INTERNATIONAL STANDARD

ISO 230-7

Second edition
2015-05-15

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)

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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).

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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.

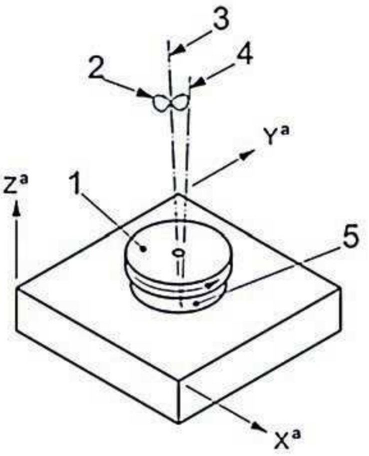
3.1.13
axis shift
<axis of rotation> quasi-static relative angular and linear displacement, between the tool side and the workpiece side, of the axis average line due to a change in conditions

Note 1 to entry: See Figure 1 c).

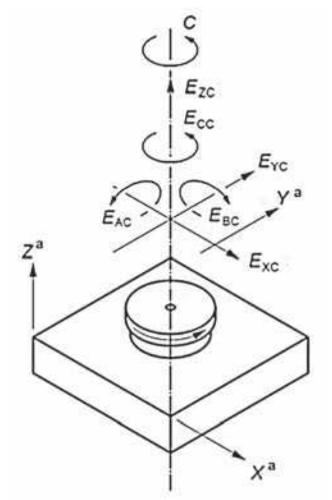
Note 2 to entry: Causes of axis shift include thermal influences, load changes, as well as speed and direction changes. Axis of rotation error motion measurements are carried out over a period of time (number of revolutions) and conditions that avoid axis shift.

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)

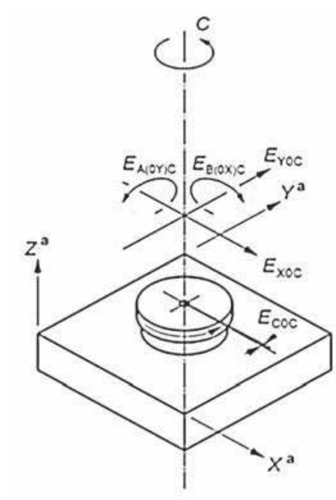
Note 1 to entry: A typical pair of specified objects is a cutting tool and a workpiece on a machine tool (e.g. lathe). In this case, the structural loop would include the workpiece holding fixture (e.g. chuck), spindle, bearings and spindle housing, the machine head stock, machine bed, the machine slideways,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

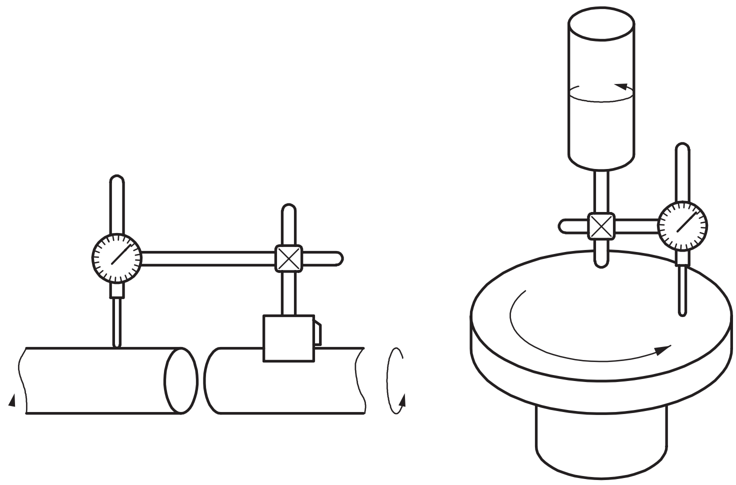


Figure 2 — Schematics of sample applications for use of stationary point run-out (radial test for concentricity and face test for parallelism)

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

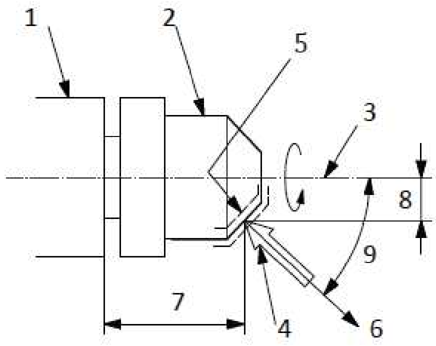
3.2.1
axis of rotation error motion
unwanted changes in position and orientation of axis of rotation relative to its axis average line as a function of angular position of the rotating component

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

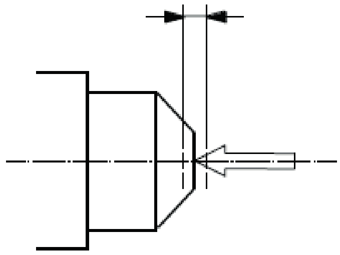
Note 1 to entry: See Figure 3.

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.

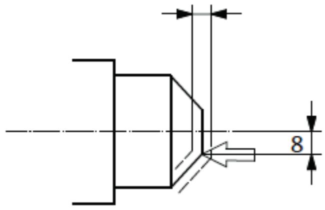
Note 3 to entry: Error motions are specified as location and direction as shown in Figure 3 a) and do not include motions due to axis shifts associated with changes in temperature, load, or rotational speed.



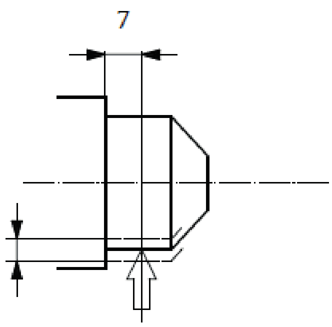
a) General case of axis of rotation error motion



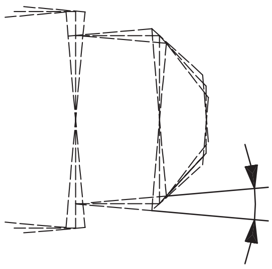
b) Axial error motion



c) Face error motion



d) Radial error motion



e) Tilt error motion

Key

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

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.

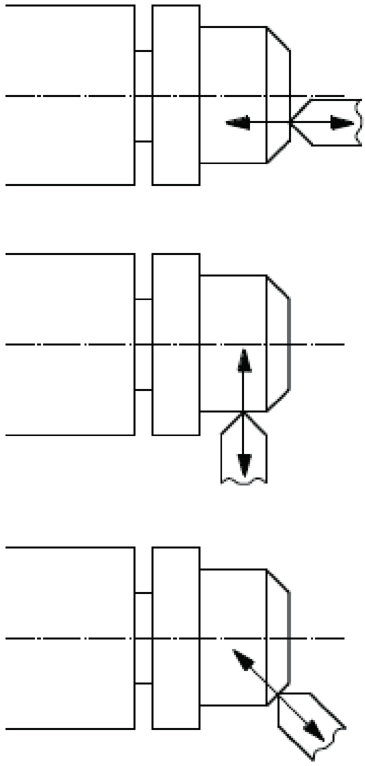


Figure 4 — Illustration of fixed sensitive directions in facing, turning, and chamfering

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.

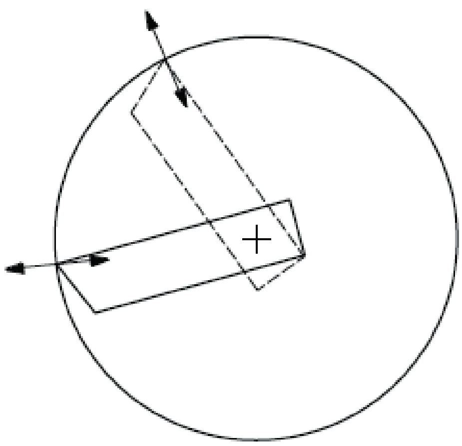


Figure 5 — Illustration of rotating sensitive direction at two instants in time in jig-boring a hole

3.3.5
varying sensitive direction
sensitive direction that changes as a function of the angular position of the rotating component (as a result of changing surface normal due to shape of the workpiece surface)

Note 1 to entry: See Figure 6.

Note 2 to entry: For example, single point turning of non-round workpiece, or machining a polygon on a turning machine, or cam grinding.

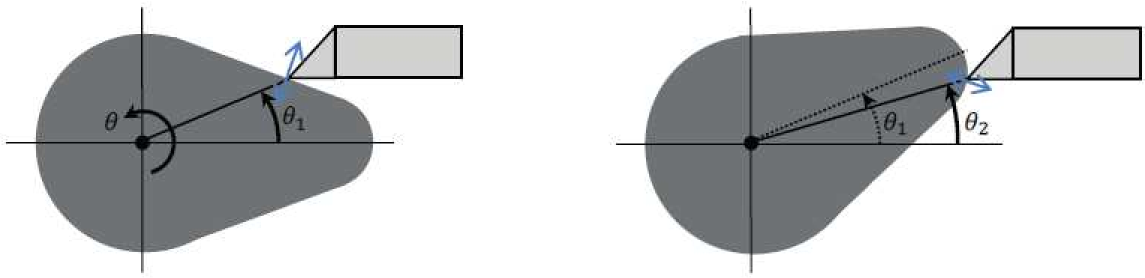


Figure 6 — Illustration of varying sensitive direction for cam turning operation

3.3.6
2D effect of axis of rotation error motion
effect of axis of rotation error motion on the position of the functional point in the plane perpendicular to the axis average line

Note 1 to entry: In the case of drilling a circular hole pattern on a workpiece mounted on a rotary table, axis of rotation error motion causes errors in the positions of the holes.

3.4 Directional decomposition of axis of rotation error motion

NOTE Similar to error motions of a linear axis (see ISO 230-1:2012, 3.4.3), error motions of axes of rotation are decomposed into directions along the three orthogonal axes. Since only the component(s) of the axis of rotation error motion along the sensitive direction(s) influence the geometry of the machined part, the error motion in three-dimensional space is measured and analysed along the sensitive direction(s). The following definitions provide the directional decomposition of the error motion.

3.4.1
radial error motion
error motion in a direction perpendicular to the axis average line and at a specified axial location

Note 1 to entry: See Figure 3 d).

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

Note 3 to entry: The term "radial run-out" includes additional errors due to centring and artefact out-of-roundness, and hence is not equivalent to radial error motion.

3.4.2
pure radial error motion
error motion in which the axis of rotation remains parallel to the axis average line and moves perpendicular to it in the sensitive direction

Note 1 to entry: Pure radial error motion is just the concept of radial error motion in the absence of tilt error motion. There should be no attempt to measure it.

3.4.3
tilt error motion
error motion in an angular direction relative to the axis average line

Note 1 to entry: See Figure 3 e).

Note 2 to entry: This motion may be evaluated as the difference between two simultaneous measurements of the radial error motion in two radial planes separated by a distance along the axis average line, divided by the axial separation distance.

Note 3 to entry: "Coning," "wobble," "swash", "tumbling", and "towering" errors are non-preferred terms for tilt error motion.

Note 4 to entry: The term "tilt error motion" rather than "angular motion" was chosen to avoid confusion with rotation about the axis or with angular positioning error of devices such as rotary tables.

3.4.4
axial error motion
error motion coaxial with the axis average line

Note 1 to entry: See Figure 3 b).

Note 2 to entry: This error motion may be measured as the motions, in the axial direction along the axis average line, of the surface of a perfect flat disk or spherical test artefact with its centreline coincident with the axis of rotation.

Note 3 to entry: "Axial slip", "end-camming", "pistoning", and "drunkenness" are non-preferred terms for axial error motion.

3.4.5
face error motion
error motion parallel to the axis average line at a specified radial location

Note 1 to entry: See Figure 3 c).

Note 2 to entry: Face error motion is a combination of axial and tilt error motions. The term "face run-out" is analogous to "radial run-out" (see 3.4.2) and hence is not equivalent to face error motion.

3.5 Decomposition of measured axis of rotation error motion based on rotational frequency

3.5.1
total error motion
error motion as recorded over multiple revolutions, composed of the synchronous and asynchronous components of the axis of rotation and structural error motions

3.5.2
synchronous error motion
portion of the total error motion that occurs at integer multiples of the rotation frequency

Note 1 to entry: It is the mean contour of the total error motion polar plot averaged over the number of revolutions.

3.5.3
fundamental error motion
sinusoidal portion of the total error motion that occurs at the rotation frequency

Note 1 to entry: See A.7.6.

Note 2 to entry: Normally, fundamental radial error motion value is considered negligible because, in case of single fixed or rotating sensitive direction, error motion in radial direction at the rotational frequency does not result in form errors in machined workpieces (e.g. roundness of turned or bored cylinders is not affected).

Note 3 to entry: In most cases, the measured (apparent) fundamental radial error motion is the result of the radial throw of the reference artefact.

Note 4 to entry: If the fundamental radial error motion is different in X- and Y-directions, then it cannot be neglected in cases of varying sensitive direction and/or determining 2D effects on the position of the functional point.

3.5.4
residual synchronous error motion
portion of the synchronous error motion that occurs at integer multiples of the rotation frequency other than the fundamental

3.5.5
asynchronous error motion
portion of the total error motion that occurs at frequencies other than integer multiples of the rotation frequency

Note 1 to entry: Asynchronous error motion is the deviations of the total error motion from the synchronous error motion.

Note 2 to entry: Asynchronous error motion comprises those components of error motion that are

a) not periodic,

b) periodic but occur at frequencies other than the rotation frequency and its integer multiples, and

c) periodic at frequencies that are sub harmonics of the rotation frequency.

3.6 Terms for axis of rotation error motion polar plots

3.6.1
error motion polar plot
representation of error motions of axes of rotation in polar coordinates generated by plotting displacement versus the angle of rotation of the spindle or rotary table/head

Note 1 to entry: See Figure 7.

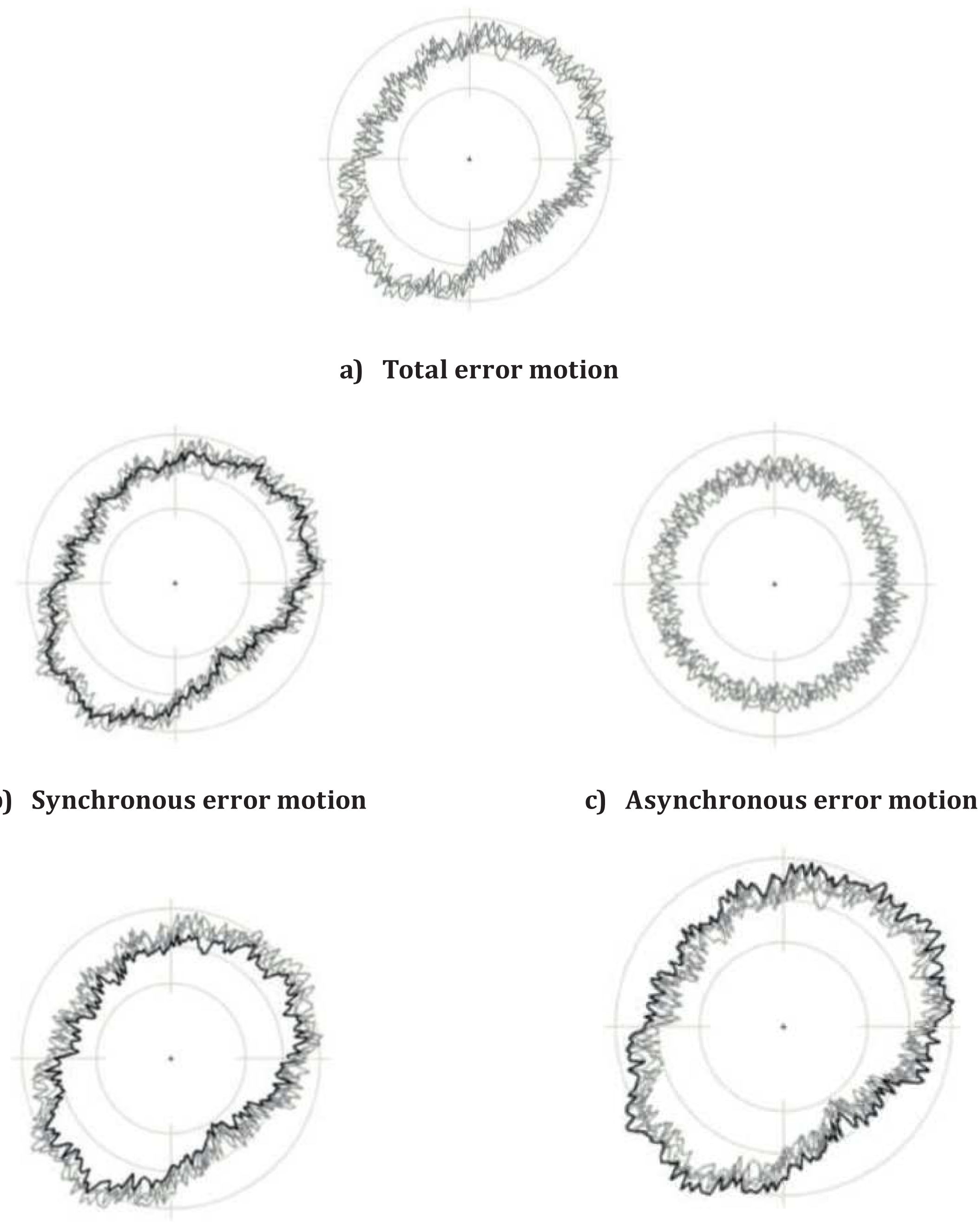
3.6.2
total error motion polar plot
polar plot of the total error motion as recorded

Note 1 to entry: See Figure 7 a).

