additional precautions.

If easily available, the range of the movements (three linear axes and two rotary axes) shall be reported.

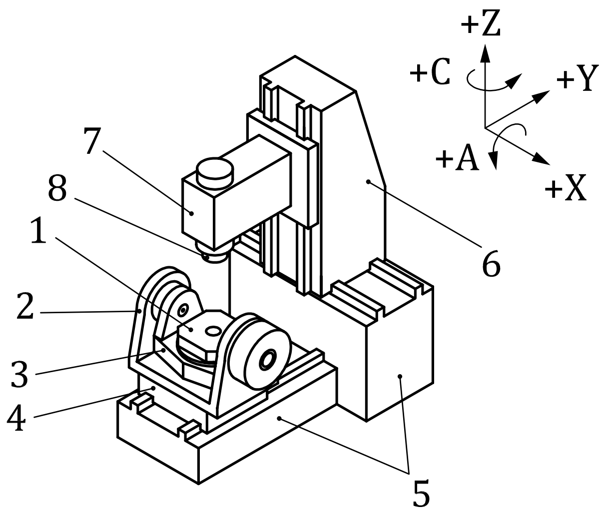
It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Annex B
(normative)

Kinematic tests for machines with two rotary axes in the workpiece side

B.1 Machine configuration and designation

The machines specified in this part of ISO 10791 can be classified based on the structure of the translational axes and the rotary axes. The structural configuration is described by using the structural codes to connect serially the motion axis from the workpiece side to the tool side, and *vice versa*. The name of axes of motion is in accordance with ISO 841:2001. As an example, the structural code of the machine shown in Figure B.1 can be described as [w C' A' Y' b X Z (C1) t] by connecting the motion axes from the workpiece side to the tool side. In this description, the workpiece side and the tool side are distinguished by naming the workpiece by “w”, the tool by “t”, and the bed by “b”; (C1) stands for the spindle axis without numerical control for angular positioning.



Key

1 rotary table (C'-axis)
2 cradle (A'-axis)
3 Trunnion
4 table saddle (Y'-axis)
5 bed
6 column (X-axis)
7 spindle head (Z-axis)
8 spindle [(C1)-axis]

Figure B.1 — Example of a typical vertical five-axis machining centre with a tilting rotary table [w C' A' Y' b X Z (C1) t]

A designation is also supplied in order to define the configuration of a machining centre, as a short code; this designation is given by the following four items in order:

— the five-axis machining centre;

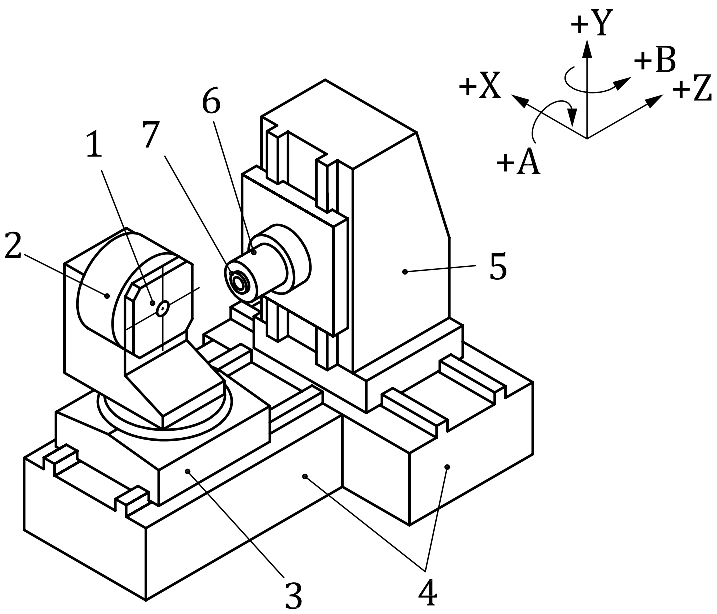
— the number of this International Standard, i.e. ISO 10791;

— the letter H for “horizontal(with a horizontal spindle) or V for “vertical” (with a vertical spindle);

— the structure configuration.

EXAMPLE 1 Designation of a machining centre, vertical spindle, with a tilting rotary table moving along the Y'-axis, the column moving along the X-axis, and the spindle head slide moving along the Z-axis (refer to Figure B.1):

Five-axis machining centre ISO 10791 V [w C' A' Y' b X Z (C1) t]



Key

1 vertical rotary table (A'-axis)

2 vertical trunnion table (B'-axis)

3 table saddle (Z'-axis)

4 bed

5 column (X-axis)

6 spindle head (Y-axis)

7 spindle [(C1)-axis]

Figure B.2 — Example of horizontal five-axis machining centre with a vertical rotary table (A') tilting around a vertical B' axis [w A’ B’ Z’ b X Y (C1) t]

EXAMPLE 2 Designation of a machining centre, horizontal spindle, with a vertical rotary table (A') tilting around a vertical B'-axis (refer to Figure B.2):

Five-axis machining centre ISO 10791 H [w A' B' Z' b X Y (C1) t]

B.2 Kinematic tests

B.2.1 General

Tests specified in this annex refer, for simplicity, to the example of machine configuration depicted in Figure B.1 but they are applicable to all configurations of machining centres equipped with two rotary axes on the workpiece side.

NOTE 1 Tests specified in this annex are also applicable, where relevant, to machining centre configurations with one continuously controlled rotary table on the workpiece side (4th axis), axis average line of which being parallel to one of the primary coordinate axes, and an additional continuously controlled rotary table that can be assembled on the first rotary table such that its axis average line is parallel to one of the other two primary coordinate axes (table-on-table configuration; see Figure B.2).

NOTE 2 The tests in this annex are in principle also applicable to five-axis machining centres with rotary axes whose average line is not parallel to any linear axes (e.g. a rotary axis tilted by 45° from linear axes).

B.2.2 Circular interpolation motion by simultaneous three axis control (BK1 and BK2)

The purpose of these tests is to check the accuracy of the circular trajectories when the circular interpolation motion of two linear axes is synchronized with the rotation of the rotary axis at a constant speed, except for start/stop phase at the beginning/end of the test.

B.2.3 Circular interpolation motion by simultaneous five-axis control (BK3 and BK4)

The purpose of these tests is to check the accuracy of the trajectories when three linear axes and two rotary axes are controlled simultaneously at constant speed, keeping the distance between the point on the table and the point on the spindle constant.

Object and test conditions	**BK1**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) with the simultaneous three-axes interpolation of two linear axes (Y'- and Z-axes) and a rotary axis (A'-axis). The sensitive direction of the measurement shall be set as follows:

a) radial to the rotary axis (A'-axis), $E_{\mathrm{int,radialA,YZA}}$;

b) parallel to the rotary axis (A'-axis), $E_{\mathrm{int,axialA,YZA}}$;

