INTERNATIONAL STANDARD

ISO 230-7

Second edition
2015-05-15

Corrected version
2015-07-15

Test code for machine tools —

Part 7: Geometric accuracy of axes of rotation

Code d'essai des machines-outils —

Partie 7: Exactitude géométrique des axes de rotation

Reference number
ISO 230-7:2015(E)

ISO copyright office
Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

Contents

Page

Foreword

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

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For an explanation 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 230–7:2006), which has been technically revised.

ISO 230 consists of the following parts, under the general title *Test code for machine tools*:

— *Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

— *Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*

— *Part 3: Determination of thermal effects*

— *Part 4: Circular tests for numerically controlled machine tools*

— *Part 5: Determination of the noise emission*

— *Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)*

— *Part 7: Geometric accuracy of axes of rotation*

— *Part 8: Vibrations* [Technical Report]

— *Part 9: Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations* [Technical Report]

— *Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools*

— *Part 11: Measuring instruments suitable for machine tool geometry tests* [Technical Report]

Introduction

This International Standard has been revised based on the comments received from industry and academia related to the applications of axis of rotation error motions to rotary tables, and other milling and drilling operations where more than one sensitive direction can be of critical importance. In this revision, the terms and definitions were updated and the special cases, where 1st order harmonic of radial error motion differs in different directions, were addressed. They are also reordered based on a modified structure for better clarifying the general concepts and their applications. The cases where there are multiple sensitive directions as well as the consequence of axis of rotation error motion in radial location of parts (2D sensitive direction) are described.

Test code for machine tools —

Part 7:
Geometric accuracy of axes of rotation

1 Scope

This part of ISO 230 is aimed at standardizing methods of specification and test of the geometric accuracy of axes of rotation used in machine tools. Spindle units, rotary heads, and rotary and swivelling tables of machine tools constitute axes of rotation, all having unintended motions in space as a result of multiple sources of errors.

This part of ISO 230 covers the following properties of rotary axes:

— axis of rotation error motion;

— speed-induced axis shifts.

The other important properties of rotary axes, such as thermally induced axis shifts and environmental temperature variation-induced axis shifts, are dealt with in ISO 230-3.

This part of ISO 230 does not cover the following properties of spindles:

— angular positioning accuracy (see ISO 230-1 and ISO 230-2);

— run-out of surfaces and components (see ISO 230-1);

— tool holder interface specifications;

— inertial vibration measurements (see ISO/TR 230-8);

— noise measurements (see ISO 230-5);

— rotational speed range and accuracy (see ISO 10791-6 and ISO 13041-6);

— balancing measurements or methods (see ISO 1940-1 and ISO 6103);

— idle run loss (power loss);

— thermal effects (see ISO 230-3).

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*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

NOTE They are presented in this sequence to help the user develop an understanding of the terminology of axes of rotation. The alphabetical cross-references for these definitions are given in Annex G.

3.1 General concepts

3.1.1
spindle unit
tool or workpiece carrying device providing a capability to rotate the tool or the workpiece around an axis of rotation

Note 1 to entry: A machine tool may have one or more spindle units.

3.1.2
rotary table
swivelling table
component of a machine tool carrying a workpiece and providing a capability for changing angular orientation of the workpiece around an axis of rotation

Note 1 to entry: If a rotary table of a machining centre can be used for turning operations, the rotary table can be seen as a spindle unit for these operations.

3.1.3
rotary head
swivelling head
component of a machine carrying a tool holding spindle unit and providing a capability for changing the angular orientation of the spindle unit around an axis of rotation

Note 1 to entry: Sometimes multiple axes of rotations may be combined in a machine component.

3.1.4
spindle
rotor
rotating element of a spindle unit (or rotary table/head)

3.1.5
spindle housing
stator
stationary element of a spindle unit (or rotary table/head)

3.1.6
bearing
element of a spindle unit (or rotary table/head) that supports the rotor and enables rotation between the rotor and the stator

3.1.7
axis of rotation
line segment about which rotation occurs

[SOURCE: ISO 230-1:2012, 3.5.2]

Note 1 to entry: See Figure 1 a).

Note 2 to entry: In general, during rotation, this line segment translates (in radial and axial directions) and tilts within the reference coordinate frame due to inaccuracies in the bearings and bearing seats structural motion or axis shifts, as shown in Figure 1 a) and b).