3.6.3
synchronous error motion polar plot
polar plot of the synchronous error motion

Note 1 to entry: See 3.5.2 and Figure 7 b).

Note 2 to entry: It is acceptable to create the synchronous error motion polar plot by averaging the total error motion polar plot over the number of revolutions.



a) Total error motion

b) Synchronous error motion

c) Asynchronous error motion

d) Inner error motion

e) Outer error motion

Figure 7 — Error motion polar plots

3.6.4
asynchronous error motion polar plot
polar plot of the asynchronous error motion

Note 1 to entry: See Figure 7 c).

3.6.5
fundamental error motion polar plot
best-fit circle passed through the synchronous axial or face error motion polar plot about a specified polar profile centre

3.6.6
residual synchronous error motion polar plot
polar plot of the residual synchronous error motion

3.6.7
inner error motion polar plot
contour of the inner boundary of the total error motion polar plot

Note 1 to entry: See Figure 7 d).

3.6.8
outer error motion polar plot
contour of the outer boundary of the total error motion polar plot

Note 1 to entry: See Figure 7 e).

3.7 Terms for axis of rotation error motion polar plot centres

NOTE Since axis of rotation error motions are visualized as polar plots, the assessment of error motion values rely on centres of these plots. This clause provides the definitions of these centres for the assessment of error motion values. Table 1 provides the preferred polar plot centres for the types of error motions. If the centre is not specified in any particular test description, the preferred centre is to be assumed.

Table 1 — Preferred polar plot centres for various error motion types

Error motion type	Preferred centre
Radial error motion	LSC centre
Tilt error motion	LSC centre
Axial error motion	PC centre
Face error motion	PC centre

3.7.1
error motion polar plot centre
centre defined for the assessment of error motion polar plots

Note 1 to entry: See Figure 8.

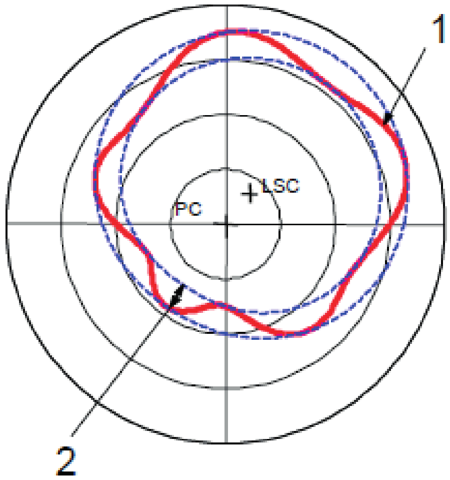
3.7.2
polar chart centre
PC centre
centre of the polar chart

Note 1 to entry: See Figure 8.

3.7.3
polar profile centre
centre derived from the polar profile by a mathematical or graphical technique

3.7.4
least-squares circle centre
LSC centre
centre of a circle that minimizes the sum of the squares of a sufficient number of equally spaced radial deviations measured from it to the error motion polar plot

Note 1 to entry: See Figure 8.



Key

1 error motion polar plot

2 error motion value for LSC centre

Figure 8 — Error motion polar plot, PC (polar chart) centre and LSC (least-square circle) centre, and error motion value for LSC centre

3.7.5
minimum radial separation centre
MRS centre
centre that minimizes the radial difference required containing the error motion polar plot between two concentric circles

3.7.6
maximum inscribed circle centre
MIC centre
centre of the largest circle that can be inscribed within the error motion polar plot

3.7.7
minimum circumscribed circle centre
MCC centre
centre of the smallest circle that will just contain the error motion polar plot

Note 1 to entry: Unless otherwise specified, the polar profile centre is determined using the synchronous error motion polar plot.

Note 2 to entry: A workpiece is centred with *zero centring error* when the polar chart centre coincides with the chosen polar profile centre.

3.8 Terms for axis of rotation error motion values

NOTE In most cases, an error motion value is equal to the difference in radii of two concentric circles that will just enclose the corresponding error motion polar plot, and the value obtained depends upon the location of the common centre of these two circles. Definitions in this clause help in understanding the phenomena and the computations. Mathematical analysis allows the values to be calculated without constructing error motion polar plots.

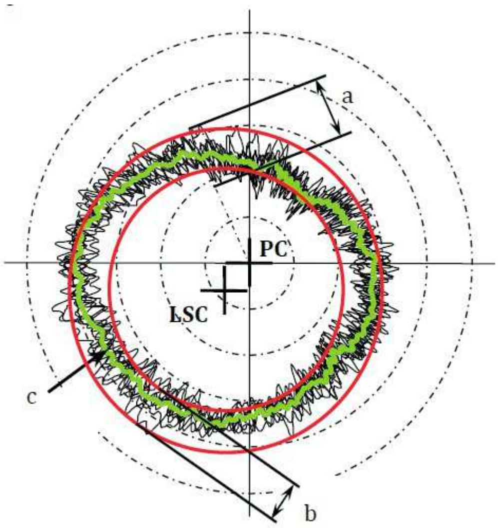
3.8.1
error motion value
magnitude assessment of an error motion component over a specified number of revolutions

3.8.2
total error motion value
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the total error motion polar plot

Note 1 to entry: Four total error motion values are defined: total radial error motion, total tilt error motion, total axial error motion, and total face error motion.

3.8.3
synchronous error motion value
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the synchronous error motion polar plot

Note 1 to entry: See Figure 9.



Key

a asynchronous error motion value based on PC centre

b synchronous error motion value based on LSC centre

c synchronous error motion plot

Figure 9 — Error motion polar plot, asynchronous error motion, and synchronous error motion values

3.8.4
asynchronous error motion value
maximum scaled width of the asynchronous error motion polar plot, measured along a radial line through a specified polar profile centre

Note 1 to entry: See Figure 9.

Note 2 to entry: Asynchronous error motion value is found from the total error motion polar plot as the maximum radial width of the "cloud band" at any angular position around the circumference. It is the only measurement that does not employ concentric circles, since it involves the radial variation at a particular angle rather than the radial variation around the full circumference. To be strictly correct, the asynchronous error motion value should be measured along a radial line from the polar chart (PC) centre rather than from a best fit centre, even though this is contrary to what seems intuitively correct (see Figure 9.)

3.8.5
fundamental axial error motion value
value equivalent to twice the scaled distance between the PC centre and a specified polar profile centre of the synchronous error motion polar plot

Note 1 to entry: Alternatively, it is the amplitude of the measured synchronous error at the rotational frequency.

Note 2 to entry: Fundamental radial error motion value is neglected (see 3.5.3) for single fixed or rotating sensitive direction.

3.8.6
residual synchronous error motion value
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the residual synchronous error motion polar plot

3.8.7
inner error motion value
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the inner error motion polar plot

3.8.8
outer error motion value
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the outer error motion polar plot

3.9 Terms for structural error motion

3.9.1
structural error motion with rotating spindle (or rotary table/head)
motion of one element of a structural loop relative another element, measured while the spindle (or rotary table/head) is rotating

Note 1 to entry: In some machines, the spindle drive system may transmit large deflections to the structure.

3.9.2
structural error motion with non-rotating spindle (or rotary table/head)
motion of one or more elements of a structural loop relative to the axis of rotation, measured while the spindle (or rotary table/head) is not rotating

Note 1 to entry: In many applications, it is important to isolate sources of structural motion to external sources, i.e. coolant or hydraulic pumps, or excitation caused by floor vibration.

3.9.3
structural error motion plot
time-based rectilinear displacement plot or polar plot for recording structural motion

Note 1 to entry: A polar plot may be desired in order to resolve which component of the total structural error motion is synchronous with the spindle rotation.

3.9.4
structural error motion value
range (max. – min.) of displacement measured over a defined time and specified operating conditions

3.10 Terms for axis shift

3.10.1
radial shift
axis shift in the direction perpendicular to the axis average line

3.10.2
tilt shift
axis shift in an angular direction relative to the axis average line

3.10.3
axial shift
axis shift in the direction parallel to the axis average line measured on a functional surface (e.g. $E_{Z0,\ TABLE}$, $E_{Z0,SPINDLENOSE}$)

3.10.4
face shift
combination of axial and tilt shifts in the axis of rotation measured at a specified radial location

Note 1 to entry: See Figure 3 c).

3.10.5
speed-induced axis shift plot
rectilinear graph of the shift in the axis of rotation as rotational speed is varied

3.10.6
speed-induced axis shift value
difference between the maximum and minimum displacement measurements of axis of rotation by a single displacement sensor (or a combination of displacement sensors for tilt and face measurements) at various specified rotational speeds

4 Preliminary remarks

4.1 Measuring units

In this part of ISO 230, all linear dimensions, deviations, and corresponding tolerances are expressed in millimetres; angular dimensions are expressed in degrees, and angular deviations and the corresponding tolerances are expressed in ratios as the primary method, but in some cases, microradians or arcseconds can be used for clarification purposes. Equivalences for units of angular deviations and angular tolerances are given by the following expression:

$$0{,}010/1\ 000 = 10\ \mu\text{rad} \approx 2''$$

4.2 Reference to ISO 230-1

To apply this part of ISO 230, 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 uncertainty of testing equipment.

4.3 Recommended instrumentation and test equipment

The measuring instruments recommended here are only examples. Other instruments capable of measuring the same quantities and having the same or smaller measurement uncertainty can be used.

a) For spindle measurements, non-contact linear displacement sensor insensitive to metallographic variations of the test artefact with adequate range, resolution, thermal stability, accuracy, and bandwidth. The required bandwidth depends upon the number of undulations per revolution it is desired to resolve, and the speed range of the spindle. For most machine tools, a bandwidth of 10 kHz is acceptable for rotational speeds of up to 6 000 r/min. Such a displacement sensor is capable of detecting up to 50 undulations per revolution at this speed. In many cases, such high number of undulations is not expected in machine tool spindles; therefore, higher spindle speeds can be accommodated using sensors with 10 kHz bandwidth. In general, proportionally higher bandwidths might be required for higher spindle speeds and higher number of undulations (see Table H.1). For rotary table/head measurements, contact-type linear displacement sensors can also be used.

b) Data acquisition equipment, such as a computer-based system to sample and store displacement data for subsequent analysis.

c) Test-mandrel, with the design to be specified in machine-specific standards or agreed between supplier/manufacturer and the user, see ISO 230-1:1996, A.3;

d) Fixture in which to mount the displacement sensors.

Long-term accuracy of the measuring equipment shall be verified, for example, by transducer drift tests.

The measuring instruments shall be thermally stabilized before starting the tests.

4.4 Environment

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

4.5 Rotary component to be tested

The rotary component shall be completely assembled and fully operational. Axis of rotation tests shall be carried out in the unloaded condition.

NOTE This is not a type test for the spindle unit or rotary table/head. Tests of the same spindle unit or rotary table/head in different machines might generate different results due to mounting, thermal effects, and vibration conditions.

4.6 Rotary component warm-up

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

If no other conditions are specified, the preliminary movements shall be restricted to only those necessary to set up the measuring instrument for rotary heads, rotary, and swivelling tables. A spindle should be tested after it has been allowed to warm-up at half of its maximum rotational speed for a minimum of 10 min.

4.7 Structural error motion tests

4.7.1 General

These tests are designed to point out relative motion between the tool and the workpiece, which is caused by the machine structure and the environment.

4.7.2 Test procedure

First, measure structural error motion with the machine's power and auxiliary systems on, but with the machine drives off, that is, the emergency stop position.

Then measure the structural error motion with the machine's power and auxiliary systems, such as hydraulics, on, and with the machine drives on, that is, with the machine in the feed-hold mode.

4.7.3 Analysis of results

The structural error motion value is the peak-to-valley (range of) displacement observed over a relatively short time period (e.g. 1 s).

5 Error motion test methods for machine tool spindle units

5.1 General

Error motions of machine spindle units in a single sensitive direction cause one-for-one form and finish errors to be cut into the work piece and thus are most significant for machine tool performance characterization. Error motions in the non-sensitive direction are not evaluated. However, there could be second order effects that are significant in some cases (such as turning parts with very small diameters).

5.2 Test parameters and specifications

The following should be addressed for each measurement taken:

a) the radial, axial, or face locations at which the measurements are made;

b) identification of all artefacts, targets, and fixtures used;

c) the location of the measurement setup;

d) the position of any linear or rotary positioning stages that are connected to the device under test.

e) the direction angle of the sensitive direction, e.g. axial, radial, or intermediate angles as appropriate;

f) presentation of the measurement result, e.g. error motion value, polar plot, time-based plot, frequency content plot;

g) the rotational speed of the spindle (zero for static error motion);

h) the time duration in seconds or number of spindle revolutions;

i) appropriate warm up or break-in procedure;

j) the frequency response of the instrumentation, given as hertz or cycles per revolution, including roll-off characteristics of any electronic filters, and, in the case of digital instrumentation, the displacement resolution and sampling rate;

k) the structural loop, including the position and orientation of sensors relative to the spindle housing from which the error motion is reported, specified objects with respect to which the spindle axes and the reference coordinate axis are located, and the elements connecting these objects;

l) time and date the measurement was taken;

m) the type and calibration status of all instrumentation used for testing;

n) other operating conditions which may influence the measurement such as ambient temperature.

5.3 Spindle axis of rotation tests — Rotating sensitive direction(s)

5.3.1 General

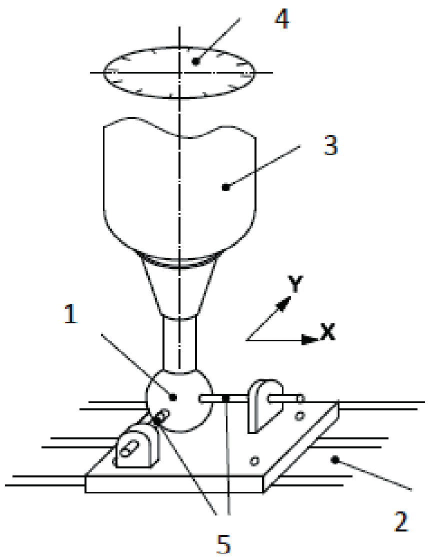
These tests are applicable to the machining operations with rotating tools, for example, boring, milling, drilling, and contour grinding.