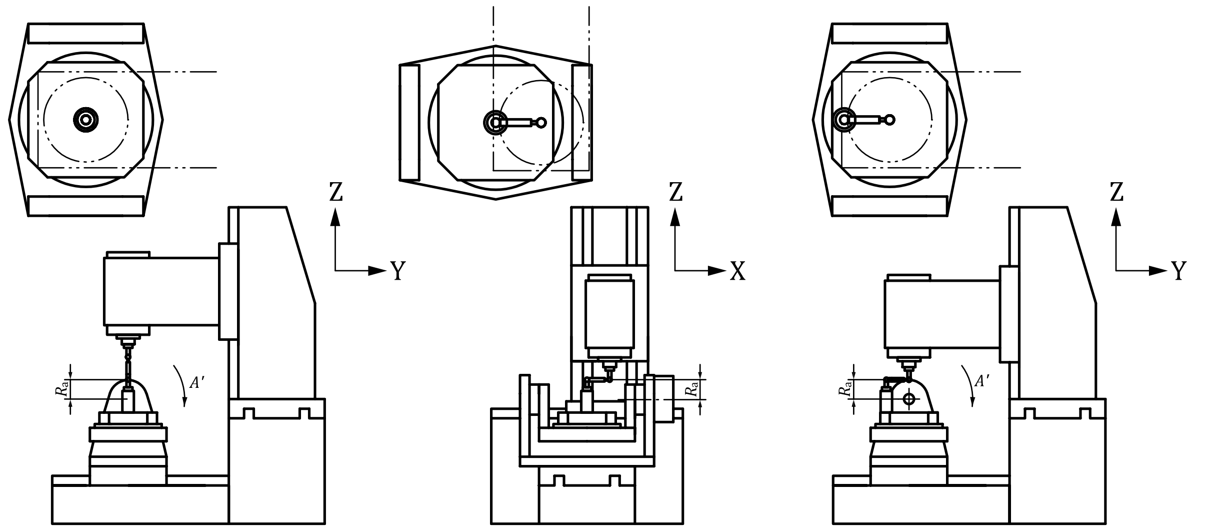
c) tangential to the rotary axis (A'-axis), $E_{\mathrm{int,tangentialA,YZA}}$.

The rotational speed of A'-axis should be 360°/min or agreed between the manufacturer/supplier and the user. The rotational angle of A'-axis should be over 180° (or the maximum stroke limited by possible interferences).

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of A'-axis motion.

NOTE Test b) can be performed as a possible alternative to the test of squareness between the A'-axis of rotation and the YZ plane, described by the corresponding geometrical test specified in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)

a) $E_{\mathrm{int,radialA,YZA\ (CW,CCW)}}$

b) $E_{\mathrm{int,axialA,YZA\ (CW,CCW)}}$

c) $E_{\mathrm{int,tangentialA,YZA\ (CW,CCW)}}$

Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.

Measured deviations

a) $E_{\mathrm{int,radialA,YZA(CW,CCW)}}$

b) $E_{\mathrm{int,axialA,YZA(CW,CCW)}}$

c) $E_{\mathrm{int,tangentialA,YZA(CW,CCW)}}$

Measuring instruments

Ball bar, or a precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012**, 11.3.5** Move A'- and C'-axes to 0°. Set the TCP control function to ON. When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used: — bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position; — move the A'-axis to 90° and zero the linear-displacement sensor; — rotate the A'-axis at a constant speed to −90° and record the readings of the linear-displacement sensor; — rotate the A'-axis to 90° and record the readings of the linear-displacement sensor; — report the difference between the maximum and minimum recorded values for a), b), and c). The offset of the sphere to A'-axis, R_a, shall be reported. The centre of the sphere shall be aligned on the spindle average line. Any misalignment influences the test result. The offset of the sphere to the spindle nose (spindle gauge line) shall be calibrated and reported. For ball bar setup and additional precautions, see Annex D. Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table. It is recommended to present test results in a graphical form, e.g. similar to Figure D.5. To perform this test by using a sphere and displacement sensor(s), the sensor (sensor's nest) is mounted on the table. Since the fixture holding the linear-displacement sensor is subject to varying gravitational forces during the measurements (due to different orientation of the rotary table), it shall be stiff enough to minimize the influence on the test results.

Object and test conditions	**BK2**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous three-axes interpolation of two linear axes (X- and Y'-axes) and a rotary axis (C'-axis). The sensitive direction of the measurement shall be set as follows:

a) radial to the rotary axis (C'-axis), $E_{\text{int,rdialC,XYC}}$;

b) parallel to the rotary axis (C'-axis), $E_{\text{int,axialC,XYC}}$;

c) tangential to the rotary axis (C'-axis), $E_{\text{int,tangentialC,XYC}}$.

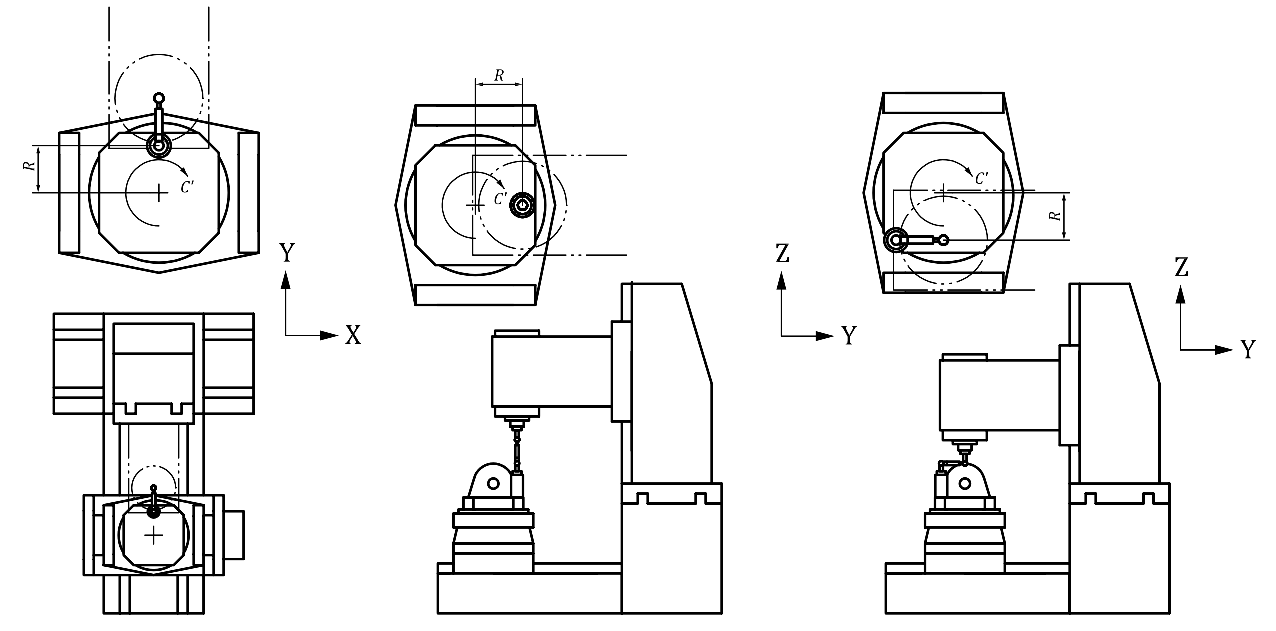
The rotational speed of the C'-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

The rotational angle of the C'-axis should be over 360°, where applicable.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion.

NOTE Test b) can be performed as a possible alternative to the test of squareness between the C'-axis of rotation and the XY plane, described by the corresponding geometrical test specified in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{\text{int,radialC,XYC(CW,CCW)}}$	a) $E_{\text{int,radialC,XYC(CW,CCW)}}$
b) $E_{\text{int,axialC,XYC(CW,CCW)}}$	b) $E_{\text{int,axialC,XYC(CW,CCW)}}$
c) $E_{\text{int,tangentialC,XYC(CW,CCW)}}$	c) $E_{\text{int,tangentialC,XYC(CW,CCW)}}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

Ball bar, or a precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012**, 11.3.5**
Move the X-axis to the C'-axis average line and the Y-axis at a distance, *R*, from the rotary table centre.
Move the A'-axis and the C'-axis to 0°. Set the TCP control function to ON.
When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:
— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position;
— move the C'-axis to 180°. Zero the linear-displacement sensor;
— rotate the C'-axis at a constant speed to –180° and continuously record the readings of the linear-displacement sensor;
— rotate the C'-axis to 180° and record the readings of the linear-displacement sensor;
— report the difference between the maximum and minimum recorded values for a), b), and c).
The offset of the sphere to the C'-axis, *R*, shall be reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.
Measurements a), b), and c) can be taken simultaneously using three-linear-displacement sensors or a sensor's nest mounted on a table.
For ball bar setup and additional precautions, see Annex D.
It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**BK3**

Checking of the deviation of the tool centre point trajectory (ideally a conical circular path) during the simultaneous five-axis interpolation of three linear axes and two rotary axes.