3.1.8
positive direction
in accordance with ISO 841, the direction of a movement that causes an increasing positive dimension of the workpiece

3.1.9
perfect spindle (or rotary table/head)
spindle or rotary table/head having no error motion of its axis of rotation relative to its axis average line

3.1.10
perfect workpiece
rigid body having a perfect surface of revolution about a centreline

3.1.11
functional point
cutting tool centre point or point associated with a component on the machine tool where cutting tool would contact the part for the purposes of material removal

[SOURCE: ISO 230-1:2012, 3.4.2]

3.1.12
axis average line
straight line segment located with respect to the reference coordinate axes representing the mean location of the axis of rotation

Note 1 to entry: See Figure 1 a).

Note 2 to entry: The axis average line is a useful term to describe changes in location of an axis of rotation in response to load, temperature, or speed changes.

Note 3 to entry: Unless otherwise specified, the position and orientation of the axis average line should be determined by connecting the calculated least-squares centres of two data sets of radial error motion taken at axially separated locations (see 3.4).

Note 4 to entry: ISO 841 defines the Z-axis of a machine as being “parallel to the principal spindle of the machine”. This implies that the machine Z-axis is parallel to the axis average line of the principal spindle. However, since axis average line definition applies to other spindles and rotary axes as well, in general, not all axes of rotation are parallel to the machine Z-axis. An axis average line should be parallel to the machine Z-axis only if it is associated with the principal spindle of the machine.

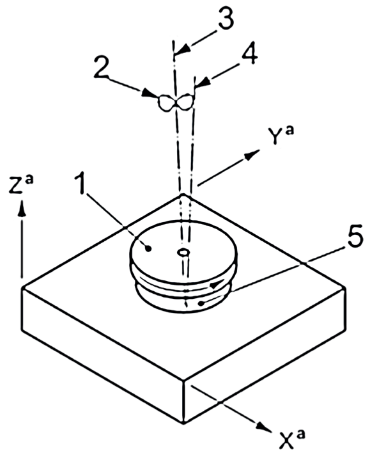
3.1.13
axis shift
<axis of rotation> quasi-static relative angular and linear displacement, between the tool side and the workpiece side, of the axis average line due to a change in conditions

Note 1 to entry: See Figure 1 c).

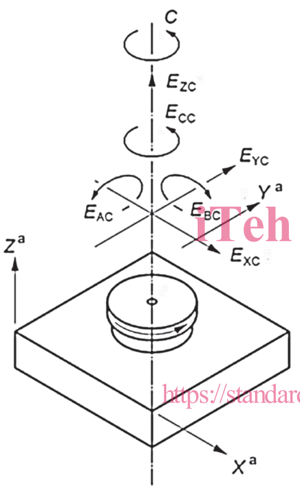
Note 2 to entry: Causes of axis shift include thermal influences, load changes, as well as speed and direction changes. Axis of rotation error motion measurements are carried out over a period of time (number of revolutions) and conditions that avoid axis shift.

3.1.14
structural loop
assembly of components which maintains the relative position and orientation between two specified objects (i.e. between the workpiece and the cutting tool)

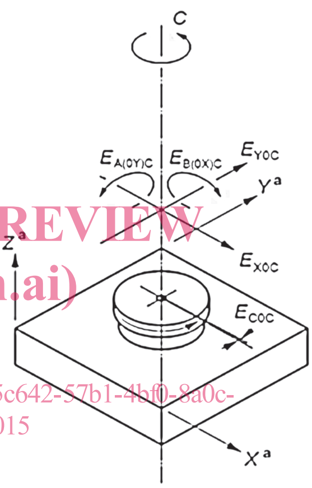
Note 1 to entry: A typical pair of specified objects is a cutting tool and a workpiece on a machine tool (e.g. lathe). In this case, the structural loop would include the workpiece holding fixture (e.g. chuck), spindle, bearings and spindle housing, the machine head stock, machine bed, the machine slideways, carriages, and the tool holding fixture.



a) Reference coordinate axes, axis of rotation, axis average line, and error motion of a spindle



b) Error motions of axis of rotation



c) Position and orientation errors (axis shift) of axis average line

Key

1 spindle (rotor)

2 error motion trajectory of axis of rotation at varying angular positions of the spindle

3 axis average line

4 axis of rotation (at a given angular position of the spindle)

5 spindle housing (stator)

E_{XC} radial error motion of C in X-axis direction

E_{YC} radial error motion of C in Y-axis direction

E_{ZC} axial error motion of C

a Reference axis.