5.3.2 Radial error motion

5.3.2.1 Test setup

Figure 10 schematically represents a test setup for the measurement. In this setup, a precision test sphere or other suitable artefact, such as a cylinder, is mounted on the machine spindle. Displacement sensors are mounted on the table (i.e. workholding component) of the machine in orthogonal orientations. The test sphere is centred on the axis of rotation (minimize radial throw). The angular position of the spindle is measured using an angle-measuring device such as a rotary encoder mounted on the spindle.

Instead of using a rotary encoder, angular position of the spindle can also be determined by mounting the test sphere slightly eccentric. This eccentricity generates one per revolution 90° phase shifted sinusoidal signals superimposed on the displacement sensor outputs. Angular position can thus be calculated using such sinusoidal signals necessary for a polar plot. However, this one-per-revolution component of the measured error shall be removed prior to the data analysis.



Key

1 reference artefact (test sphere)

2 table

3 spindle

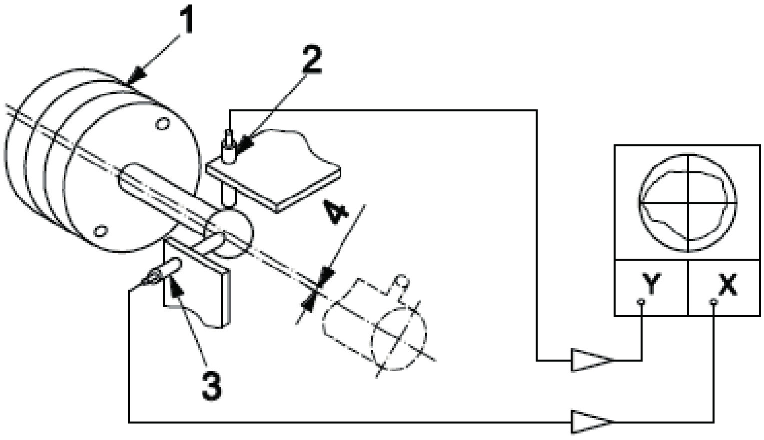
4 angular position measuring device

5 displacement sensor

Figure 10 — Schematic of test setup for radial error motion with rotating sensitive direction using angular position measuring device and centred reference artefact (sphere) (Vanherck/Peters method)

The use of the oscilloscope is simplest in the case of radial error motion measurement with a rotating sensitive direction, using a method described by Tlusty.[9] Figure 11 is a schematic diagram showing horizontal and vertical displacement sensors which sense radially against a reference test sphere. The sensor signals are amplified and fed to the respective horizontal and vertical axes of the oscilloscope. By use of a wobble plate, the reference sphere is made eccentric to the axis average line. For a perfect axis of rotation, the result would be a perfect circle as the axis rotates. For an imperfect axis, radial error motion in the direction of the reference sphere eccentricity alters the shape of the oscilloscope display. Motion at right angles to the reference sphere eccentricity moves the oscilloscope pip tangent to the base circle, causing a negligible effect on the shape. Thus the arrangement yields a measurement of radial error motion along a rotating sensitive direction, which is parallel to a line from the axis average line to the geometric centre of the eccentric reference sphere. If the tool or sensor can be mounted on the axis in only one angular orientation, the reference sphere shall be eccentric in this direction.

If the orientation is arbitrary, then the axis should be tested with the sphere eccentric at least in two directions separated by 90°.



Key

1 wobble plate

2 vertical sensor

3 horizontal sensor

4 reference sphere offset in direction of tool

Figure 11 — Test method for radial error motion with rotating sensitive direction and sphere mounted eccentric to the spindle (Tlusty method)

5.3.2.2 Test procedure

Radial error motion measurements shall be carried out at three spindle rotational speeds[1]. These rotational speeds shall be specified as the percentages of the maximum speed in the machine specific standards. At each rotational speed, displacement sensor readings shall be recorded as a function of the spindle angular position.

5.3.2.3 Data analysis

The radial error motion is determined by recording the radial displacements of the spindle (rotor) as functions of spindle angular position with respect to the stationary reference measured by two

1) It is recommended that the machine user simply observe the output of the measurement system while changing the spindle speed slowly throughout its total speed range. Speeds could be observed where excessive error motion results due to structural error motion. Where such speeds exist, they should be avoided when machining.

displacement sensors located perpendicular to each other and by computing and displaying the error motion polar plot according to Formula (1):

$$r(\theta) = r_0 + \Delta X(\theta)\cos\theta + \Delta Y(\theta)\sin\theta \quad (1)$$

where

θ	is the angular position of the spindle;
$r(\theta) - r_0$	is the radial error motion at angular position θ;
$\Delta X(\theta)$	is the output of the displacement sensor oriented with the X-axis;
$\Delta Y(\theta)$	is the output of the displacement sensor oriented with the Y-axis;
r_0	is the value to scale the polar plot for visual representation.

Formula (1) assumes θ coincides with the rotating sensitive direction. Such an alignment might not be possible during the tests. Therefore, the zero position of θ with respect to rotating sensitive direction shall be reported. At each speed, a polar plot of the spindle axis of rotation error motion shall be made for a sufficient number of revolutions[2]. A typical plot for a single spindle speed is shown in Figure 7 a). For the purposes of this part of ISO 230, only two error-motion values will be computed from the error motion plot (using LSC centre), the asynchronous radial error motion value and the synchronous radial error motion value; see Figures 7 b), 7 c), and 9. The radial error motion values shall be specified with the axial location at which the measurements are taken. The synchronous and asynchronous radial error motion values corresponding to each of the three spindle rotational speeds shall be reported.

For spindles used in turning of non-axisymmetric (non-round) parts, the effect of radial error motion along the varying sensitive direction, $r_n(\theta)$, (perpendicular to the part surface as part rotates with the spindle) can also be calculated using Formula (2).

$$r_n(\theta) = r_0 + \Delta X(\theta)\cos\theta_n + \Delta Y(\theta)\sin\theta_n \quad (2)$$

Where, θ_n is the angle of the surface normal of the workpiece at a given angular orientation of the rotating axis θ. It is a function of θ.

For spindles carrying tools with multiple cutting tips (multiple orientations), the effects of radial error motion along each of those directions are calculated using Formula (2). In such cases, angle θ_n represents increments of 360°/number of cutting tips.

5.3.3 Tilt error motion

5.3.3.1 Test setup

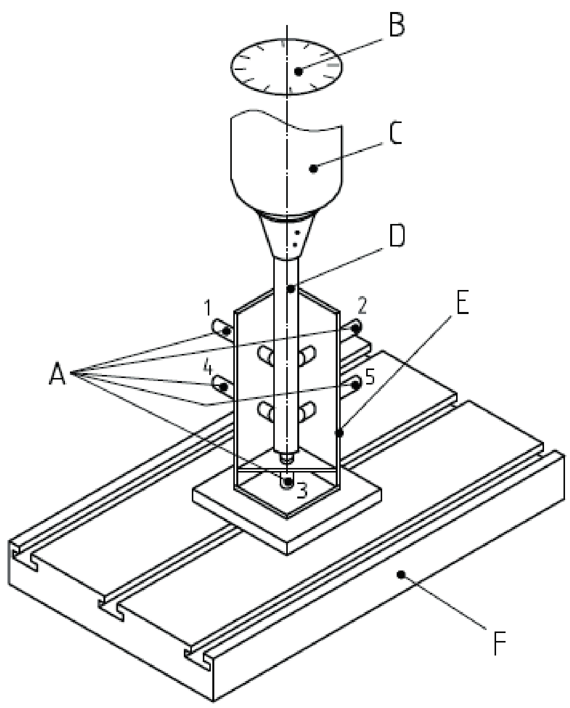
Measurement of the tilt error motion requires measurements of the radial error motion at two spatially separated points, as shown in Figure 12. A test artefact with two precision test spheres spaced some distance apart or a cylindrical mandrel can be attached to the spindle and aligned to the axis of spindle rotation. The recommended minimum distances between the spheres/displacement sensors for different sizes of spindles are given in Table 2.

Two methods are discussed for measuring tilt error motion. Method 1 describes the use of two displacement sensors and Method 2 describes using four displacement sensors for measuring tilt. Both procedures are acceptable. However, due to synchronization difficulties between the two sets of data obtained at two different time periods, the results obtained by the two methods might not be the same. Therefore, Method 2 is preferable.

2) For spindles the minimum is 20 revolutions.

Table 2 — Recommended minimum axial separation between spheres/displacement sensors for tilt error motion measurements

Nominal diameter of spindle at front bearing mm		Minimum axial distance between displacement sensors mm
>	<	
	10	25
10	18	32
18	30	40
30	50	50
50	80	63
80	120	80
120	180	100
180	250	125
250		150



Key

A sensors (1 to 5)
B angular measuring device
C spindle
D test mandrel
E fixture
F table

Figure 12 — Five-sensor test system for measurement of rotating sensitive direction spindle error motions (used for Method 2 of tilt error motion measurements)

5.3.3.2 Test procedure — Method 1

First, mount a test sphere or other artefact and displacement sensors according to 5.3.2.1, and carry out radial error motion measurements at three spindle speeds[3]. These rotational speeds shall be specified as the percentages of the maximum speed in the machine specific standards. At each rotational speed, displacement sensor readings shall be recorded as a function of the spindle angular position.

Next, re-fixture the ball or other artefact at a minimum recommended axial distance (see Table 2) from the previous position and a second set of measurements are taken at the same three spindle speeds.

5.3.3.3 Data analysis — Method 1

The synchronous radial error motion and the asynchronous radial error motion corresponding to each spindle speed at both axial positions shall be determined according to 5.3.2.3. The difference in the synchronous radial error motion measurements divided by the distance between them (see Table 2) is defined as the synchronous tilt motion error, in radians. The difference in the asynchronous radial error motion measurements divided by the length is defined as the asynchronous tilt motion error, in radians.

5.3.3.4 Test procedure — Method 2

Mount the test artefact and displacement sensors according to 5.3.3.1, and carry out measurements at three spindle speeds. These rotational speeds shall be specified as the percentages of the maximum speed in the machine specific standards. At each rotational speed, displacement sensor readings shall be recorded as a function of the spindle angular position.

5.3.3.5 Data analysis — Method 2

The synchronous radial error motion and the asynchronous radial error motion corresponding to each spindle speed at both axial positions shall be determined according to 5.3.2.3. The differences between the outputs of sensors 1 and 4 and sensors 2 and 5 are used as the ΔX and ΔY in the radial error equation given in 5.3.2.3 and r_0 is set equal to zero (note that sensor No. 3 shown in Figure 12 is not required). The synchronous tilt motion, in radians, is obtained by dividing the synchronous error by the distance between the sensors in the test setup. A polar plot is constructed and analysed as in 5.3.2.3. The asynchronous error motion, in radians, is obtained by dividing the asynchronous error by the distance between the sensors in the test setup.

5.3.4 Axial error motion

5.3.4.1 Test setup

Figure 13 schematically represents a test setup for the measurement. In this setup, a precision test sphere is mounted in the machine spindle. A displacement sensor is mounted to the table of the machine axially against the test sphere. The sphere is centred on the axis of rotation to minimize concentricity error. The angular position of the spindle is measured using an angle-measuring device such as a rotary encoder mounted on the spindle.

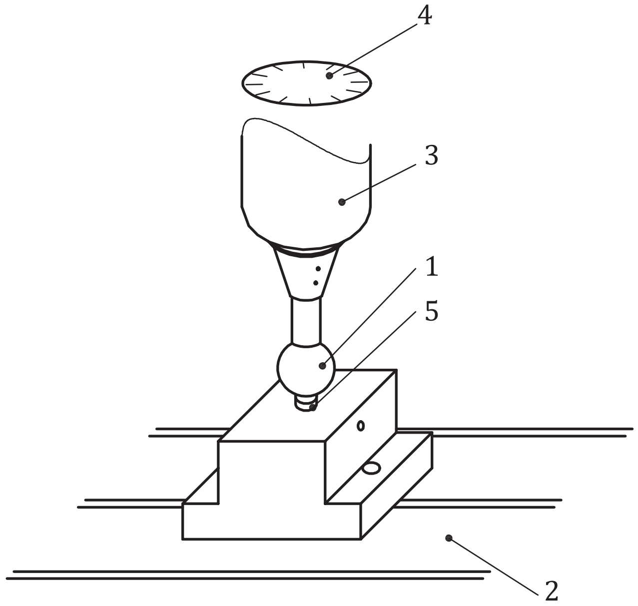
5.3.4.2 Test procedure

Position the displacement sensor as indicated in the axial position as shown in Figure 13 and carry out axial error motion measurements at three spindle speeds[4]. These rotational speeds shall be specified

3) It is recommended that the machine user simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. Speeds could be observed where excessive error motion results due to structural error motion. If such speeds exist, they should be avoided when machining.

4) It is recommended that the machine user simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. Speeds could be observed where excessive error motion results due to structural error motion. If such speeds exist, they should be avoided when machining.

as the percentages of the maximum speed in the machine specific standards. At each rotational speed, displacement sensor readings shall be recorded as a function of the spindle angular position.



Key

1 reference artefact (test sphere)
2 table
3 spindle
4 angular position measuring device
5 displacement sensor

Figure 13 — Setup for axial error motion measurement

5.3.4.3 Data analysis

The analysis of the error motion polar plot for axial error motion is also conceptually identical to that for radial error motion, except that fundamental error motion should not be removed analytically. The axial error motion can be presented on a linear plot of error motion versus spindle angular orientation. The asynchronous axial error motion value shall be the maximum range of the displacement over a sufficient number of revolutions[5)] of the spindle. The synchronous axial error motion value shall be the range of the average axial deviations corresponding to angular orientation of the spindle.

5.4 Spindle tests — Fixed sensitive direction

5.4.1 General

These tests are applicable to the machining operations with fixed sensitive direction, for example, turning and cylindrical grinding.

5.4.2 Test setup

Figure 14 schematically represents some test setups suitable for the measurement of the spindle error motions for the case of fixed sensitive direction, i.e. for a work spindle. (In the following tests, it is

5) For spindles the minimum is 20 revolutions.

assumed that a signal, proportional to the angular orientation of the spindle, is generated so that polar plots of the error motion as a function of spindle angle can be generated.) A precision test sphere, or other suitable artefact, is mounted in the machine spindle and the displacement sensor is mounted to the tool post or to a fixture rigidly attached to the tool post. The sphere or artefact should be centred around the axis of rotation so as to minimize radial throw. Note that radial throw can be mistaken for fundamental axial error motion.