The angle between the base circle of the programmed cone and the table surface, and the apex angle of the programmed cone, shall be respectively either 10° and 30°, or 30° and 90°.

The ball of the table side of the ball bar shall be mounted with a (minimum) offset *d* of 10 % of the diameter of rotary table size (as long as the test can be done within the linear axes travel range) from the axis average line of the C'-axis.

The axis of cone is tilted around the direction of the offset *d* (see diagram).

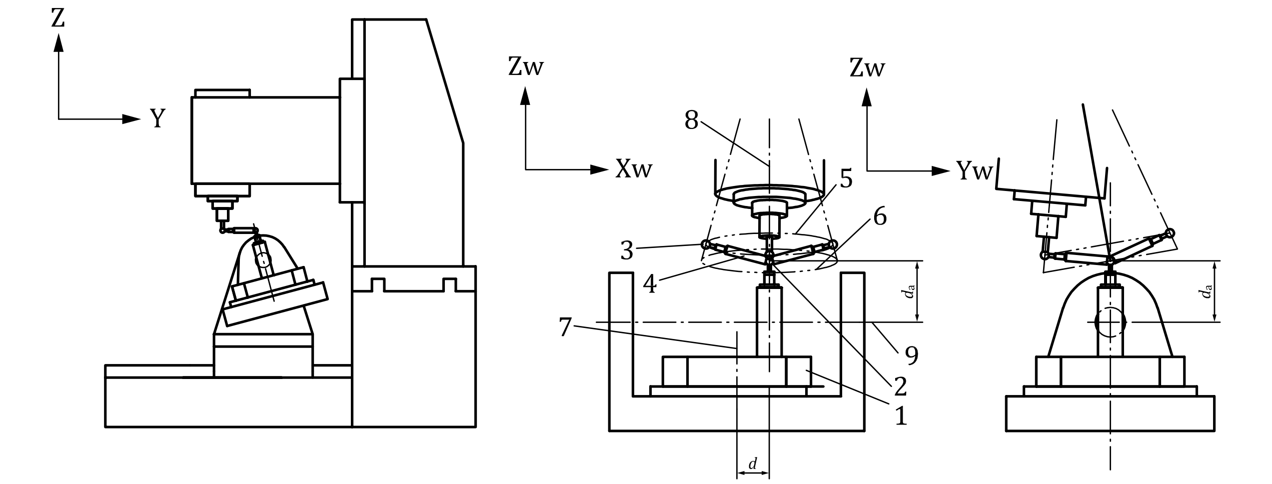
The ball bar shall be set approximately perpendicular to the cone surface.

The diameter of the circular path should be approximately 200 mm, and the peripheral feed speed should be 1 000 mm/min.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion.

NOTE The second setup (angle of the base circle: 30°, apex angle of the cone: 90°) requires larger range of movements of particularly A- and Z-axes than the first setup.

Diagram



Trajectory in the workpiece coordinate system

Key

1 rotary table

2 table-side ball

3 spindle-side ball

4 ball bar

5 trajectory of spindle-side ball

6 imaginary cone's bottom trajectory

7 C'-axis average line

8 axis of programmed cone

9 A'-axis average line

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
— $E_{int,cone30°,XYZAC(CW,CCW)}$ or $E_{int,cone90°,XYZAC(CW,CCW)}$ Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	— $E_{int,cone30°,XYZAC(CW,CCW)}$ or — $E_{int,cone90°,XYZAC(CW,CCW)}$

Measuring instruments

Ball bar.

Observations and reference to ISO 230-1:2012**, 11.4**
If the diameter differs from the above value, the feed speed shall be adjusted according to Annex C of ISO 230-4:2005.
It is desirable that the ball of the table side is located higher than the centre line of the A'-axis. The offset of the table-side sphere to the A'-axis average line, d_a, shall be reported.
For each test, record the readings of the ball bar (changes of its length) during the interpolated motion.
Report the difference between the maximum and minimum recorded values.
The nominal diameter of the circular path and the offset *d* shall be recorded.
Offset of the spindle-side ball of the ball bar to spindle nose (spindle gauge line) shall be calibrated. The spindle-side ball of the ball bar shall be aligned at the spindle axis average line. Any misalignment influences the test result. See Annex D for further precaution for this test.
Since the fixture holding the magnetic socket of the ball bar on the rotary table is subject to varying gravitational forces during the measurements (due to different orientations of the rotary table), it shall be stiff enough to minimize the influence on the test results.
If easily available, the range of movement of each axis (three linear axes and two rotary axes) shall be reported.
It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**BK4**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during simultaneous five-axis interpolation of three linear axes and two rotary axes.

a) in the workpiece coordinate system X-axis direction, $E_{int,X,XYZAC}$

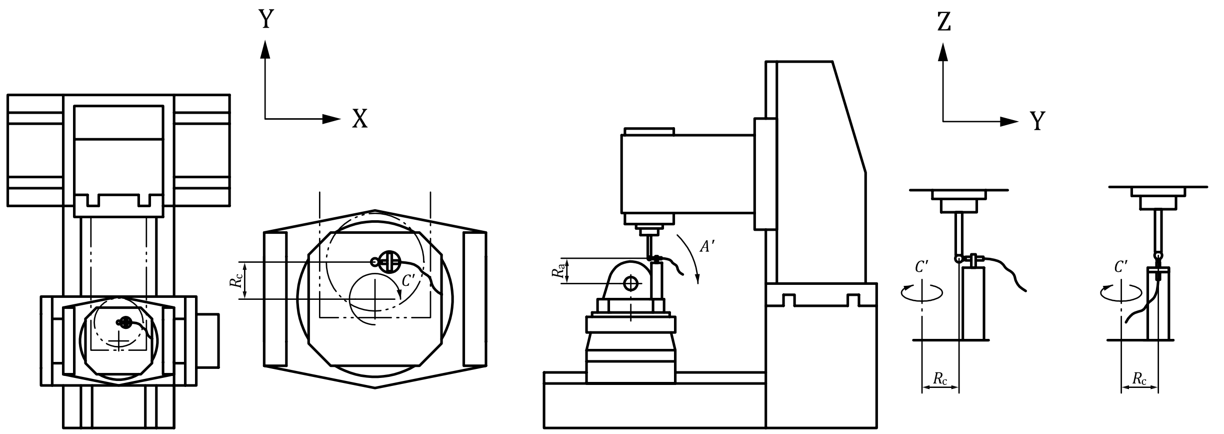
b) in the workpiece coordinate system Y-axis direction, $E_{int,Y,XYZAC}$

c) in the workpiece coordinate system Z-axis direction, $E_{int,Z,XYZAC}$

The offset of the precision sphere to spindle nose (spindle gauge line), L, should be approximately 150 mm and the rotational speed of C'-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{int,X,XYZAC(CW,CCW)}$	a) $E_{int,X,XYZAC(CW,CCW)}$
b) $E_{int,Y,XYZAC(CW,CCW)}$	b) $E_{int,Y,XYZAC(CW,CCW)}$
c) $E_{int,Z,XYZAC(CW,CCW)}$	c) $E_{int,Z,XYZAC(CW,CCW)}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

A precision sphere with stem and flat-ended linear-displacement sensor(s), or sensor's nest (e.g. R-test), or ball bar.

Observations

Move A'-axis and C'-axis to 0°. Move the Y-axis at a distance R_c away from the axis average line of the rotary Table C', and move Z-axis at a distance R_a away from the axis average line of A'-axis. Set the TCP control function to ON.