E_{AC} tilt error motion of C around X-axis

E_{BC} tilt error motion of C around Y-axis

E_{CC} angular positioning error motion of C

E_{X0C} error of the position of C in X-axis direction

E_{Y0C} error of the position of C in Y-axis direction

$E_{A(0Y)C}$ error of the orientation of C in A-axis direction; squareness of C to Y

$E_{B(0X)C}$ error of the orientation of C in B-axis direction; squareness of C to X

E_{C0C} zero position error of C-axis

Figure 1 — Reference coordinate axes, axis average line, and error motions of an axis of rotation shown for a C spindle or a C rotary axis

3.1.15
radial throw of a rotary axis at a given point
distance between the geometric axis of a part (or test artefact) connected to a rotary axis and the axis average line, when the two axes do not coincide

[SOURCE: ISO 230-1:2012, 3.5.10]

3.1.16
run-out of a functional surface at a given section
total displacement measured by a displacement sensor sensing against a moving surface or moved with respect to a fixed surface

Note 1 to entry: The terms “TIR” (total indicator reading) and “FIM” (full indicator movement) are equivalent to run-out.

Note 2 to entry: Measured run-out of a rotating surface includes surface profile (form) errors, radial throw of the axis, axis of rotation error motions and possibly motion of the surface with respect to axis of rotation (due to dynamic excitation of the workpiece) and structural error motion.

[SOURCE: ISO 230-1:2012, 3.9.7]

3.1.17
stationary point run-out
total displacement measured by a displacement sensor sensing against a point on a rotating surface which has negligible lateral motion with respect to the sensor when both the sensor and the surface rotate together

Note 1 to entry: See Figure 2 and ISO 230-1:2012, 10.2.2.

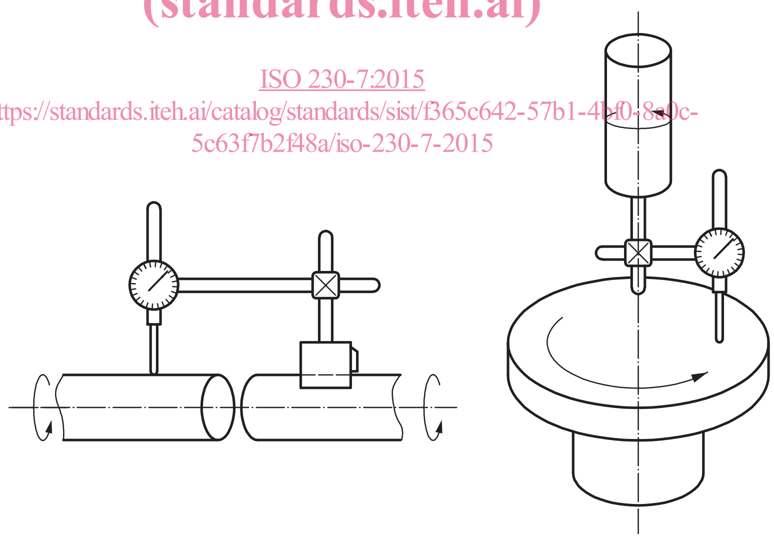


Figure 2 — Schematics of sample applications for use of stationary point run-out (radial test for concentricity and face test for parallelism)

3.1.18
squareness error between two axis average lines
angular deviation from 90° between the axis average line of a rotating component of the machine and (in relation to) the axis average line of another rotating component of the machine

[SOURCE: ISO 230-1:2012, 3.6.9]

3.1.19
squareness error between a linear axis of motion and an axis average line
angular deviation from 90° between the reference straight line of a point on a linear moving component and (in relation to) the axis average line of a rotating component of the machine

Note 1 to entry: The positive direction associated with the axis of rotation is taken as the positive direction of the linear motion resulting from the right-hand rule according to ISO 841.