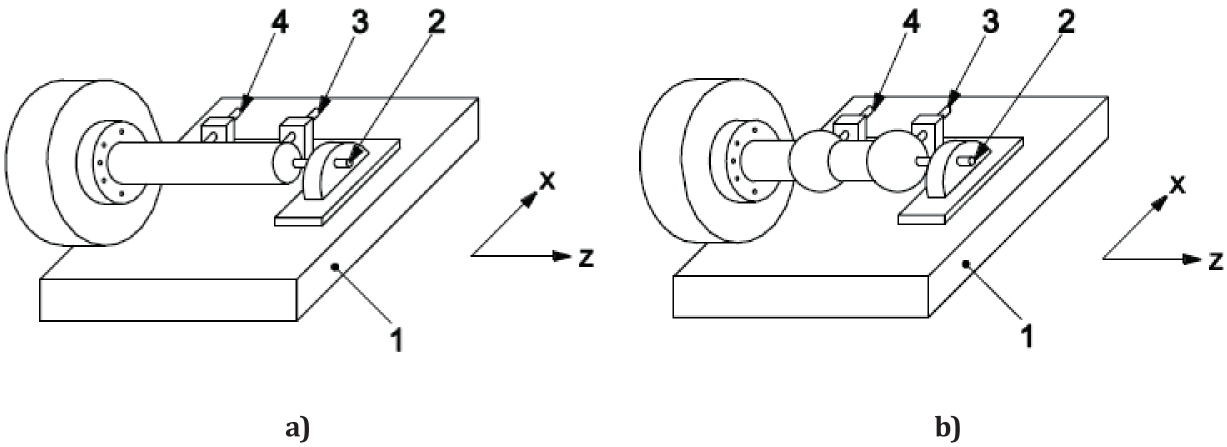
5.4.3 Radial error motion

5.4.3.1 Test procedure

The radial error motion shall be measured by positioning the displacement sensor in the radial direction, as shown in Figure 14.

The sensors in the radial direction shall be mounted in the given sensitive direction. Unlike in 5.3.2.1 (Figures 10 and 11), only one displacement sensor is mounted at each Z position, because the test objective is to measure the radial error motion in this sensitive direction.

Radial error motion measurements shall be made at three spindle speeds[4]. These rotational speeds shall be specified as the percentages of the maximum speed in the machine specific standards. At each rotational speed displacement sensor readings shall be recorded as a function of the spindle angular position.



Key

1 cross slide

2 axial displacement sensor

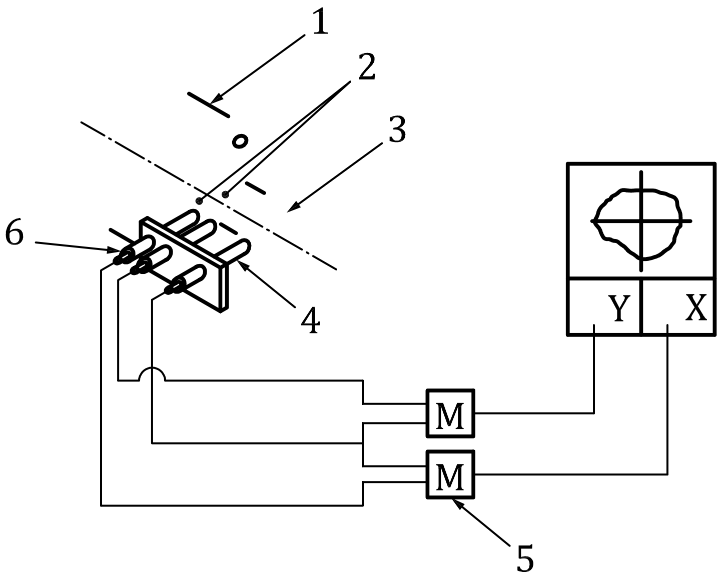
3 radial displacement sensor 2

4 radial displacement sensor 1

Figure 14 — Test setups used for measuring spindle fixed sensitive direction error motion

Use of an oscilloscope for radial error motion measurement with a fixed sensitive direction requires a separate means for generating the base circle. Figure 15 shows a method described by Bryan et al.[10] Two circular cams, eccentric by 0,1 mm in perpendicular directions, are sensed by comparatively low magnification displacement sensors to generate sine and cosine signals for the base circle; a single cam with the sensors 90° apart could also be used. Radial error motion is detected by a third high-magnification displacement sensor sensing against a reference test sphere, which is centred (as closely as possible) on the axis average line. The sine and cosine signals are each multiplied by the radial error motion signal and are then fed into the two axes of the oscilloscope. The modulation of the base circle by the signal from the fixed radial error motion sensor yields a polar plot of radial error motion versus the angular position of the axis of rotation. The eccentric cams and low magnification sensors can be replaced with a small commercial angular measuring device physically attached to the axis of rotation.[12]

Determination of angular position by the above described method can also be used for rotating sensitive direction measurements.



Key

1 wobble plate
2 circle generating cams
3 spherical reference
4 displacement sensor
5 multiplier
6 low magnification sensors

Figure 15 — Test method for radial error motion with fixed sensitive direction (Bryan method)

5.4.3.2 Data analysis

If the displacement sensor is aligned with the fixed sensitive direction, then to determine radial error motion [$r(\theta) - r_0$], Formula (1) is reduced to:

$$r(\theta) = r_0 + \Delta X(\theta) \tag{3}$$

where

$\Delta X(\theta)$ is the output of the displacement sensor oriented with the fixed sensitive direction.

However, if fixed sensitive direction is at an angle θ_f with respect to X-axis, then either the sensor is aligned to the sensitive direction and the reduced equation above is used or a second sensor is used in the orthogonal direction (Y). In this case, Formula (1) becomes:

$$r(\theta)=r_0+\Delta X(\theta)\cos\theta_f+\Delta Y(\theta)\sin\theta_f \quad (4)$$

where

θ	is the angular position of the spindle;
$r(\theta) - r_0$	is the radial error motion at angular position θ
θ_f	is the angle between the fixed sensitive direction and the X-axis;
$\Delta X(\theta)$	is the output of the displacement sensor oriented with the X-axis;
$\Delta Y(\theta)$	is the output of the displacement sensor oriented with the Y-axis;
r_0	is the value to scale the polar plot for visual representation.

At each rotational speed, a polar plot of the spindle error motion shall be made for a sufficient number of revolutions[6]. A typical plot for a single spindle speed is shown in Figure 7 a). It shall be emphasized that, although the plots look the same for fixed sensitive direction and rotating sensitive direction, they are not. These plots represent the measure of different quantities. For the purposes of this part of ISO 230, only two error-motion values will be computed from the error motion plot. The asynchronous error motion value shall be the maximum scaled width of the total error motion polar plot (before averaging) measured along a radial line through the polar chart centre, as shown in Figure 9. The synchronous error motion polar plot shall be computed by averaging the total error motion polar plot results for the total number of revolutions. A typical synchronous error motion polar plot is shown as the dark line in Figure 7 b) and Figure 9. The synchronous radial error motion value is the scaled difference in radii of two concentric circles centred at the LSC centre just sufficient to contain the synchronous error motion polar plot. The radial error motion values have to be specified with the axial location at which the measurements are taken.

5.4.4 Axial error motion

5.4.4.1 Test procedure

The axial error motion shall be measured by positioning the displacement sensor in the axial direction, as shown in Figure 13. Axial error motion shall be measured following the same procedure and at the same spindle speeds as those specified for rotating sensitive direction axial error motion according to 5.3.4.2.

5.4.4.2 Data analysis

The analysis of the error motion polar plot for axial error motion is also conceptually identical to that for radial error motion, except that fundamental error motion (concentricity error) should not be removed analytically. The axial error motion can be presented on a linear plot of error motion versus spindle angular orientation. The asynchronous axial error motion value shall be the maximum range of the displacement over a sufficient number of revolutions[7] of the spindle. The synchronous axial error motion value shall be the range of the average axial deviations corresponding to angular orientation of the spindle.

6) For spindles the minimum is 20 revolutions.

7) For spindles the minimum is 20 revolutions.

5.4.5 Tilt error motion

5.4.5.1 Test setup

Measurement of the tilt error motion in the fixed sensitive direction requires measurement of the radial error motion at two spatially-separated points, as shown in Figure 14, using radial displacement sensors 1 and 2. A test artefact with two spheres with their centres spaced some distance apart (see Table 2) or a precision test mandrel can be attached to the spindle and precisely aligned to the axis of spindle rotation in order to minimize radial throw.

Two methods are provided for measuring tilt error motion. Method 1 describes the use of one displacement sensor and Method 2 describes the use of two displacement sensors for measuring tilt. Both procedures are acceptable. However, due to synchronization difficulties between the two sets of data obtained at two different time periods, the results obtained by the two methods might not be the same.

5.4.5.2 Test procedure — Method 1

Mount the test sphere or mandrel and a displacement sensor in accordance with 5.4.3.1 (using a single displacement sensor in the sensitive direction) and carry out radial error motion measurements at three different spindle speeds. These rotational speeds shall be specified as the percentages of the maximum speed in the machine specific standards. At each rotational speed, displacement sensor readings shall be recorded as a function of the spindle angular position.

Next, remount the sphere or mandrel and displacement sensor at a distance of 50 mm to 100 mm away from the previous location and perform a second set of measurements at the same rotational speeds recording displacement sensor readings as a function of the spindle angular position.

5.4.5.3 Data analysis — Method 1

The synchronous radial error motion value and the asynchronous radial error motion value corresponding to each spindle speed at both axial positions shall be determined according to 5.4.3.2. The difference in the radial error motion measurements divided by the distance between them is defined as the synchronous tilt motion error value. The difference in the asynchronous radial error motion values divided by the length is defined as the asynchronous tilt motion error value in radians.

5.4.5.4 Test procedure — Method 2

The analysis below assumes that the two displacement sensors are set upon the equators of the spheres or along the test mandrel, at a distance L_d from one another. The two displacement sensors can be adjusted such that their sensitivity (output voltage/displacement) is the same and their outputs subtracted from each other before input into a spindle analyser, or their gains calibrated and the subtraction performed in software.

The spindle shall be run for a sufficient number of revolutions[8)] at the three spindle speeds selected, as in 5.4.5.2, and the differences between the two readings (displacement sensor 1 and displacement sensor 2) plotted on a polar plot.

8) For spindles the minimum is 20 revolutions.

5.4.5.5 Data analysis — Method 2

The asynchronous tilt error motion value shall be the asynchronous component of the total error motion polar plot obtained from the difference between the two displacement sensor readings, measured along a radial line through the polar chart centre and divided by the distance L_d between the two sensors. That is:

(5)

where

$\beta(\theta)$ is the tilt error motion value, in radians;

$r_2(\theta)$ is the radial error motion value at displacement sensor 2;

$r_1(\theta)$ is the radial error motion value at displacement sensor 1;

L_d is the distance between the two displacement sensors;

θ is the angular orientation of the spindle (angle on polar chart).

The synchronous tilt error motion value is obtained by dividing the difference between the two synchronous error motion values, corresponding to two positions, by the distance between the two displacement sensors.

When the displacement sensor is not aligned with the fixed sensitive direction, Formula (5) can be modified similarly as in 5.4.3.2.

6 Error motion test methods for machine tool rotary tables/heads

6.1 General

Axis of rotation error motions for machine tool rotary tables and rotary heads have similar characteristics as the machine spindles. However, the rotational speeds are much lower than that of the spindles and the rotational travel ranges are, in many cases, limited to less than 360°. Therefore, although the methods and concepts are similar, the test conditions are different.

For low-speed rotary axes such as rotary tables and trunnions, both fixed and rotating sensitive direction cases can be dealt with by use of a polar recorder whose angular drive is mechanically or electrically synchronized to the axis of rotation. For the rotating sensitive direction, the reference test sphere is supported from the machine frame, and the displacement sensor is supported on the axis of rotation. For one or a few revolutions of the axis, it is usually possible to coil the sensor cable around the axis in a non-influencing manner; for continuous rotation, slip rings, wireless data transmission, or their equivalent are necessary.

Rotary tables and rotary heads are used for positioning of tools and workpieces similar to linear axes of machine tools. Therefore, test conditions for measuring their radial, axial and tilt error motions follow similar procedures as described in ISO 230-1.

In some cases, especially for swivelling tables, it is not possible to place the artefact (e.g. small precision sphere) centred on the axis of rotation. For these cases, special calibrated test artefacts would be needed (e.g. partial spheres or partial cylinders of large diameters). A measurement setup using three displacement sensor nest measuring the position of a test sphere (R-test) can be used in such cases (see ISO 230-1:2012, 11.3.5.3). However, it should be kept in mind that measurement uncertainty increases due to the contributions of the error motions of linear axes involved in the measurement.

6.2 Axial error motion

6.2.1 Test setup

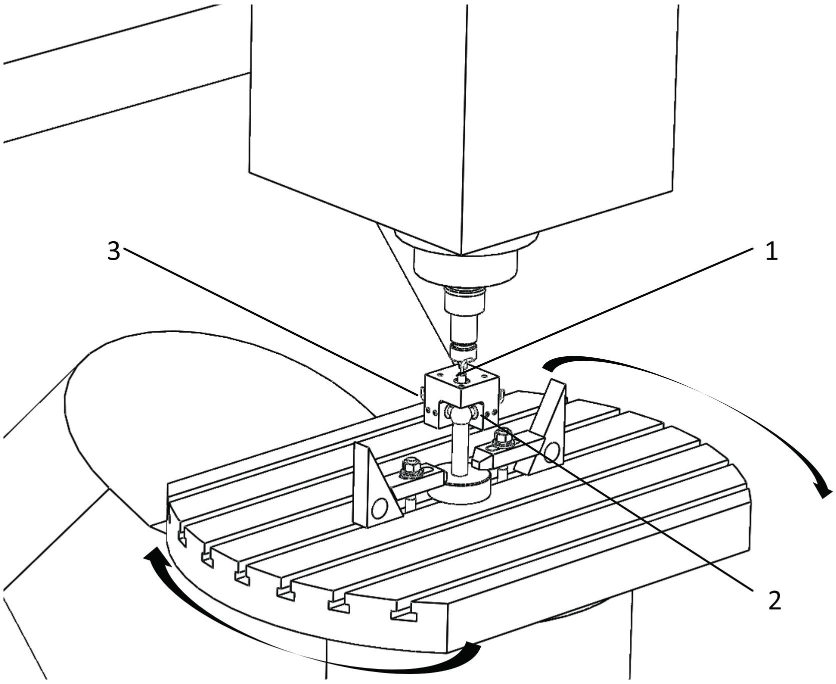
A precision test sphere, or other suitable artefact, is mounted on the machine rotating component, with appropriate fixture to locate the sphere on the axis of rotation, and the displacement sensor is mounted on the non-rotating component, in the axial direction, such that the resulting measurement represents the relative motion between the tool and the workpiece. The sphere or artefact should be centred around the axis of rotation (minimize radial throw). See Figure 16.

6.2.2 Test procedure

The rotary machine component (table or head), motion of which is to be tested, shall be moved to a series of target positions over its travel range of interest. The measurement interval shall be no larger than 1/10 of the axis travel range for axes of 90° or less. For rotary axes with multiple full rotation capability (360°), the interval shall be no larger than 30°. At a target position, the machine shall remain at rest long enough for the measurement data to be recorded. The measurement can be carried out in continuous mode dependent on the measuring instrument used and the intended use of the machine tool.

For rotary tables, the minimum is five revolutions in the clockwise and five in the anticlockwise (counter-clockwise) direction are required. For rotary heads and swivelling tables, the minimum of five rotations over the full travel range in the clockwise and five in the anticlockwise (counter-clockwise) direction are required.

Default rotational speed shall be at a level to suit the measuring equipment and setup being used and/or the intended use of the machine tool.



Key

1 axial displacement sensor

2 radial displacement sensor in X-direction

3 radial displacement sensor in Y-direction

4 reference test sphere

Figure 16 — Setup for measurement of axial and radial error motions of rotary table

6.2.3 Data analysis

The axial error motion can be presented on a polar or linear plot of error motion versus spindle angular orientation. The asynchronous axial error motion value shall be the maximum range of the displacement over the number of revolutions of the rotating component. The synchronous axial error motion value shall be the range of the average axial deviations corresponding to angular orientation of the rotary table/head.

6.3 Radial error motion

6.3.1 Test setup

A precision test sphere or other suitable artefact, such as a cylinder, is mounted in the machine rotating component with appropriate fixture to locate the sphere on the axis of rotation. Displacement sensors are mounted to the non-rotating component of the machine in orthogonal orientations, such that the relative motion between the tool and the workpiece can be observed. The test sphere is centred on the axis of rotation (minimize radial throw). See Figure 16.