When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:

— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position. Zero the displacement sensor against the sphere;

— move C'-axis from 0° to 180° and simultaneously A'-axis from 0° to 90°. Then continuously rotate C'-axis from 180° to 360° while rotating A'-axis from 90° to 0°. A'- and C'-axes rotations could be limited due to possible interference with the precision sphere with stem;

— record the linear-displacement sensor readings;

— report the difference between the maximum and minimum recorded values for a), b), and c).

Distances R_a and R_c shall be reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result. The offset of the sphere to the spindle nose (spindle gauge line) shall be calibrated and reported.

Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.

For ball bar setup and additional precautions, see Annex D.

If easily available, the range of the movement of X-, Y-, and Z-axes shall be reported.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

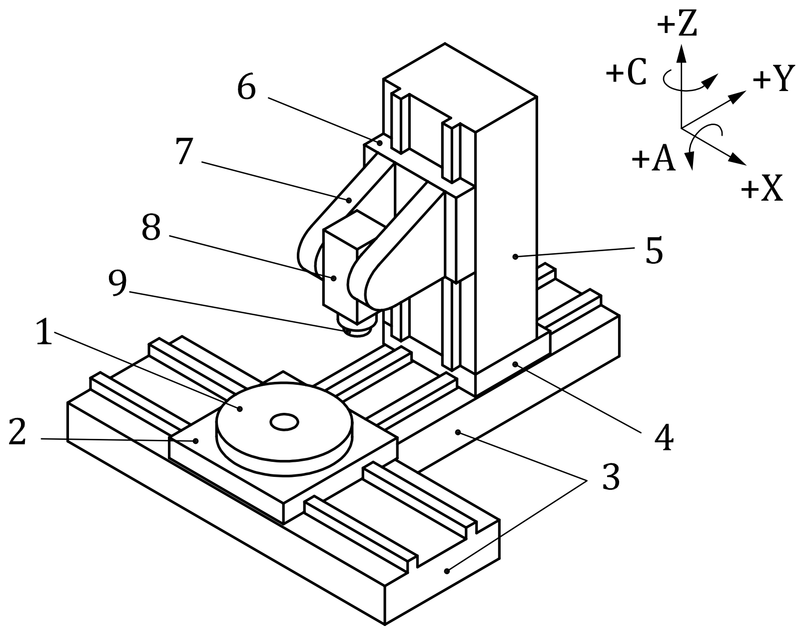
To perform this test by using a sphere and displacement sensor(s), the sensor (sensor's nest) is mounted on the table. Since the fixture holding the linear-displacement sensor is subject to varying gravitational forces during the measurements (due to different orientation of the rotary table), it shall be stiff enough to minimize the influence on the test results.

Annex C
(normative)

Kinematic tests for machines with a swivel head and/or a rotary table

C.1 Machine configuration and designation

The machines specified in this part of ISO 10791 can be classified based on the structure of the translational axes and the rotary axes. The structural configuration is described by using the structural codes to connect serially the motion axis from the workpiece side to the tool side, and vice versa. The name of axes of motion is in accordance with ISO 841:2001. As an example, the structural code of the machine shown in Figure C.1 can be described as [w C' X' b Y Z A (C1) t] by connecting the motion axes from the workpiece side to the tool side. In this description, the workpiece side and the tool side are distinguished by naming the workpiece by “w”, the tool by “t”, and the bed by “b”; (C1) stands for the spindle axis without numerical control for angular positioning.



Key

1 rotary table (C'-axis)
2 table saddle (X'-axis)
3 bed
4 column saddle (Y-axis)
5 column
6 yoke saddle (Z-axis)
7 yoke
8 spindle tilt head (A-axis)
9 spindle [(C1)-axis]

Figure C.1 — Example of a typical vertical five-axis machining centre with a swivel head and a rotary table [w C' X' b Y Z A (C1) t]

A designation is also supplied in order to define the configuration of a machining centre, being a short code; this designation is given by the following four items in order:

— the five-axis machining centre;

— the number of this International Standard, i.e. ISO 10791;

— the letter H for “horizontal” (with a horizontal spindle) or V for “vertical” (with a vertical spindle);

— the structure configuration.

EXAMPLE Designation of a machining centre, vertical spindle, with a rotary table (C'-axis) moving along the X'-axis, the column moving along the Y-axis, and the yoke saddle with a swivel spindle head (A-axis) moving along the Z-axis (refer to Figure C.1):

Five-axis machining centre ISO 10791 V [w C' X' b Y Z A (C1) t]

C.2 Kinematic tests

C.2.1 General

For simplicity, the tests specified in Annex C refer to the example machine configuration depicted in Figure C.1, though these tests are applicable to all configurations of machining centres equipped with a swivel head and/or a continuously controlled rotary table.

NOTE Tests specified in this annex are also applicable, where relevant, to machining centre configurations with one single continuously controlled rotary table

C.2.2 Circular interpolation motion by simultaneous three-axis control (CK1 and CK2)

The purpose of these tests is to check the accuracy of the circular trajectories when the circular interpolation motion of two linear axes is synchronized with the rotation of the rotary axis at constant speed, except for start/stop phase at the beginning/end of the test.

C.2.3 Circular interpolation motion by simultaneous five-axis control (CK3 and CK4)

The purpose of these tests is to check the accuracy of the trajectories when three linear axes and two-rotary axes are controlled simultaneously at constant speed, keeping the distance between the point on the table and the point on the spindle constant.

Object and test conditions	**CK1**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous three-axes interpolation of two linear axes (Y- and Z-axes) and a rotary axis (A-axis).

a) along the Y-axis direction, $E_{int,Y,YZA}$

b) along the Z-axis direction, $E_{int,Z,YZA}$

c) along the X-axis direction, $E_{int,X,YZA}$

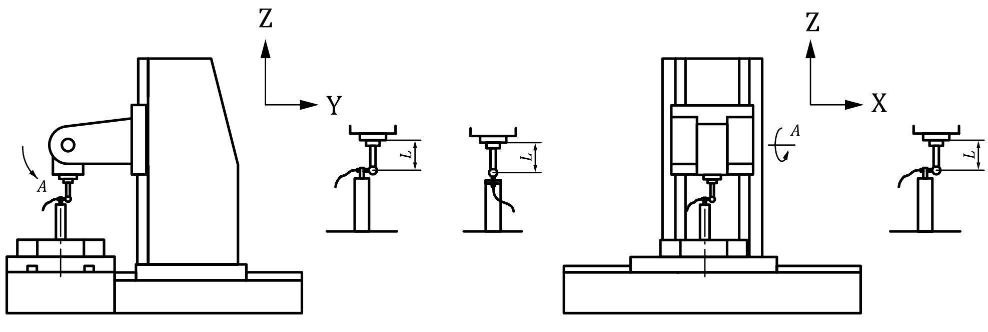
The offset of the precision sphere to spindle nose (spindle gauge line), L, should be approximately 150 mm and the rotational speed of A-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

The rotational angle of the A-axis should be over the maximum stroke, limited by possible interference between the precision sphere and the linear-displacement sensor.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of A-axis motion.