[SOURCE: ISO 230-1:2012, 3.6.8]

3.1.20
play
condition of zero stiffness over a limited range of displacement due to clearance between elements of a structural loop

[SOURCE: ISO 230-1:2012, 3.3.3]

3.1.21
hysteresis
linear (or angular) displacement between two objects resulting from the sequential application and removal of equal forces (or moments) in opposite directions

Note 1 to entry: Hysteresis is caused by mechanisms, such as drive train clearance, guideway clearance, mechanical deformations, friction, and loose joints.

[SOURCE: ISO 230-1:2012, 3.3.4]

3.1.21.1
setup hysteresis
hysteresis of various components in a test setup, normally due to loose mechanical connections

[SOURCE: ISO 230-1:2012, 3.3.5]

3.1.21.2
machine hysteresis
hysteresis of the machine structure when subjected to specific loads

[SOURCE: ISO 230-1:2012, 3.3.6]

3.2 Error motion terms

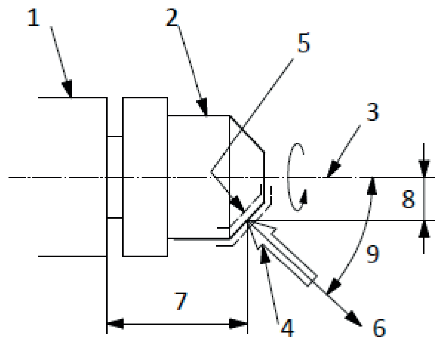
3.2.1
axis of rotation error motion
unwanted changes in position and orientation of axis of rotation relative to its axis average line as a function of angular position of the rotating component

[SOURCE: ISO 230-1:2012, 3.5.4 — modified to improve clarity]

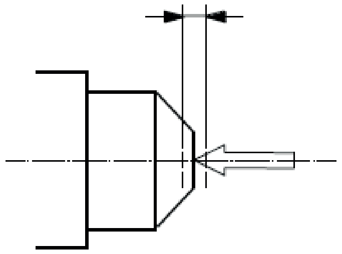
Note 1 to entry: See Figure 3.

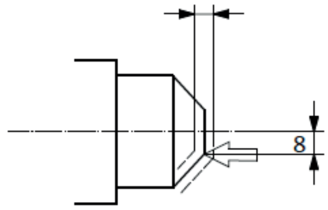
Note 2 to entry: This error motion may be measured as motions of the surface of a perfect cylindrical or spherical test artefact with its centreline coincident with the axis of rotation.

Note 3 to entry: Error motions are specified as location and direction as shown in Figure 3 a) and do not include motions due to axis shifts associated with changes in temperature, load, or rotational speed.

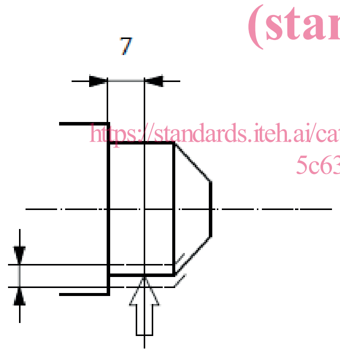


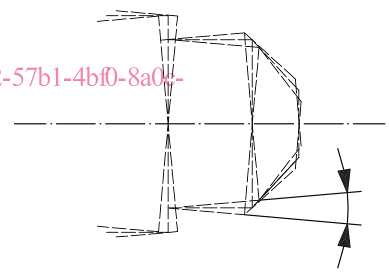
a) General case of axis of rotation error motion





b) Axial error motion **c) Face error motion**





d) Radial error motion **e) Tilt error motion**

Key

1	spindle	6	sensitive direction
2	perfect workpiece	7	axial location
3	axis average line	8	radial location
4	displacement sensor	9	direction angle
5	error motion		

Figure 3 — General case of axis of rotation error motion and axial, face, radial, and tilt error motions for fixed sensitive direction

3.2.2
structural error motion
error motion caused by internal or external excitation and affected by elasticity, mass, and damping of the structural loop

Note 1 to entry: See 3.9

Note 2 to entry: Structural error motion can be reaction to the rotation of the spindle/rotary table/head that can influence the measurements.

3.2.3
bearing error motion
error motion due to imperfect bearing between stationary and rotating components of a rotary axis

Note 1 to entry: See Annex A.

3.2.4
static error motion
special case of error motion in which error motion is sampled with the spindle (or rotary table/head) at rest at a series of discrete rotational positions

Note 1 to entry: This is used to measure error motion exclusive of any dynamic influences.