6.3.2 Test procedure

The rotary machine component (table or head), motion of which is to be tested, shall be moved to a series of target positions over its travel range of interest. The measurement interval shall be no larger than 1/10 of the axis travel range for axes of 90° or less. For rotary axes with multiple full rotation capability (360°), the interval shall be no larger than 30°. At a target position, the machine shall remain at rest long enough for the measurement data to be recorded. The measurement can be carried out in continuous mode dependent on the measuring instrument used and the intended use of the machine tool.

For rotary tables, the minimum is four revolutions in the clockwise and four in the anticlockwise (counter-clockwise) direction are required. For rotary heads and swivelling tables, the minimum of two rotations in the clockwise and two in the anticlockwise (counter-clockwise) direction are required.

Default rotational speed shall be at a level to suit the measuring equipment and setup being used and/or the intended use of the machine tool.

6.3.3 Data analysis for rotating sensitive direction

The radial error motion is determined by recording the radial displacements of the rotating component as functions of its angular position measured by two displacement sensors located perpendicular to each other and by computing and displaying the error motion polar plot according to Formula (6):

$$r(\theta) = r_0 + \Delta X(\theta) \cos\theta + \Delta Y(\theta) \sin\theta \qquad (6)$$

where

θ	is the angular position of the machine rotating component;
$r(\theta) - r_0$	is the radial error motion at angular position θ;
$\Delta X(\theta)$	is the output of the displacement sensor oriented with the X-axis;
$\Delta Y(\theta)$	is the output of the displacement sensor oriented with the Y-axis;
r_0	is the value to scale the polar plot for visual representation.

A typical plot of radial error motion is shown in Figure 7 a). For the purposes of this part of ISO 230, only two error-motion values will be computed from the error motion plot (using LSC centre): the asynchronous radial error motion value and the synchronous radial error motion value, see Figures 7 b), 7 c), and 9. The radial error motion values shall be specified with the axial location at which the measurements are taken. The synchronous and asynchronous radial error motion values shall be reported.

For rotary tables carrying workpieces the effect of radial error motion on the location of the workpiece in the plane perpendicular to the axis average line (2D effect of axis of rotation error motion) is given by [$\Delta X(\theta)$, $\Delta Y(\theta)$].

6.3.4 Data analysis for fixed sensitive direction

The radial error motion is determined by recording the radial displacements of the rotating component as functions of its angular position measured by one of the displacement sensors. A typical plot of radial error motion is shown in Figure 7 a). For the purposes of this part of ISO 230, only two error-motion values will be computed from the error motion plot (using LSC centre): the asynchronous radial error motion value and the synchronous radial error motion value, see Figures 7 b), 7 c), and 9. The radial error motion values shall be specified with the axial location at which the measurements are taken. The synchronous and asynchronous radial error motion values shall be reported.

The asynchronous error motion value shall be the maximum scaled width of the total error motion polar plot (before averaging) measured along a radial line through the polar chart centre, as shown in Figure 9. The synchronous error motion polar plot shall be computed by averaging the total error motion polar plot results for the total number of revolutions. A typical synchronous error motion polar plot is shown as the dark line in Figure 7 b) and Figure 9. The synchronous radial error motion value is the scaled difference in radii of two concentric circles centred at the LSC centre just sufficient to contain the synchronous error motion polar plot. The radial error motion values have to be specified with the axial location at which the measurements are taken.

6.4 Tilt error motion

6.4.1 Test setup

Measurement of the tilt error motion requires measurements of the radial error motion at two spatially separated points. A test artefact with two precision test spheres spaced some distance apart or a cylindrical mandrel may be attached to the machine rotating component and aligned to the axis of spindle rotation.

Both methods that are described in 5.3.3 and 5.4.5 are acceptable.

6.4.2 Test procedure

The rotary machine component (table or head), motion of which is to be tested, shall be moved to a series of target positions over its travel range of interest. The measurement interval shall be no larger than 10° for axes of 90° or less. For rotary axes with multiple full rotation capability (360°), the interval shall be no larger than 30°. At a target position, the machine shall remain at rest long enough for the measurement data to be recorded. The measurement can be carried out in continuous mode dependent on the measuring instrument used and the intended use of the machine tool.

For rotary tables, the minimum is four revolutions in the clockwise and four in the anticlockwise (counter-clockwise) direction are required. For rotary heads and swivelling tables, the minimum of two rotations in the clockwise and two in the anticlockwise (counter-clockwise) direction are required.

Default rotational speed shall be at a level to suit the measuring equipment and setup being used and/or the intended use of the machine tool.

If the test setup with one test sphere is used, then the sphere shall be relocated at a different axial location and test procedure shall be repeated.

6.4.3 Data analysis for rotating sensitive direction

The synchronous radial error motion value and the asynchronous radial error motion value at both axial positions shall be determined according to 5.3.2.3. The difference in the synchronous radial error motion measurements divided by the distance between them is defined as the synchronous tilt motion error value, in radians. The difference in the asynchronous radial error motion values divided by the length is defined as the asynchronous tilt motion error value, in radians.

If the test setup with two test spheres is used, then the difference between the outputs of the two displacement sensors in the same direction (X or Y) is used for calculating synchronous and asynchronous (pseudo) radial error motion values. Dividing these values by the distance between the test spheres results in the synchronous and asynchronous tilt error motion values.

6.4.4 Data analysis for fixed sensitive direction

The synchronous radial error motion value and the asynchronous radial error motion value at both axial positions shall be determined according to 5.4.3.2. The difference in the synchronous radial error motion measurements divided by the distance between them is defined as the synchronous tilt motion error value, in radians. The difference in the asynchronous radial error motion values divided by the length is defined as the asynchronous tilt motion error value, in radians.

If the test setup with two test spheres is used, then the difference between the outputs of the two displacement sensors in the same direction (X or Y) is used for calculating synchronous and asynchronous (pseudo) radial error motion values. Dividing these values by the distance between the test spheres results in the synchronous and asynchronous tilt error motion values.

Annex A
(informative)

Discussion of general concepts

A.1 Overview

This annex discusses the general concepts related to specification and measurement of the quality of axes of rotation found in machine tools. It is based on CIRP Unification document on axes of rotation.[8]

For purpose of clarity, this annex uses specific examples in presenting concepts, such as the spindle of a lathe. However, it is emphasized that the concepts under discussion can be applied to all rotational axes found in a machine tool, e.g. rotary tables, trunnion tables, live centres, etc.

A.2 Perfect axis of rotation

A.2.1 General

It is helpful to begin by considering the requirements to be met by a perfect axis of rotation. While this might seem obvious enough to be covered by a simple phrase such as “capable of pure rotation of a workpiece about a line fixed in space”, several important points are noted that show this phrase is inadequate.

A.2.2 Relative motion

Consider a lathe mounted aboard a ship that is rolling in the ocean. The spindle axis clearly undergoes large motions “in space” without influencing the workpiece accuracy. What is important is relative motion between the workpiece and the cutting tool. This involves only the structural loop (the chuck, spindle shaft, spindle bearings, spindle housing/headstock, frame, slides, and tool post in the present example), see 3.1.14.

A.2.3 Sensitive direction

Assume that a flat facing cut is being made in a lathe. If imperfections of the spindle bearings cause small axial movements of the workpiece relative to the tool at the point of cutting, one-for-one errors will be cut into the workpiece, and hence the axial movement is in a sensitive direction. By contrast, small motions that are tangent to the face do not cause cutting errors, and hence these motions are in a non-sensitive direction. Figure 4 shows several examples. In general, the sensitive direction is parallel to a line, which is perpendicular to the surface of revolution being generated and through the point of machining. Any line perpendicular to the sensitive direction is a non-sensitive direction.

A.2.4 Rotating sensitive direction

In case of a boring operation, where the workpiece is fixed and the cutting tool rotates, since the sensitive direction is always parallel to a line through the point of machining, the sensitive direction rotates with the tool (see Figure 5). Different test methods are used for axes of rotation depending on whether the machine’s sensitive direction is fixed or rotating with respect to the machine frame. Similarly, for a milling operation, there are multiple (based on the number of cutting tips/inserts on the tool) rotating sensitive directions.

A.2.5 Varying sensitive direction

Assume that a cam being turned on a lathe by coordinating the spindle rotation and cross-slide motion. Since the geometry of the cam is not rotationally symmetric, the direction of the surface normal of the cam varies with respect to the angular position of the spindle. Therefore, sensitive direction varies as a function of the angular position of the spindle (see Figure 6).

A.2.6 Multiple sensitive directions

Depending on the application of the rotary axes, there may be more than one sensitive direction. For example, a milling spindle carrying multi-insert milling cutter has multiple rotating sensitive directions. Similarly, a rotary table used for single point turning of a workpiece in two orthogonal directions (at two different axial positions) would have two fixed sensitive directions.

A.2.7 Displacement sensors versus cutting tools

The above examples all referred to cutting tools. The term “tool” should be interpreted broadly, so as to include such things as grinding wheels. Furthermore, all of the above concepts apply with equal validity to measuring devices, with a displacement sensor replacing the cutting tool.

Based on the above discussion, it is possible to give a more precise statement of the requirements for a perfect axis of rotation in a machine tool:

“A perfect axis of rotation is capable of rotating a workpiece about a line that does not move in the sensitive direction with respect to a tool (or vice versa for the case of a fixed workpiece and rotating tool)”.

Strictly speaking, the above statement is defective in not limiting the relative motion in the non-sensitive direction, since any motion in this direction will cause some error when dealing with a curved surface such as the cylinder of Figure A.1. However, it can be argued that the practical consequences of not measuring real axes of rotation in the non-sensitive direction involve a negligible measurement error in return for a substantial reduction in effort. On the other hand, in some cases, such as drilling a hole pattern on a workpiece supported by a rotating table, error motion along any non-sensitive direction may cause one-to-one error in the location of the holes. In such cases, it might be required to measure the changes in the location of the axis of rotation in the plane perpendicular to the axis average line (it is called 2D effect of axis of rotation error motion, see 3.3.7). The following formula is useful in estimating the error caused by the motion along non-sensitive direction. Let

E_N = motion in the non-sensitive direction

E_S = error in the sensitive direction due to E_N

R = part radius

Then

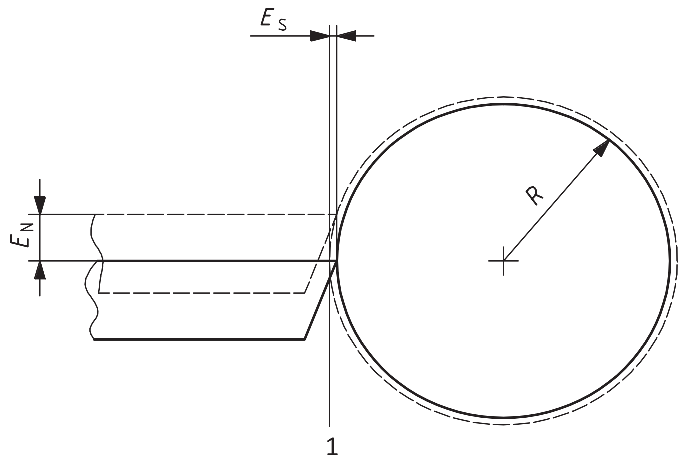
$$E_S = \frac{(E_N)^2}{2R} \quad \text{(if } E_N \text{ is small compared to } R\text{)} \qquad \text{(A.1)}$$

For example, let E_N = 0,02 mm and R = 10 mm.

Then

$$E_S = \frac{(0{,}02)^2}{2 \times 10} = 2 \times 10^{-5} \text{mm} = 0{,}02\ \mu\text{m}$$

For a radius of 10 mm, an error motion of 20 µm in the non-sensitive direction causes an error of only 0,02 µm in the sensitive direction, i.e. it is a “second-order” error. Thus, ignoring motion in the non-sensitive direction is justified if it is reasonable to assume that it is approximately the same as the motion in the sensitive direction and if the error motion is small compared to the radius.



Key

1 non-sensitive direction

Figure A.1 — Second-order error due to relative motion in the non-sensitive direction along a curved surface

A.3 Imperfect axis of rotation — Error motion

For a real axis of rotation, the general term "error motion" is used to describe relative displacements in the sensitive direction between the tool and the workpiece. The physical causes of error motion can be thought of as bearing error motion due to factors such as non-round bearings components, and structural error motion due to the finite mass, compliance, and damping of the structural loop in conjunction with internal or external sources of excitation. The separation of error motion test data into these two categories is not always possible, although the recording of data on synchronized polar charts is useful in this regard, as will be discussed in A.7.5.

A.4 Structural error motion

The term "structural error motion" is used rather than "vibration" to emphasize the relationship to the structural loop and to relative motion. It would be incorrect, for example, to measure the structural error motion by attaching an accelerometer to the tool post of a lathe and integrating the output twice, since this would yield the absolute motion. For a rigid structural loop, the entire loop could undergo virtually the same absolute vibratory motion, resulting in a negligible structural error motion.

Since only relative motion is important, the structural loop is as important to the functional use of an axis of rotation as the C-frame and anvil are to a hand micrometre. To attempt to include structural error motion due to noisy rolling element bearings and exclude that from drive gears or motors, or to include resonance in a spindle shaft but not a tool post, seems arbitrary and unrealistic. The approach taken in this part of ISO 230 has been to include structural error motion from all sources as a valid topic of discussion, but to leave to the user the choice of the structural loop best suited to his/her objectives. Thus, this part of ISO 230 can be applied to testing a spindle as a "stand alone" unit on a surface plate or as an integrated part of a complete machine. There should be no ambiguity regarding the structural loop associated with an error motion measurement or specification.

A.5 Thermal effects

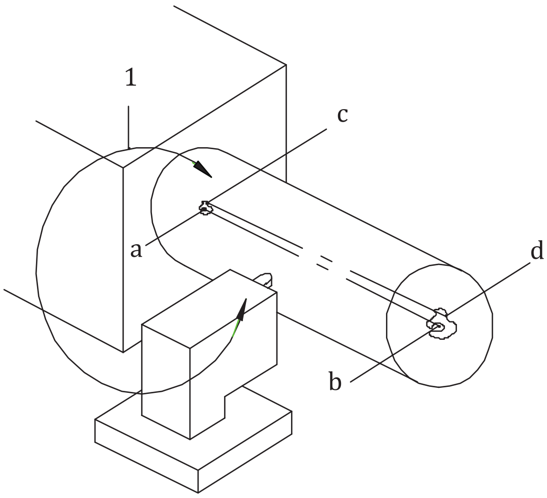
An additional cause of relative motion between the tool and the workpiece is a changing temperature distribution within the structural loop. The relative motion in the sensitive direction due to the accompanying thermal expansion or contraction is referred to as thermal effect. Thermal effect is treated separately from error motion because it usually occurs on a slower time scale than error motion, allowing separation of the two measurements. Additional advisory material on thermal effects can be found in ISO 230-3.

A.6 Error motion geometry

A.6.1 General

The objective of this clause is to develop the geometric relationship which will allow the error motion for any workpiece size and shape to be predicted from a few basic error motion measurements, assuming that the workpiece can be treated as a rigid body and that the workpiece rotates.

It is convenient to deal with the relative motion of the tool and the workpiece in terms of the relative motion of two line segments, as shown in Figure A.2. One of these, the axis of rotation, is embedded in the workpiece and moves with it. The other is fixed with respect to the tool at the average position of the axis of rotation, so that the two would coincide for a perfect axis of rotation, and is referred to as the axis average line.