NOTE Test c) can be performed as a possible alternative to the test of squareness between the A-axis of rotation and the YZ plane, described by the corresponding geometrical test specified in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

Diagram



Tolerance (to be agreed between manufacturer/supplier and user)	**Measured deviations**
a) $E_{int,Y,YZA(CW,CCW)}$	a) $E_{int,Y,YZA(CW,CCW)}$
b) $E_{int,Z,YZA(CW,CCW)}$	b) $E_{int,Z,YZA(CW,CCW)}$
c) $E_{int,X,YZA(CW,CCW)}$	c) $E_{int,X,YZA(CW,CCW)}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

A precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations and reference to ISO 230-1:2012**, 11.3.5**
X-axis at mid travel. Set the TCP control function to ON. Move the A-axis to 0°.
When a precision sphere and flat-ended linear-displacement sensor(s) are used:
— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position. Zero the linear-displacement sensor;
— rotate the A-axis to −90° and record the readings of the linear-displacement sensor;
— rotate the A-axis to 0° and record the readings of the linear-displacement sensor;
— report the difference between the maximum and minimum recorded values for a), b), and c).
The offset of the precision sphere to the spindle nose (spindle gauge line), *L*, shall be calibrated and reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.
Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.
For ball bar setup and additional precautions, see Annex D.
It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**CK1 (alternative)**

Checking of the deviation of the tool centre point trajectory [ideally a circular path in a) and c), and a fixed point in b)] during the simultaneous three-axis interpolation of two linear axes (Y- and Z-axes) and a rotary axis (A-axis).

The sensitive direction of the measurement shall be set as follows:

a) radial to the swivel axis (A-axis), $E_{\text{int,radialA,YZA}}$;

b) parallel to the swivel axis (A-axis), $E_{\text{int,axialA,YZA}}$ ($E_{\text{int,X,YZA}}$);

c) tangential to the rotation of the swivel axis (A-axis), $E_{\text{int,tangentialA,YZA}}$.

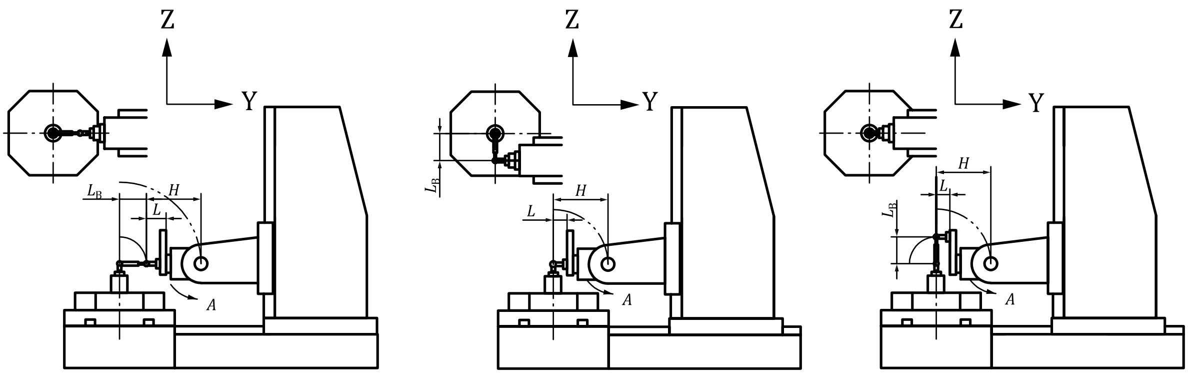
The offset of the ball on the spindle side to the spindle nose (spindle gauge line), L, should be approximately 150 mm. The reference length of the ball bar L_B is 100 mm, and the rotational speed of the A-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

The rotational angle of A-axis should be over the maximum stroke limited by possible interferences.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of A-axis motion.

NOTE Test b) can be performed as a possible alternative to the test of squareness between the A-axis of rotation and the YZ plane, described by the corresponding geometrical test specified in ISO 10791-1, ISO 10791-2, or ISO 10791-3.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{\text{int,radialA,YZA(CW,CCW)}}$	a) $E_{\text{int,radialA,YZA(CW,CCW)}}$
b) $E_{\text{int,axialA,YZA(CW,CCW)}}$ [$E_{\text{int,X,YZA(CW,CCW)}}$]	b) $E_{\text{int,axialA,YZA(CW,CCW)}}$ [$E_{\text{int,X,YZA(CW,CCW)}}$]
c) $E_{\text{int,tangentialA,YZA(CW,CCW)}}$	c) $E_{\text{int,tangentialA,YZA(CW,CCW)}}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

Ball bar, or a precision sphere with stem and a sensor's nest (e.g. R-test).

Observations and reference to ISO 230-1:2012**, 11.3.5**

The ball of the spindle side is mounted on the spindle axis average line. The axis of the ball bar is kept radial to the A-axis in a), parallel to the A-axis in b), and tangential to the A-axis in c).

The circular interpolation motion is conducted by the Y- and Z-axes while rotating the swivel axis (A-axis) of the spindle head. Set the TCP control function to ON.

For each test, continuously record the readings of the ball bar (changes of its length) during the interpolated motion. Report the difference between the maximum and minimum recorded values for a), b), and c).

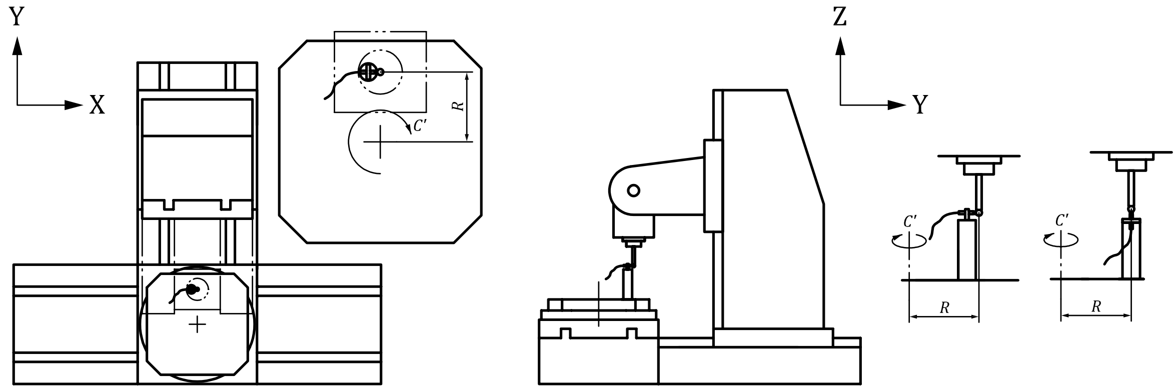
The reference length L_B of the ball bar and the offset of the spindle-side ball to spindle nose, L, shall be calibrated and reported. In a) and c), the table-side ball of the ball bar shall be aligned at the centre of the trajectory of the spindle-side ball in the workpiece coordinate system (for this alignment procedure, see Figure D.2). Any misalignment influences the test result.

A sensor's nest (e.g. R-test) can be also used when it can be mounted in the spindle side. See Annex D for precautions for test procedure and for additional precautions.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**CK2**
Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous three-axes interpolation of two linear axes (X'-and Y-axes) and a rotary axis (C'-axis). The sensitive direction of the measurement shall be set as follows: a) tangential to the rotation of the rotary axis (C'-axis), $E_{\text{int,tangentialC,XYC}}$; b) radial to the rotary axis (C'-axis), $E_{\text{int,radialC,XYC}}$; c) parallel to the rotary axis (C'-axis), $E_{\text{int,axialC,XYC}}$ ($E_{\text{int,Z,XYC}}$). The rotational speed of the C'-axis should be 360°/min or agreed between the manufacturer/supplier and the user. The rotational angle of the C'-axis should be over 360°, where applicable. Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion. NOTE Test c) can be performed as a possible alternative to the test of squareness between the C'-axis of rotation and the XY plane, described by the corresponding geometrical test specified in ISO 10791-1, ISO 10791-2, or ISO 10791-3.	

Diagram



Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{\text{int,tangentialC,XYC(CW,CCW)}}$ b) $E_{\text{int,radialC,XYC(CW,CCW)}}$ c) $E_{\text{int,axialC,XYC(CW,CCW)}}$ Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	a) $E_{\text{int,tangentialC,XYC(CW,CCW)}}$ b) $E_{\text{int,radialC,XYC(CW,CCW)}}$ c) $E_{\text{int,axialC,XYC(CW,CCW)}}$

Measuring instruments

A precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations and reference to ISO 230-1:2012**, 11.3.5**

Move the X'-axis to the rotary table centre and the Y-axis at a distance *R* from the C-axis average line. Move the A-axis and the C'-axis to 0°. Set the TCP control function to ON.