3.3 Consequences of axis of rotation error motion

NOTE The measurement of axis of rotation error motion takes into consideration the intended use of the axis of rotation. As provided in definition 3.2.1, the axis of rotation error motion indicates the overall motion, in three-dimensional space, of the axis of rotation with respect to its axis average line. Consequences of this motion on the accuracy of machined workpieces vary depending on the type of machining application. For example, for the simplest cases of machining such as single point turning and boring operations, only the component of the error motion in the direction of the cutting tool at any given time is of importance. But, for a milling operation with multiple cutting edges, error motion at multiple directions might be of importance. Similarly, axial drilling of holes on a part mounted on a rotary table requires the axis of rotation error motion of the rotary table corresponding to the hole pattern in the plane perpendicular to the axis average line to be known. Furthermore, turning of non-round surfaces presents a case where error motion in the direction of cutting tool is not sufficient to describe the relationship between the axis of rotation error motion and its consequence on the machined part profile. The following definitions provide the basis for the measurement and analysis methods of this error motion taking into account the applications.

3.3.1
sensitive direction
direction perpendicular to the workpiece surface at the functional point

Note 1 to entry: See Figure 3.

Note 2 to entry: Although for many machining and measurement applications there is only one sensitive direction of interest at a time, for some other applications there may be multiple sensitive directions of interest. However, for testing purposes, considering only a single sensitive direction may be adequate unless otherwise specified.

3.3.2
non-sensitive direction
direction perpendicular to the sensitive direction

3.3.3
fixed sensitive direction
sensitive direction where the functional point in machine coordinate system does not change with the angular position of the rotating component

Note 1 to entry: See Figure 4.

Note 2 to entry: For a fixed sensitive direction, the results of the measurement of the relative displacement between the tool and the workpiece correspond to the shape error of the manufactured surface of a workpiece.

Note 3 to entry: A single-point turning operation has a fixed sensitive direction. However, this is not the case for turning non-round surfaces.

Note 4 to entry: A rotary table may have multiple fixed sensitive directions. For example, rotary table used for single point turning in X or Y directions, may have two fixed sensitive directions.

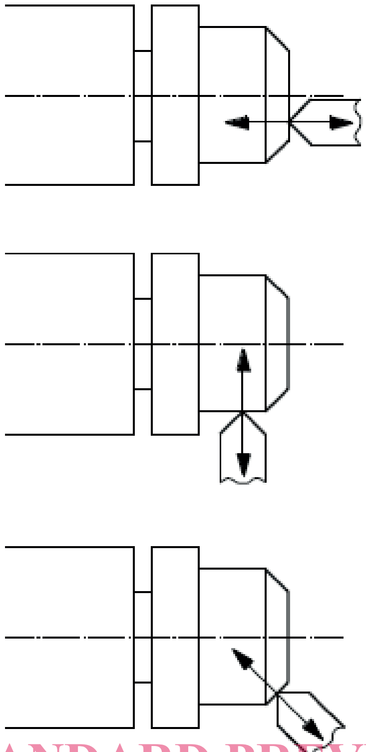


Figure 4 — Illustration of fixed sensitive directions in facing, turning, and chamfering

3.3.4
rotating sensitive direction
sensitive direction that rotates synchronously with the angular position of the rotating component

Note 1 to entry: See Figure 5.

Note 2 to entry: A jig borer has a rotating sensitive direction. A milling spindle with multiple-teeth milling cutter has multiple rotating sensitive directions.

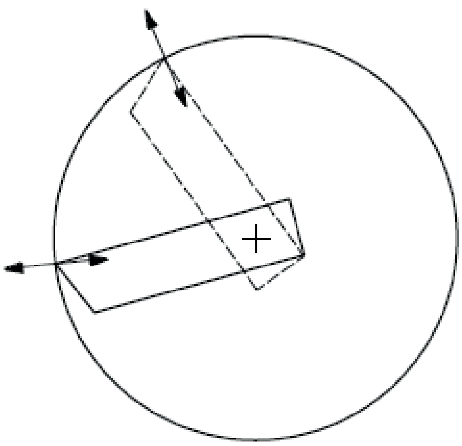


Figure 5 — Illustration of rotating sensitive direction at two instants in time in jig-boring a hole