Key

1 structural loop

ab axis average line

cd axis of rotation at time *t*

Figure A.2 — Axis of rotation example: ab fixed relative to tool, cd imbedded in workpiece

In general, the workpiece has six degrees of freedom, consisting of three linear motions and three angular motions as shown individually in Figure A.3, at a given instant in time, *t*. Of these, angular motion C about the axis average line is the intended function of the axis of rotation. Which of the remaining five degrees of freedom contribute significantly to the error motion depends on the sensitive direction and the axial and radial location of the point of machining. For the lathe operations, it can be concluded that the sensitive direction always lies in the plane parallel to the slide travels.

NOTE If, for example, a turning tool is approaching using a Y-axis motion, then the sensitive direction will lie in the Y-Z plane.

Examination of other machine tools, where the workpiece rotates, shows that in most cases, the sensitive direction is restricted to one plane. Calling this the X′-Z′ plane and the axis of rotation C for convenience, it follows that the motions $E_{YC}(t)$ and $E_{AC}(t)$ are in most cases (e.g. except for varying sensitive direction) in a non-sensitive direction and can be ignored. In such cases, the only motions of concern are the motions $E_{XC}(t)$, $E_{ZC}(t)$, and $E_{BC}(t)$ which appear in the X′-Z′ projection plane. The terms given in A.6.2 to A.6.4 will be used[9)].

A.6.2 Pure radial error motion

Motion $E_{XC}(t)$ in Figure A.3 a), in which the axis of rotation remains parallel to the axis average line and moves perpendicular to it in the sensitive direction.

A.6.3 Axial error motion

Motion $E_{ZC}(t)$ in Figure A.3 a), in which the axis of rotation remains co axial with the axis average line and moves axially with respect to it.

A.6.4 Tilt error motion

Motion $E_{BC}(t)$ in Figure A.3 a), in which orientation of the axis of rotation changes with respect to the axis average line and in the plane of the axial and pure radial error motions.

A.6.5 Radial error motion

In general, tilt error motion and pure radial error motion occur at the same time, and the sum at any particular axial position is referred to as radial error motion. A knowledge of radial error motion $E_{XC}(t)\big|_{z1}$ at one axial position and tilt error motion $E_{BC}(t)$ allows the radial error motion $E_{XC}(t)\big|_{z2}$ at another axial position to be predicted as shown in Figure A.4 a),

$$E_{XC}(t)\ \big|_{z2} = E_{XC}(t)\ \big|_{z1} + L \text{ x } E_{BC}(t)\ [\text{assuming } E_{XC}(t) << L] \tag{A.2}$$

where L is the distance between the two axial locations. Since radial error motion varies with axial position, it is necessary to specify the axial location of a radial error motion measurement.

A.6.6 Face motion

Another special term is face motion, which denotes error motion in the axial direction at a specified distance, R, from the axis average line, as shown in Figure A.4 b). Face motion $E_{ZC}(\mathrm{t})\big|_{R}$ is related to axial and tilt error motion:

$$E_{ZC}(t)\ \big|_{R} = E_{ZC}(t) - R \times E_{BC}(t)\ [\text{assuming } E_{ZC}(t)\ \big|_{R} << R] \tag{A.3}$$

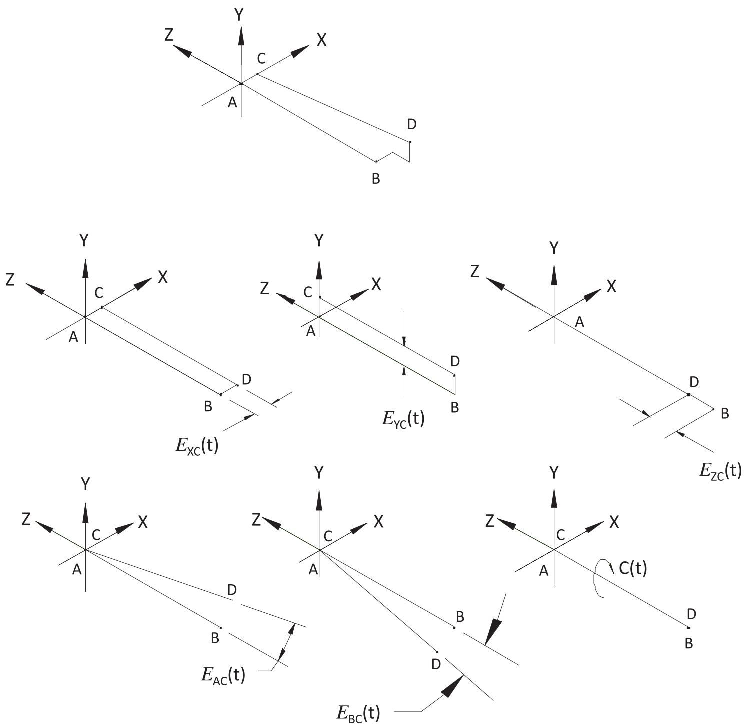
Since face motion varies with radial position, it is necessary to specify the radius of a face motion measurement.

A.6.7 Error motion – General case

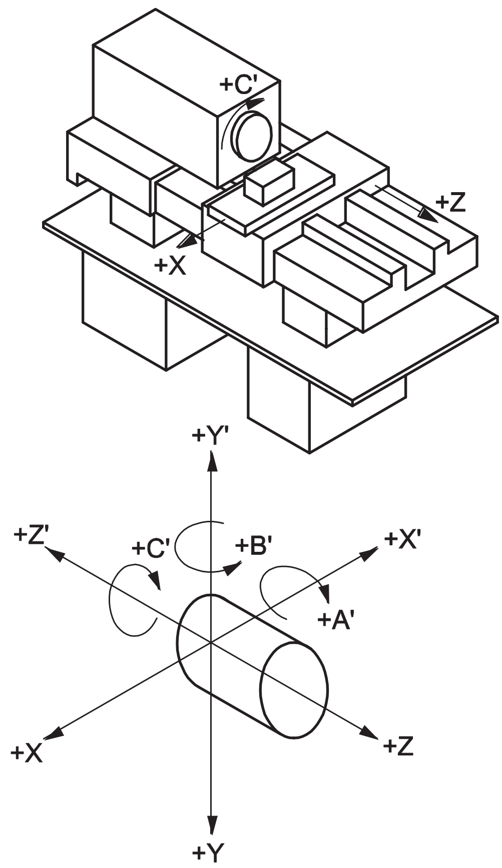
The most general case of error motion involves an arbitrary angle, θ, of the sensitive direction with respect to the axis average line, as for the spherical surface shown in Figure A.5. The error motion depends on both the axial and radial locations, which must be specified together with θ. The formula for error motion $e(t)$ in terms of axial, radial, and tilt motion is

$$e(t) = E_{XC}(t)\sin\theta + F(t)\cos\theta = E_{XOC}(t)\sin\theta + E_{ZC}(t)\cos\theta + E_{BC}(t)(L\sin\theta - R\cos\theta) \tag{A.4}$$

9) For a lathe, the coordinate system shown in Figure A.3 is in accordance with ISO 841. According to ISO 841, “The positive direction of movement of a component is that which causes an increasing positive dimension of the workpiece [see Figure A.3 b)]. On the schematic drawings of the machines, an unprimed letter is used when a tool movement is being dealt with. When a workpiece movement is being dealt with, a primed letter is used and the positive direction of this movement is opposite to the corresponding unprimed letter movement”. ISO 841 represents the rotary motions about the X′, Y′, and Z′ axes by A′, B′, and C′. However, in this part of ISO 230, in order to simplify the reading, these motions are represented without prime (′) notations.



a) Schematic diagrams of general relative motion and six basic degrees of freedom between axis average line and axis of rotation at time, *t*



b) ISO 841 standard coordinate system

Figure A.3 — Designation of axis of rotation error motion for a lathe

It can be seen from Formulae (A.2), (A.3), and (A.4) that error motion in general or any of the special cases can be obtained from a knowledge of axial error motion $E_{ZC}(t)$, tilt error motion $E_{BC}(t)$, and radial error motion $E_{XC}(t)\big|_{z1}$ at a known axial position (z_1).

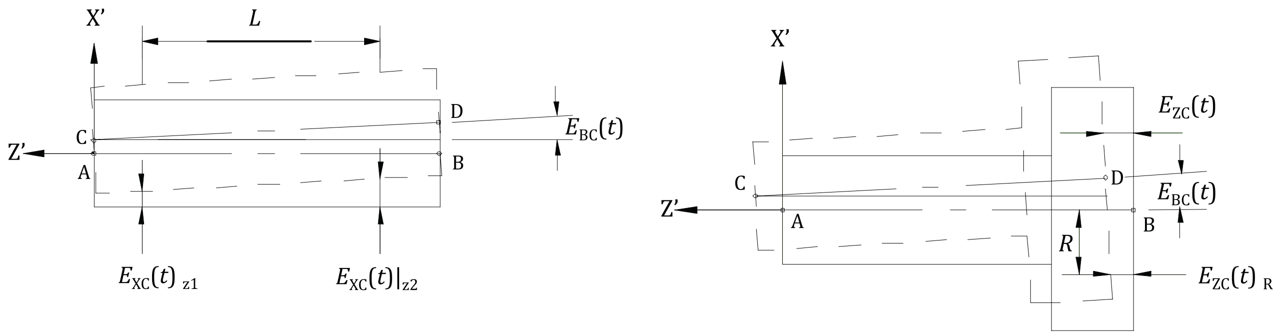
Tilt error motion is derived from face motion by use of Formula (A.3),

$$E_{BC}(t) = (1/R)\ [E_{ZC}(t) - E_{ZC}(t)\ \big|_{R}\ ] \tag{A.5}$$

A second radial error motion measurement is used to obtain tilt error motion from Formula (A.2),

$$E_{BC}(t) = (1/L)\ [E_{XC}(t)\big|_{z2} - E_{XC}(t)\big|_{z1}] \tag{A.6}$$

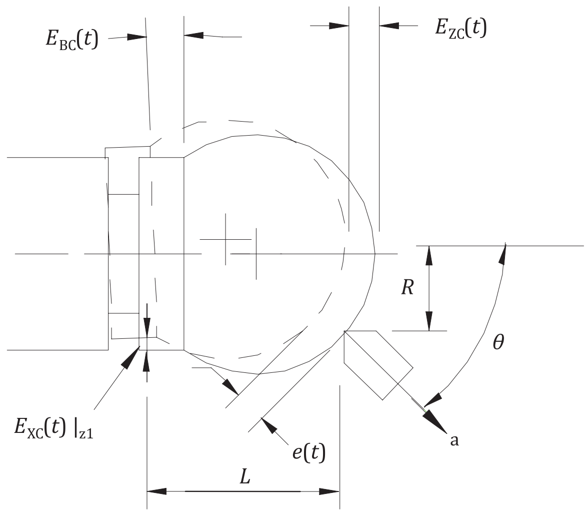
It should be noted that pure radial error motion $E_{XC}(t)$ does not appear in any of the above formulae. It is useful as a concept in understanding error motion geometry but is not a factor that has to be measured in determining the behaviour of an axis of rotation.



a) Radial error motion variation with axial distance

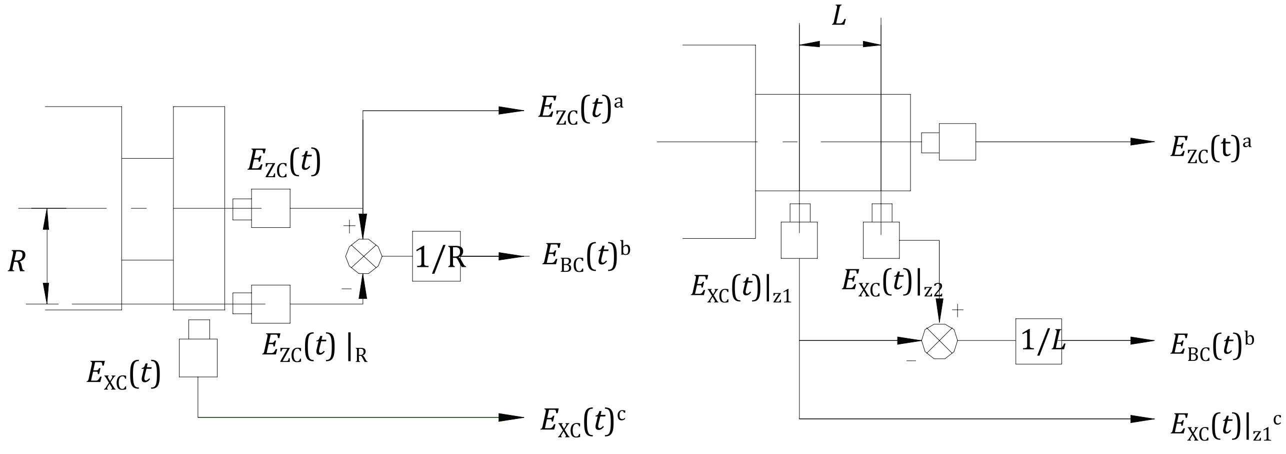
b) Face motion variation with radius

Figure A.4 — Geometry of radial error and face motion



a Sensitive direction.

Figure A.5 — General case of error motion



a) Test arrangement using radial, face, and axial error motion measurements

b) Test arrangement using two radial and an axial error motion measurement

a Axial motion.

b Tilt motion.

c Radial motion.

Figure A.6 — Schematic test arrangements for radial, axial, and tilt motion with a fixed sensitive direction

A.7 Error motion polar plots

A.7.1 General

A very useful form for displaying error motion measurements of an axis of rotation is a polar plot of the error motion versus the rotation angle of the axis, C(t) (or θ) [see Figure A.3 a)]. The following advantages for this method will be listed and discussed in turn:

a) prediction of the part roundness and surface finish potential of a machine tool;

b) diagnosis of bearing error motion and structural error motion;

c) reduction of the required accuracy of centring the reference test sphere;

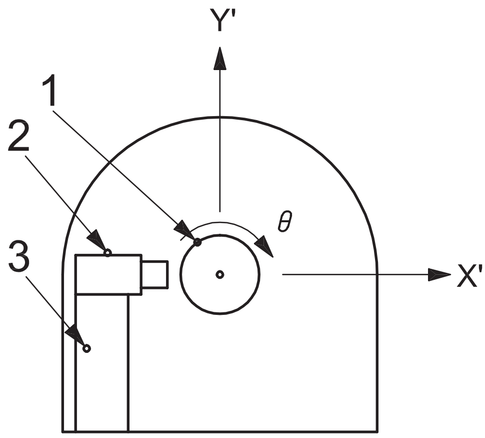
d) assessment of the error motion value.

A.7.2 Specific example — Radial error motion polar plot

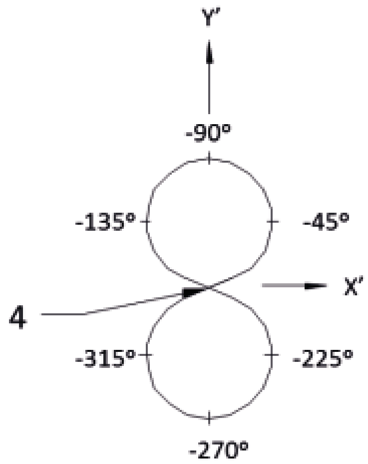
A specific example of an error motion polar plot for a fixed sensitive direction will be used as a basis of discussion. Using radial error motion for illustration, Figure A.7 a) shows a test arrangement involving a reference test sphere (assumed to be perfectly round and perfectly concentric with the axis of rotation) with a displacement sensor arranged to measure in the sensitive direction[10]. Figure A.7 b) shows an enlarged view of the assumed path of the axis of rotation in the X′–Y′ plane relative to the displacement sensor. The assumed path consists of a repetitive figure-eight pattern, which has been labelled with the angle of rotation at various points. Figure A.7 c), shows a rectilinear plot of the radial error motion measured by the displacement sensor versus angle of rotation as a result from the motion of the sphere in the figure-eight pattern. Note that motion of the sphere away from the displacement sensor results in

10) It is important to note that for a lathe, the normal rotation of the spindle is in the negative sense of θ.