When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:

— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position;

— zero the linear-displacement sensor;

— rotate the C'-axis to 360° and continuously record the readings of the linear-displacement sensor;

— rotate the C'-axis to 0° and record the readings of the linear-displacement sensor;

— report the difference between the maximum and minimum recorded values for a), b), and c).

The distance *R* shall be reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.

Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.

See Annex D for precautions for test procedure and for additional precautions.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**CK3**

Checking of the deviation of the tool centre point trajectory (ideally a conical circular path) during the simultaneous five-axis interpolation of three linear axes and two rotary axes.

The angle between the base circle of the programmed cone and the table surface, and the apex angle of the programmed cone, shall be respectively either 10° and 30°, or 30° and 90°.

The ball of the table side of the ball bar shall be mounted with a (minimum) offset *d* of 10 % of the diameter of rotary table size (accommodating the linear axes travel range) from the axis average line of the C'-axis.

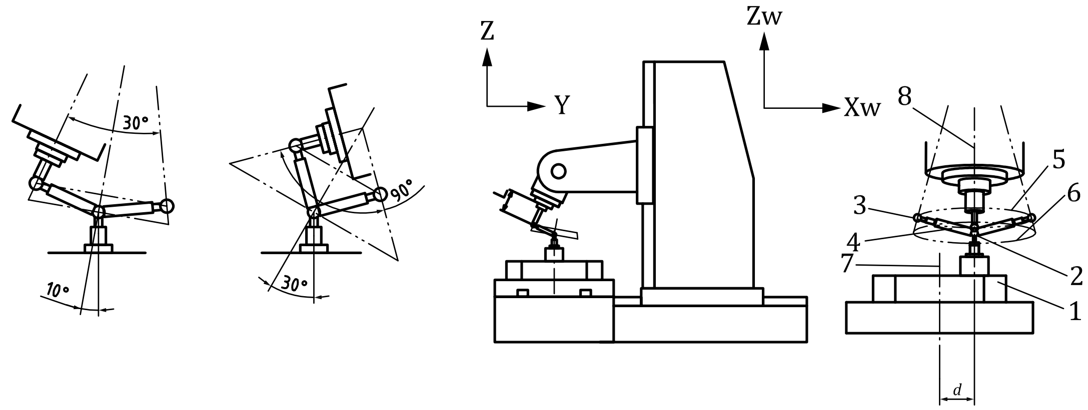
The axis of cone is tilted around the direction of the offset *d* (see diagram).

The ball bar shall be set approximately perpendicular to the cone surface.

The diameter of the circular path should be approximately 200 mm, and the peripheral feed speeds should be 1 000 mm/min.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion.

Diagram



Key

1 rotary table

2 table-side ball

3 spindle-side ball

4 ball bar

5 trajectory of spindle-side ball

6 imaginary cone’s bottom trajectory

7 C'-axis average line

8 axis of programmed cone

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
— $E_{int,cone30°, XYZAC(CW,CCW)}$ or $E_{int,cone90°, XYZAC(CW,CCW)}$ Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	— $E_{int,cone30°, XYZAC(CW,CCW)}$ or — $E_{int,cone90°, XYZAC(CW,CCW)}$

Measuring instruments

Ball bar.

Observations and reference to ISO 230-1:2012, 11.4

If the diameter differs from the above value, the feed speed shall be adjusted according to Annex C of ISO 230-4:2005.

For each test, record the readings of the ball bar (change of its length) during the interpolated motion.

Report the difference between the maximum and minimum recorded values.

The diameter of the circular path and the offset *d* shall be recorded. The offset of the spindle-side ball of the ball bar to spindle nose (spindle gauge line), *L*, shall be calibrated and reported. The spindle-side ball of the ball bar shall be aligned at the spindle axis average line. Any misalignment influences the test result. See Annex D for further precaution for this test.

If easily available, the range of movement of each axis (three linear axes and two rotary axes) shall be reported.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Object and test conditions	**CK4**

Checking of the deviations of the tool centre point trajectory (ideally a fixed point in the workpiece coordinate system) during the simultaneous five axes interpolation of three linear axes and two rotary axes.

a) in the workpiece coordinate system X-axis direction, $E_{\text{int,X,XYZAC}}$

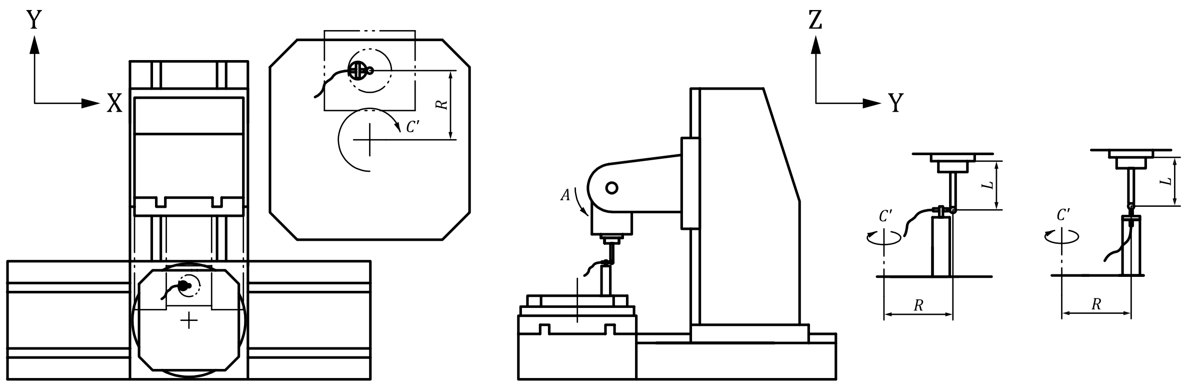
b) in the workpiece coordinate system Y-axis direction, $E_{\text{int,Y,XYZAC}}$

c) in the workpiece coordinate system Z-axis direction, $E_{\text{int,Z,XYZAC}}$

The offset of the precision sphere to spindle nose (spindle gauge line), *L*, should be approximately 150 mm and the rotational speed of C'-axis should be 360°/min or agreed between the manufacturer/supplier and the user.

Measurements shall be conducted for clockwise and counter-clockwise (anticlockwise) directions of C'-axis motion.

Diagram



a) b) c)

Tolerance (to be agreed between the manufacturer/supplier and the user)	**Measured deviations**
a) $E_{\text{int,X,XYZAC(CW,CCW)}}$	a) $E_{\text{int,X,XYZAC(CW,CCW)}}$
b) $E_{\text{int,Y,XYZAC(CW,CCW)}}$	b) $E_{\text{int,Y,XYZAC(CW,CCW)}}$
c) $E_{\text{int,Z,XYZAC(CW,CCW)}}$	c) $E_{\text{int,Z,XYZAC(CW,CCW)}}$
Each value for clockwise (CW) and counter-clockwise (anticlockwise) (CCW) directions shall be reported.	

Measuring instruments

A precision sphere with stem and flat-ended linear-displacement sensor(s) or sensor's nest (e.g. R-test), or ball bar.

Observations

Move the A-axis and the C'-axis to 0°. Move the y-axis at a distance *R* away from the axis average line of the rotary Table C'-axis. Set the TCP control function to ON.