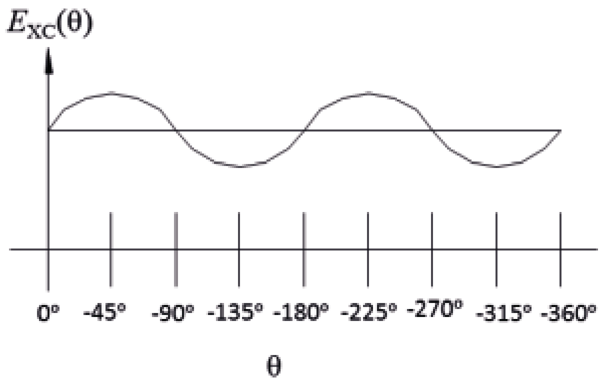
positive error motion (for the normal sign convention, see ISO 841). Figure A.7 d) shows the same data as Figure A.7 c) in the form of a polar plot of radial error motion with respect to a constant arbitrary radius. Thus, the figure-eight pattern results in a tilted elliptical radial error motion polar plot. Of course, it is not necessary to have a figure-eight pattern to produce an ellipse, since other motions in the non-sensitive direction could occur without changing the radial error motion.



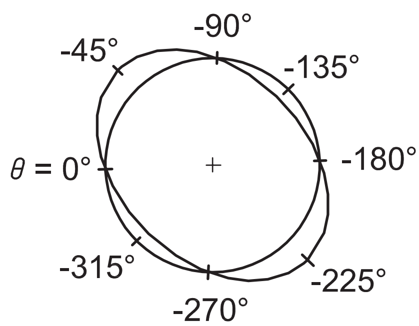
a) Schematic radial error motion test for a lathe end view



b) Enlarged end view of assumed path of axis of rotation in the X′–Y′ plane



c) Rectilinear plot of radial error motion [X′ component in b) versus angle of rotation]



d) Radial error motion polar plot [polar plot of c)]

Key

1 reference sphere
2 displacement sensor
3 tool post
4 X, Z reference axis
θ angle of rotation

Figure A.7 — Hypothetical example of radial error motion measurement and plotting

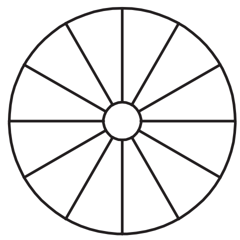
A.7.3 Average radial error motion and part roundness

If the displacement sensor in Figure A.7 a) were replaced by an ideal cutting tool (capable of cutting in exact accordance with its position, without deflection, wear, etc.), it is clear that the figure-eight motion would result in a non-round part. Since the part radius is influenced only by axis motion in the sensitive direction, it follows that a positive radial error motion (from the tool post) will lead to a larger part radius and vice-versa. If the part is removed and placed in an error-free roundness-measuring machine, the roundness chart will be identical to that of Figure A.7 d) as shown in Figure A.8. The out-of-roundness of the two charts is identical, and hence the radial error motion polar plot of a spindle axis of rotation predicts the best workpiece roundness the machine is capable of producing under ideal cutting conditions. Other factors such as non-ideal cutting (built-up edge, tool wear, variable tool deflection, etc.), feed marks, chucking distortion, thermal distortion, and release of residual stresses can result in this capability not being realized.

If the above part was left in place after cutting and the displacement sensor was replaced on the tool post, then under the present assumptions of ideal cutting and repetitive radial error motion, the radial run-out of the part surface would be zero. The radial error motion and the part roundness errors cancel due to their equal magnitudes and opposite signs. This is one example of the difference between radial error motion and radial run-out measurements (see A.8).

The above example is idealized in that the error motion of the axis of rotation was assumed to be exactly repetitive from revolution to revolution. Figure 7 a) shows a more typical case of error motion, which is non-repetitive. Figure 7 a) is known as a total error motion polar plot. Figure 7 b) shows a synchronous error motion polar plot, which is obtained from Figure 7 a) by averaging the radial error motion at each angular position over the number of revolutions recorded. Figure 7 c) shows an asynchronous error motion polar plot, which consists of the difference between the total and the synchronous error motion polar plots.

It can be argued that, for turning operations, the synchronous error motion polar plot is indicative of form error (such as roundness for radial error motion). This is true to the extent that the shape of the total error motion polar plot for any single revolution is similar to the shape of the synchronous error motion polar plot.



a) Radial error motion polar plot

b) Part roundness profile

Figure A.8 — Relationship of radial error motion to part roundness for example of Figure A.7

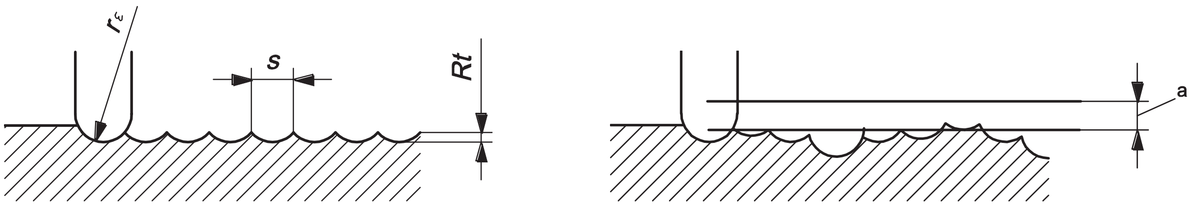
A.7.4 Asynchronous error motion and surface roughness

It can also be shown that the asynchronous error motion polar plot can be used to predict the surface roughness obtained under ideal cutting conditions. Recalling that surface roughness is ordinarily measured transverse to the lay (i.e. parallel to the axis for a cylinder or radially on a flat face), it follows that the measurement corresponds to crossing a number of successive revolutions at one particular angle on the total error motion polar plot. If the asynchronous error motion were zero, the only irregularity present would be the scallop-marks associated with the tool radius as shown in Figure A.9 a), which is referred as the “theoretical finish”. The peak-to-valley height, R_t, of the theoretical finish associated with a tool radius r_ε and a feed per revolution s is

$$Rt = \frac{s^2}{8r_\varepsilon} \quad \text{(if s is small compared to } r_\varepsilon\text{)} \qquad \text{(A.7)}$$

The value of R_t can easily be made quite small, e.g. if s = 0,02 mm/rev and r_ε = 5 mm, then R_t = 0,01 µm.

However, if asynchronous error motion is present, then the surface is cut to varying levels on successive revolutions as in Figure A.9 b). It is evident that a given asynchronous error motion level is translated into an equal peak-to-valley surface roughness if the roughness cut-off width (usually 0,08 mm for a feed rate of 0,02 mm/rev) is several times larger than the feed per revolution. The sum of the asynchronous error motion level and R_t from Formula (A.7) represents the potential peak-to-valley surface roughness for the machine under ideal cutting conditions, with the R_a (average height) value being approximately one quarter as large. This potential can be realized for sharp chip-free diamond tools cutting certain nonferrous metals, but under most cutting conditions the presence of a built-up edge on the tool leads to a larger surface roughness. In some situations the tool has repeated contact with the same point on the work for a large number of revolutions, such as turning with a flat-nosed tool, cylindrical grinding with a flat-faced wheel or dwell at zero federate with any tool. In such a case it can be argued that material will be removed to the level of the maximum excursions of the work toward the tool, and hence (using the sign convention of Figure A.7) the potential part roundness can be predicted from the inner error motion polar plot, consisting of the contour of the inner boundary of the total error motion polar plot as shown in Figure 7 e). For operations inside a cylindrical bore, the outer error motion polar plot has a similar significance [see Figure 7 d)]. The reliability of such a prediction is limited by the similarity of a succession of such plots, as well as by non-ideal cutting conditions.



a) Theoretical finish for ideal cutting with zero asynchronous error motion

b) Effect of asynchronous error motion on peak-to-valley roughness with ideal cutting

a Asynchronous error motion.

Figure A.9 — Relationship of surface roughness to asynchronous error motion

A.7.5 Bearing and structural error motions

In addition to being useful in predicting the performance of a spindle, the polar plot can be used in diagnosing the physical causes of the observed error motion. In this context, it is helpful to view the total error motion as an asynchronous error motion superimposed on a completely repetitive synchronous error motion profile. It can be shown mathematically that a repetitive profile can involve only those frequencies that are equal to, or whole-number multiples of, the axis rotational frequency. Thus, the spindle (or rotary table/head) bearings and its drive system are the most likely sources of synchronous error motion. Fluid film bearings (hydrodynamic, hydrostatic, aerostatic) in particular show highly repetitive patterns.

The term asynchronous error motion does not require that the physical causes of asynchronous error motion be random in the statistical sense, but simply refers to the appearance of the total error motion polar plot after a number of revolutions. In fact, asynchronous error motion is often due to non-random sources such as motors or pumps operating at frequencies that are not whole-number multiples of the axis rotational frequency.

The above discussion suggests that synchronous error motion can be equated with bearing error motion and similarly for asynchronous and structural error motions. This is usually an oversimplification. Asynchronous error motion can originate in a bearing, due to low-level air-hammer instability in an aerostatic bearing or imperfect balls, rollers or raceways in a rolling element bearing. Ball and roller bearings sometimes exhibit a pattern, which is repetitive only every other revolution[11]), associated with the rolling elements travelling at approximately one-half of the shaft speed. Plain bearings can have a similar behaviour due to a hydrodynamic effect called half-speed whirl. In these cases, the deviation between successive revolutions represents asynchronous error motion, which is caused by

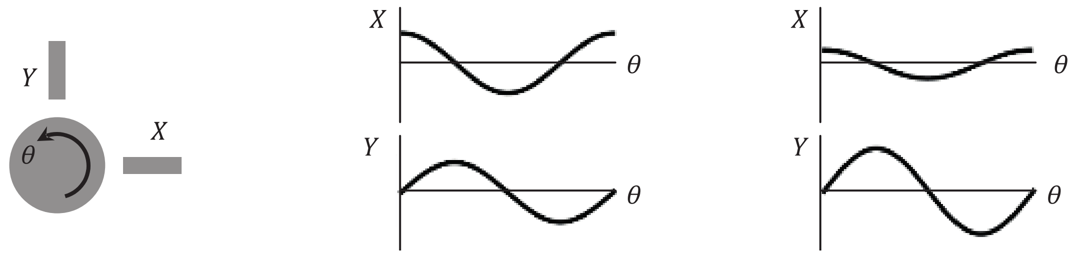
11) The exact number of revolutions, x, for repetitive patterns associated with rolling elements depends on the inner radius R_i of the bearing and the radius R_b of the circle of the centres of the rolling elements: $x = 2\ R_b/R_i$.

bearing error motion. Synchronous motion can also be caused by sources other than axis bearings, such as a drive component operating at a whole-number multiple of the axis rotational frequency or a piece of equipment unrelated to the axis having a chance synchronization with the axis rotational frequency. A useful technique for locating the sources of error motion is to note changes as potential sources are turned on and off or varied in speed. An alternative approach is to vary the axis speed of rotation. At zero axis speed, the remaining "cloud band" thickness represents asynchronous error motion due to sources other than the axis bearings and drive system. The synchronous error motion polar plot at zero axis speed can also be obtained from a static error motion polar plot, performed by placing the non-rotating axis in a succession of discrete angular positions. It should be noted that unless these angular positions are closely spaced, any high frequency components (in terms of cycles per revolution) maybe filtered out of the average error motion polar plot. The possibility of high frequency components being present in the synchronous error motion polar plot prevents the use of a low-pass filter to eliminate asynchronous error motion, since a portion of the synchronous error motion may also be removed. Frequency analysis such as FFT can be used to separate the synchronous and asynchronous components of the error motion.

This document does not specify which sources of error motion are to be included in the assessment of an axis of rotation. For example, if a machine is subjected to a high level of building vibration, the usual view could be that the machine is being victimized by its environment. However, it is conceivable that the machine was purchased with special design features intended to deal with such an environment, in which case the error motion tests would intentionally include building vibration as a source.

A.7.6 Fundamental and residual error motion

The once-per-revolution sinusoidal component (1st order harmonic) of an error motion is called fundamental error motion. Fundamental error motion observed by the displacement sensors in orthogonal directions [see Figure A.10 a)] may be different due to various sources such as directionally-varying structural stiffness of the rotating component. If there are no structural differences between the *X*- and *Y*-directions, then the observed fundamental error motions are identical except for a 90° phase lag, as seen in Figure A.10 b). However, if a structural asymmetry exists, then the fundamental error motions along *X*- and *Y*- directions may have different amplitudes and phases, as shown in Figure A.10 c).



a) Spindle with sensors **b) Error motion due to structural symmetry** **c) Error motion due to structural asymmetry**

Figure A.10 — Spindle error motions due to structural symmetry and structural asymmetry

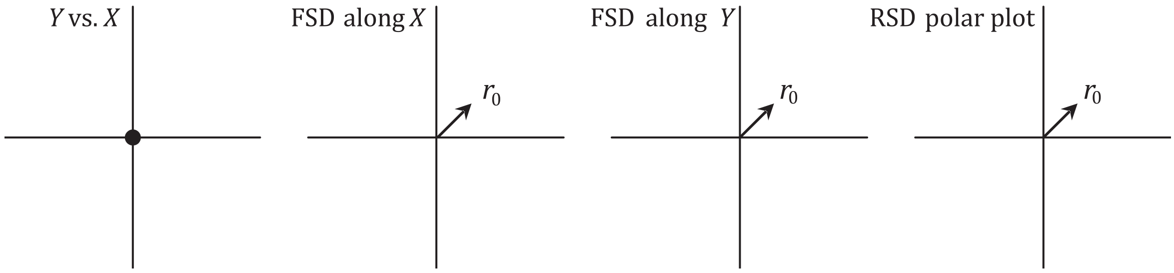
For example, Figure A.11 shows how axis of rotation measurements are affected by error motions due to both structural symmetry and structural asymmetry. For a perfect spindle ($\Delta X = \Delta Y = 0$) measurements exhibit perfect circles in the fixed sensitive direction (FSD) polar plots as well as in the rotating sensitive direction (RSD) polar plot, as seen in Figure A.11 a). The radius r_0 is a basic circle radius chosen for plotting, as stated previously.

For a spindle with a fundamental error motion due to a structural symmetry, *e*, [see Figure A.11 b)] the motions observed by the displacement sensors are represented by Formula (A.8).

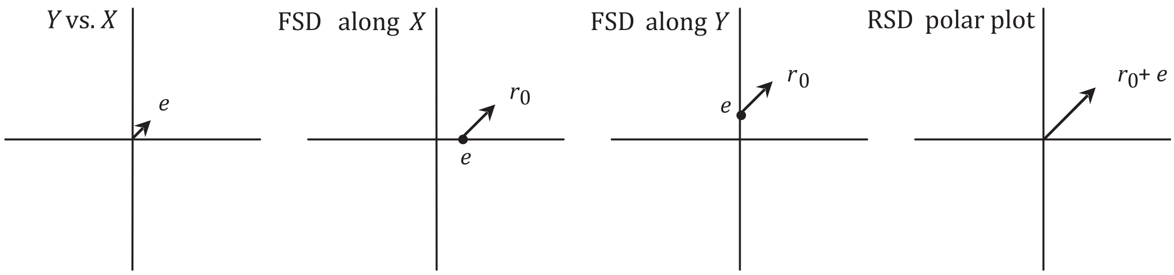
$$\Delta X_e = e\cos(\theta), \Delta Y_e = e\sin(\theta) \qquad \text{(A.8)}$$

where *e* is uniform one per revolution error motion component due to an elastic structure with directionally invariant compliance.