When a precision sphere with stem and flat-ended linear-displacement sensor(s) are used:

— bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position. Zero the displacement sensor against the sphere;

— move C'-axis from 0° to 180° and simultaneously A-axis from 0° to −90°. Then continuously rotate C'-axis from 180° to 360° while rotating A-axis from −90° to 0°;

— C'-axis rotations could be limited due to possible interference with the precision sphere with stem;

— record the linear-displacement sensor readings;

— report the difference between the maximum and minimum recorded values for a), b), and c);

— A- and C-axes rotations could be limited due to possible interferences.

Distance *R* and the offset of precision sphere to spindle nose (spindle gauge line), *L*, shall be calibrated and reported. The centre of the precision sphere shall be aligned on the spindle average line. Any misalignment influences the test result.

Measurements a), b), and c) can be taken simultaneously using three linear-displacement sensors or a sensor's nest mounted on a table.

If easily available, the range of the movements (three linear axes and two rotary axes) shall be reported.

For ball bar setup and additional precautions, see Annex D.

It is recommended to present test results in a graphical form, e.g. similar to Figure D.5.

Annex D
(informative)

Precautions for test setup for Annexes A to C

D.1 General

Test results in Annexes A to C using either of a) a precision sphere with stem and flat-ended linear-displacement sensor(s), b) a precision sphere with stem and a sensor's nest (e.g. R-test), and c) the ball bar might be affected by the setup of measuring instruments. This Annex gives precautions for test procedure to minimize the influence of setup errors.

D.2 Tests with ball bar

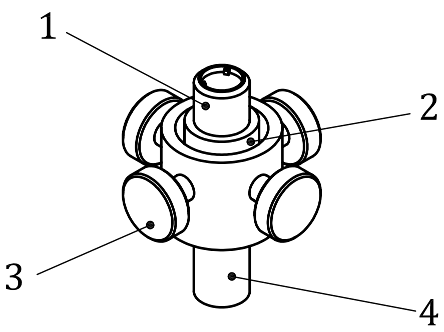
D.2.1 Alignment of precision spheres.

In all tests in Annexes A to C except for AK1 (alternative), AK2 (alternative), and CK1 (alternative), the precision sphere of the ball bar in the spindle side is aligned to the axis average line of the spindle. Any misalignment influences the test result.

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

Alternatively, when the rotary axis under the test is not in the spindle side (i.e. all tests in Annex B and CK2), the position of the sphere centre relative to the axis average line of the spindle is measured, and then the machine coordinate system can be 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 by using a linear-displacement sensor.

The table-side ball of the ball bar is located at a position such that the ball bar is directed to the measurement's sensitive direction specified in each test. In all tests in Annexes A to C except for AK1 (alternative), AK2 (alternative), and CK1 (alternative), the table-side sphere of the ball bar does not have to be precisely located. It does not affect the test result (effect of 2nd order).



Key

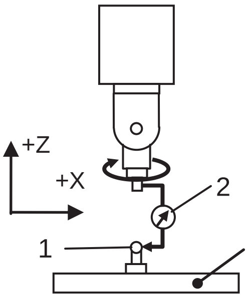
1 magnetic socket

2 magnet holder

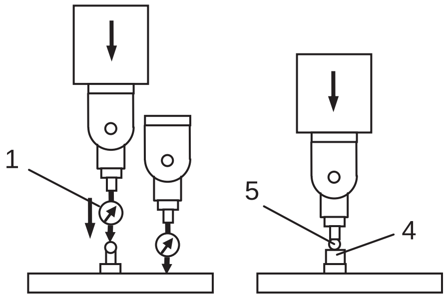
3 screw

4 stem to chuck

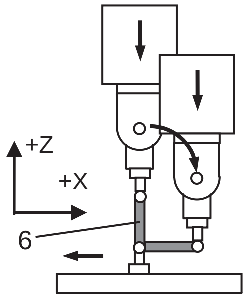
Figure D.1 — An example of an fixture to align the sphere in the spindle-side



a) Measurement of XY position



b) Measurement of Z position



c) An alternative way to measure X and Z positions by using a ball bar

Key

1 table-side precision sphere
2 linear-displacement sensor
3 table
4 tool length setting system
5 spindle-side precision sphere
6 ball bar

Figure D.2 — Procedure to measure the table-side ball location

In AK1 (alternative), AK2 (alternative), and CK1 (alternative), the table-side sphere of the ball bar is aligned at the centre of the trajectory of the spindle-side sphere in the workpiece coordinate system. When the table-side sphere is placed on the machine table, its position in the machine coordinate system is measured by using a linear-displacement sensor and a tool length setting system [see Figures D.2 a) and b)] or a ball bar [see Figure D.2 b)]. For example, the Z-position of the table-side sphere is typically calibrated as follows [Figure D.2 c)]: first, the Z-direction distance of the table-side sphere centre to the table surface is measured by using a linear-displacement sensor attached to the spindle. Then, the spindle-side sphere is installed on the spindle, and its Z-position is calibrated by 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 pre-calibrated, the Z-position of the table-side sphere relative to the spindle-side sphere can be calculated. In these tests, the position of the spindle-side sphere of the ball bar does not affect the test result (effect of 2nd order).

D.2.2 Programming

Tests AK1, AK2, AK4, BK1, BK2, BK4, CK1, CK2, and CK4 can be performed by using either the ball bar or the precision sphere with stem and linear-displacement sensor(s).

The rotary axis (axes) is 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.

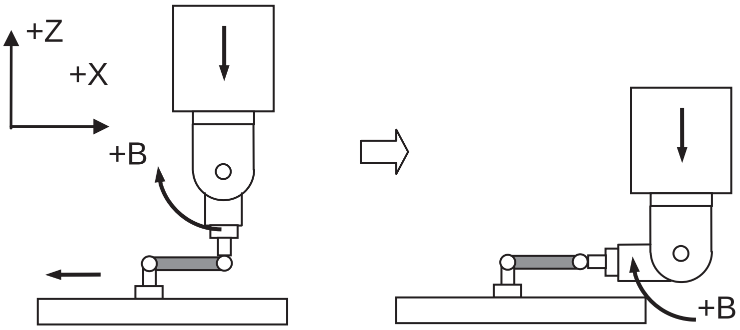


Figure D.3 — Ball bar test for AK1 (X-direction)

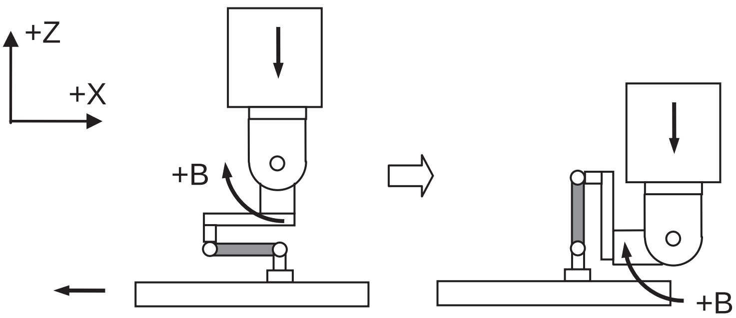


Figure D.4 — Ball bar test for AK1 (alternative) (tangential direction)

For example, in AK1 (X direction), X and Z trajectories are given such that the ball bar is always directed approximately in the X-axis direction. In AK1, AK2, AK4, and CK1 (i.e. measurements in the machine coordinate system X-, Y-, and Z-directions), the command trajectory for linear axes is exactly the same as in the case with the precision sphere and linear-displacement sensor(s). See Figure D.3 for an example of ball bar test setup in AK1 (X-direction).

In AK1 (alternative), AK2 (alternative), and CK1 (alternative), the sphere of the ball bar in the table side (i.e. the side without the rotary axis of interest) is located at the same position of the sphere in their original test (AK1, AK2, and CK1). For example, in the test c) (tangential) of AK1 (alternative) (see Figure D.4), the table-side sphere is located at the centre of the circular trajectory (i.e. on the spindle axis average line). A fixture, such as the one depicted in Figure D.4, is needed to put the spindle-side sphere away from the spindle axis average line. This setup measures the error tangential to the rotation of the swivel axis (B-axis) at the position of the table-side sphere. The tests in AK1 (alternative) can be thus seen kinematically equivalent to the tests in AK1. The ball bar is set up similarly in BK1 and BK2 as well.

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

In all tests in Annexes A to C, feed 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.

D.2.3 Test procedure

In all tests in Annexes A to C, the reference length L_B of the ball bar should be known, and the offset of the precision sphere on the spindle side to the spindle nose (spindle gauge line) should 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. 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 on the spindle, and its Z-position is measured by using the same setup. 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.

In all tests in Annexes A to C, two actual paths are measured consecutively in clockwise and counter-clockwise (anticlockwise) directions of the rotary axis under the test.

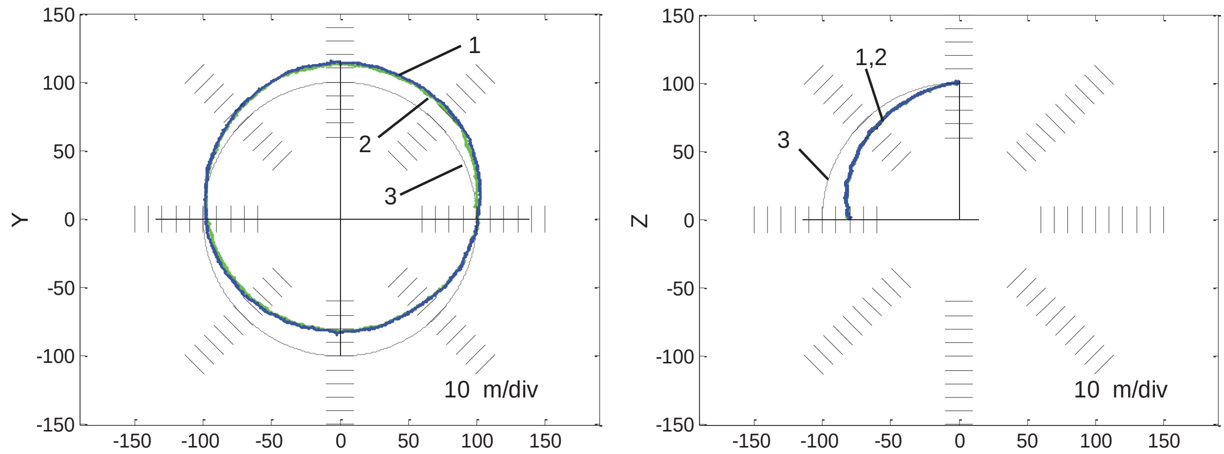
D.2.4 Presentation of results

All measured data corresponding to the actual path, including reversal points and any peaks at start and end points, are used in the evaluation.

It is preferred to display the measured displacement in a polar format as circular tests in ISO 230-4:2005. The deviation has to be plotted with the nominal angular position of the rotary axis of interest. For example, in BK2, it is plotted with the nominal angular position of C-axis, assuming its constant angular velocity except for the start/end phase (see Figure D.5 for examples). For the presentation of results for five-axis movements, the nominal angular position of the C-axis is taken as reference for the angular position of the deviations.

Some commercial software for circular tests by default perform automatic centring to evaluate the circular deviation. It should be turned off to evaluate "raw" readings of the ball bar (changes of its length). When possible, the ball bar displacement has to be reset to zero at the start of measurement.

The tests only require reporting the difference between the maximum and minimum recorded values.



a) BK2 (in the radial direction to C-axis) **b) BK1 (in the radial direction to A-axis)**

Key

1 measured displacement (clockwise)

2 measured displacement [counter-clockwise (anticlockwise)]

3 reference circular trajectory

X X-position, in millimetres

Y Y-position, in millimetres

Z Z-position, in millimetres

Figure D.5 — Examples of data presentation for BK1 and BK2

D.3 Tests with a precision sphere with stem and linear-displacement sensor(s) or sensor's nest

D.3.1 Alignment of precision sphere

A precision sphere with stem can be assembled on tool side or on table side. All tests except for AK1 (alternative), AK2 (alternative) and CK1 (alternative), however, require that the precision sphere is mounted in the spindle side. The sphere centre is aligned to the axis average line of the spindle. The offset of the precision sphere to the spindle nose (spindle gauge line) is calibrated.

In all tests except for AK1 (alternative), AK2 (alternative), and CK1 (alternative), where a precision sphere with stem is mounted on the tool side, error motions in X-, Y-, and Z-directions in the workpiece coordinate system are measured. In AK1 (alternative), AK2 (alternative), and CK1 (alternative), sensitive directions are radial, parallel, and tangential to the rotary axis. It is possible to geometrically convert to each other by the coordinate transformation.

Some commercial R-test devices allow the installation of the sphere either in the spindle side (with the sensor's nest on the table) or in the table side (with the sensor's nest to the spindle). To perform AK1 (alternative), AK2 (alternative), and CK1 (alternative), the sphere is be mounted in the table side. The sphere position is aligned at the centre of the circular trajectory in the workpiece coordinate system in an analogous manner as presented in D.2.1.

NOTE Test procedures with a precision sphere with stem and linear-displacement sensor(s), or a sensor's nest (e.g.R-test), can be the same as those with the ball bar when the same offsets, diameter, and velocity are used (see D.2.2). When the sensor's nest is mounted on a tilting axis (e.g. BK1), the fixture's stiffness should be high enough to make the gravity-induced deformation sufficiently small.

D.3.2 Test procedure

When the precision sphere is installed to the spindle, the general test procedure is as follows: position the sphere as is specified in each test. Bring the linear-displacement sensor to sense the precision sphere and rotate the spindle to find the mean run-out position. Zero the linear-displacement sensor. Then, start the test motion and record the readings of the linear-displacement sensor.

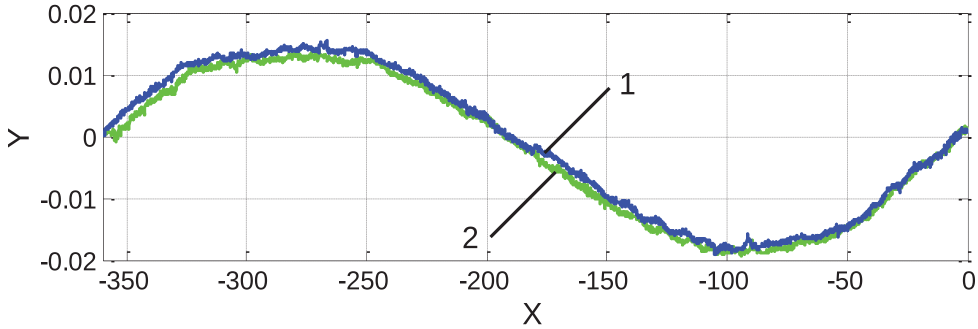
In all tests in Annexes A to C, two actual paths are measured consecutively in clockwise and counter-clockwise (anticlockwise) directions of the rotary axis under the test.

D.3.3 Presentation of results

All measured data corresponding to the actual path, including any peaks at starting and end points, and reversal points, are used in the evaluation.

It is preferred to display the measured displacement in a polar format as circular tests in ISO 230-4:2005. When it is not available, an X-Y plot with the nominal angular position of the rotary axis of interest is acceptable (see Figure D.6 for example). For the presentation of results for five-axis movements, the nominal angular position of the C-axis is taken as reference for the angular position of the deviations

The tests only require reporting the difference between the maximum and minimum recorded values.



Key

1 clockwise

2 counter-clockwise (anticlockwise)

X C-axis angular position in degrees

Y displacement in millimetres

Figure D.6 — An example of data presentation for BK2

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