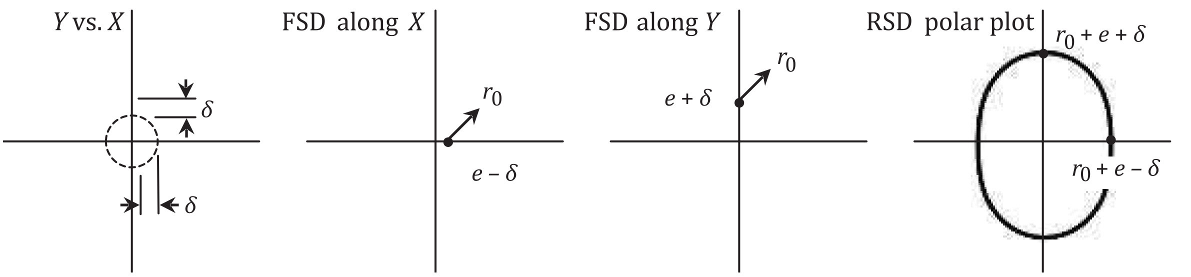
Motion	Fixed sensitive direction X polar plot	Fixed sensitive direction Y polar plot	Rotating sensitive direction plot



a) Perfect spindle



b) Spindle with structural symmetry, *e*



c) Spindle with structural symmetry, *e*, and structural asymmetry, *δ*

Figure A.11 — Effects of structural symmetry and asymmetry on spindle error motion

The polar plots in both fixed and rotating sensitive directions representing such motion are shown in Figure A.11 b). From these plots, it can be interpreted that, for turning operations (fixed sensitive direction), the resulting motion does not affect the form of the turned part. Similarly, for boring operation (rotating sensitive direction), the profile of the holes will still be circular, no form error. On the other hand, the effect of such motion is observed in the dimension of the part, which is adjusted by the tool offset used during machining. Therefore, by centring a test sphere on the axis of rotation, the contribution of this type of fundamental error motion is removed during the measurements.

For a spindle with a fundamental error motion due to a structural asymmetry, δ, [see Figure A.11 c)], the motions observed by the displacement sensors are represented by Formulae (A.9) and (A.10):

$$\Delta X_{\delta} = -\delta \cos(\theta), \Delta Y_{\delta} = \delta \sin(\theta) \quad \text{(A.9)}$$

where δ is one per revolution error motion component due to an elastic structure with directionally varying compliance (structural asymmetry).

If caused by an asymmetry in stiffness, the value for δ is a function of the rotation frequency, the mass imbalance, and the spindle stiffness in the X and Y directions.[14]

As seen in Figure A.11 c), the combination of the structural symmetric and asymmetric components causes the otherwise perfect axis of rotation to move in an elliptical trajectory instead of a circular one. In this case, the motions observed by the displacement sensors are represented by the following equations:

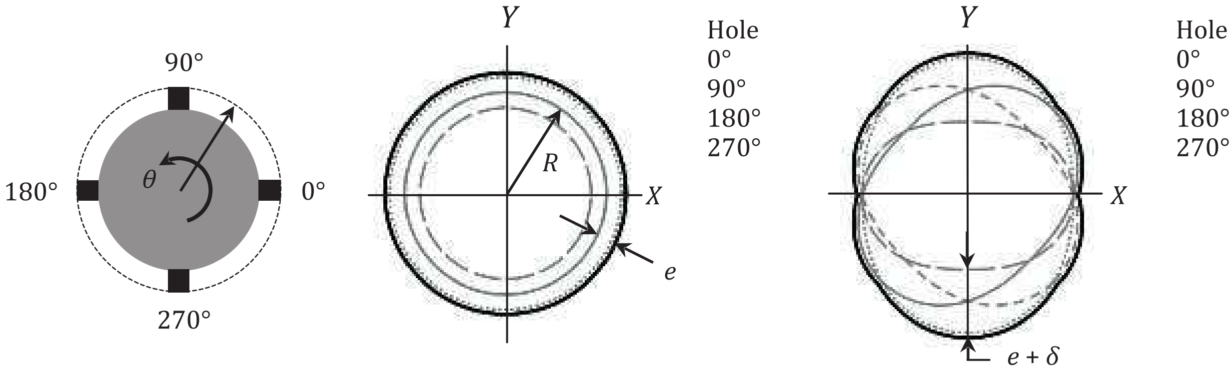
$$\Delta X = (e - \delta)\cos(\theta), \Delta Y = (e + \delta)\sin(\theta) \quad \text{(A.10)}$$

An ellipse implies that the amplitudes of the fundamental error motion in the X- and Y-directions are different, as shown in Figure A.10 c). Consequently, the RSD polar plot is no longer a circle but rather a shape distorted by the structural asymmetry, δ. For a special case of infinite stiffness in X direction and elastic behaviour in Y direction, from Formula (A.10) one can infer that $e = \delta$, which result in an ellipse with X-axis of r_0 and Y-axis of $r_0 + 2\delta$. Therefore, the fundamental error motion due to structural asymmetry can cause non-negligible form errors.

In summary, there are two components of the fundamental error motion: the positive-fundamental component associated with once-per-revolution sinusoidal error motion that changes with the direction of rotation (θ) and a negative-fundamental component associated with once-per-revolution sinusoidal error motion that changes opposite to the direction of rotation ($-\theta$).[14] Specifically, the X and Y data for Figure A.11 c) can be decomposed into two pairs: one pair of sinusoids with amplitudes of e in which a 90° phase lag exists between the X and Y data, similar to Figure A.11 b), and another pair of sinusoids with amplitudes of δ in which a 90° phase lead exists. The “positive” or “negative” nature of the fundamental error component pairs can be seen in X-Y space; the vector (X,Y) rotates with θ (positive direction) for the first pair due to structural symmetry, while the vector (X,Y) rotates with $-\theta$ (negative direction) for the second pair due to structural asymmetry.

Similarly, the effects of fundamental component of tilt error motion due to structural symmetry (as the direction of the axis average line) can be compensated by the motion of linear axes, therefore, fundamental tilt error motion is not considered in any axis of rotation checks. This can be understood by visualizing a perfect cylinder mounted on an imperfect axis of rotation. If the mounting is adjusted so that the cylinder has no centring error at either end, then there can be no once-per-revolution tilt error motion. Since familiar terms such as “coning”, “wobble”, and “swash” suggest a once-per-revolution component, they are inappropriate names for tilt error motion.

Structural asymmetry can cause non-negligible form errors for cases involving more than one rotating sensitive direction. For example, Figure A.12 a) shows the profile of a boring bar with four cutters orientated evenly around its diameter. When in contact during boring, each cutter can produce a hole profile that is known according to the rotating sensitive direction equation, Formula (1). If a pure structural symmetry exists according to Formula (A.8), then the bored hole will be circular in form but slightly larger than its nominal diameter, R, as seen in Figure A.12 b). However, if both structural symmetry and asymmetry exists according to Formulae (A.8) and (A.9), then the hole will be larger and non-circular with its form depending on the structural asymmetry, δ, as seen in Figure A.12 c).



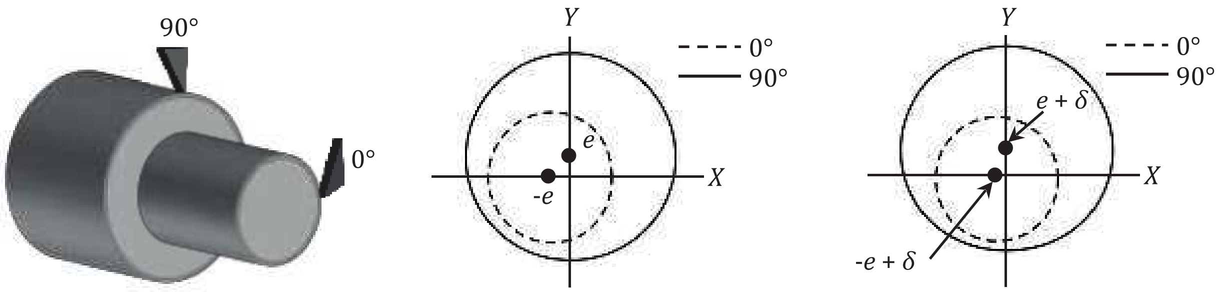
a) **Boring bar with four cutters at various angles**

b) **Bored hole profile due to only structural symmetry**

c) **Bored hole profile due to both structural symmetry and asymmetry**

Figure A.12 — Hole profiles for multi-cutter boring bar due to structural symmetry and structural asymmetry

Both structural symmetry and asymmetry can cause non-negligible position and orientation errors for cases involving more than one fixed sensitive direction. For example, Figure A.13 a) shows a workpiece with two shafts being turned via two orthogonal cutters. Each cutter can produce a shaft profile that is shown in Figure A.11 b). If a pure structural symmetry exists according to Formula (A.8), then the turned shafts will be nominally cylindrical in form (to within first-order) but with centre offset (*Co*)of magnitude $e\sqrt{2}$, as seen in Figure A.13 b). Similarly, if a pure structural asymmetry exists according to Formula (A.9), then the turned shafts will be nominally cylindrical (once again, to first-order only) with centre offset (*Co*) modified by *δ*, as seen in Figure A.13 c).



$$C_o = e\sqrt{2}$$

$$C_o = \sqrt{2(e^2 + \delta^2)}$$

a) **Turning with two orthogonal cutters**

b) **Shaft profiles due to only structural symmetry**

c) **Shaft profiles due to both structural symmetry and asymmetry**

Figure A.13 — Shaft profiles for multi-orientation turning due to structural symmetry and structural asymmetry

Situations involving varying sensitive direction also exist and should be addressed because non-negligible form and position and orientation errors can arise. For a given fundamental error motion caused by structurally symmetric and asymmetric components e and δ, the effect of the radial error motion along the varying sensitive direction can be driven using Formulae (1) and (A.10) in the following form:

$$r_n(\theta) = r + e\cos(\theta_n - \theta) - \delta\cos(\theta_n + \theta) \quad \text{(A.11)}$$

Where θ_n is the angle of the sensitive direction as a function of θ.

As an example, Figure A.14 shows the deviations from a parabolic profile resulting from fundamental error motion due to both structural symmetry and asymmetry.

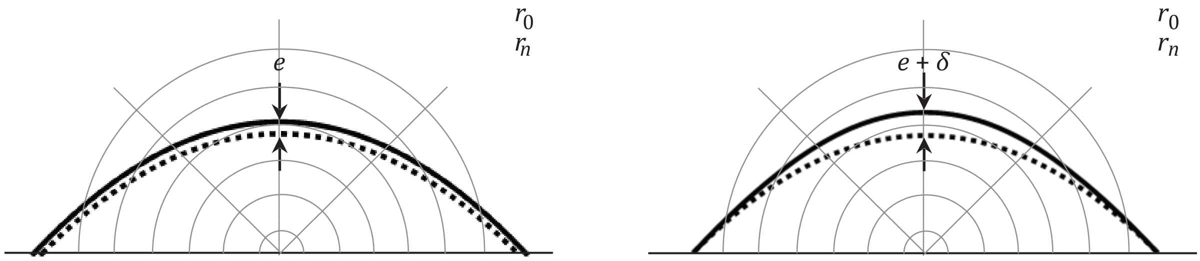


Figure A.14 — The effect of fundamental error motion due to structural symmetry and asymmetry on the varying sensitive direction

In contrast, the effect of fundamental component of axial error motion causes one-to-one form error of the machined part. It consists of a once-per-revolution axial sliding motion of the axis of rotation along the axis average line, and can arise, for example, from out-of-square thrust bearing components. Therefore, it is usually evaluated in axis of rotation checks.

Reference to Formula (A.3) shows that fundamental face motion does exist and is equal to fundamental axial error motion. This can be understood by visualizing a perfectly flat disc mounted on a perfect axis of rotation. Mounting error can result in a once-per-revolution sinusoidal face motion (increasing in direct proportion to radius), but this will vanish if the disc is perfectly square to the axis of rotation. Assuming perfect squareness and then changing from a perfect axis to an axis having fundamental axial error motion, it follows that the same fundamental error motion will occur at all radii. Thus, a perfectly flat disc is square to an imperfect axis of rotation if the fundamental face motion is the same at all radii. It is possible to cancel the fundamental face motion by mounting the disc out-of-square to the axis of rotation, but this cancellation can only occur at one radius. The out-of-squareness angle necessary for this cancellation becomes larger as the radius becomes smaller, reaching an impossible situation at zero radius.

The fundamental face motion has an interesting consequence in machining and measuring flat faces. If a flat disc is faced on an axis that is perfect except for the presence of fundamental axial error motion, then the part can be viewed as made up of many flat-faced thin rings, each of which is out-of-square with the axis of rotation by an amount, which increases with decreasing radius. Such a part is not flat over its full area. However, if the part is mounted in a roundness-measuring machine with the transducer sensing axially, then the part can be tilted so that no flatness error is sensed during a trace around a circular path concentric with the part centre. Such a part is said to have circular flatness. Since it does not have area flatness, it follows that circular flatness measurements can be misleading if they are not properly understood.

Residual error motion is the general term applied to the difference between synchronous and fundamental error motion. The consequences of residual error motion are analogous to those of synchronous radial error motion. For example, residual face motion during machining leads to errors in circular flatness in the same way that synchronous radial error motion leads to errors in roundness. In the general case of error motion with an arbitrary sensitive direction angle φ from the axis average line, the fundamental error motion is proportional to cosine φ times the fundamental axial error motion [see Formula (A.4)]. Thus a 45° taper involves 70,7 % as much fundamental error motion as a flat face.

A.8 Effect of unbalance

Unbalance of the rotating elements introduces a once-per-revolution sinusoidal force with maximum amplitude varying as the square of the spindle speed, in a rotating sensitive direction. In machining, the consequence of this for an otherwise perfect axis is that although a perfectly round part can be machined at a given speed it will exhibit a centring error at other speeds. If two cylindrical sections are machined on the same part at different speeds, their geometric centre lines will not be coaxial. If the shift of the axis of rotation with respect to the rotation object involves a tilt as well as a radial component, then the centre lines of the above two cylinders will not be parallel. Shifts in tilt also change the parallelism or squareness of the axis of rotation to the machine slide ways, causing cylinders to be machined with a taper and flat faces to be machined conical.

In the above discussion, unbalance is assumed to cause a circular orbit of an initially centred test ball. If the structural loop has nonlinear and/or asymmetric compliance, unbalance can excite higher harmonic motions, which lead to roundness and flatness errors. Balancing of rotating elements can be as important for this reason as any other.

In the case of surface finish, it can be demonstrated that, in single point turning, there is no relationship between surface finish and unbalance. This is difficult for some people to believe since the necessity of a smooth, quiet, vibration-free machine for achieving mirror finishes seems obvious. It is, in fact, absolutely essential for a cylindrical grinding machine. To understand why it is not necessary for a lathe requires insight into the difference between synchronous and asynchronous vibration. Unbalance introduces synchronous error motion, which, in single point turning, does not affect finish, since the relative position of the tool with respect to the axis of rotation at each complete revolution is the same. An otherwise perfect lathe with a large amount of unbalance will achieve theoretical finish [see Figure A.9 a)].

Asynchronous error motion, on the other hand, is motion of the tool with respect to the spindle at frequencies other than integer multiples of the spindle frequency. It affects the position of the tool with respect to the axis of rotation at each complete revolution and therefore affects surface finish [see Figure A.9 b)] The surface finish achieved by cylindrical grinders is influenced by unbalance because the wheel spindle rotates at a different speed than the work spindle and synchronous error motion of the wheel spindle automatically becomes asynchronous error motion with respect to the work spindle.

A.9 Reference test sphere errors

Thus far it has been assumed that a geometrically perfect reference test sphere or equivalent was being used in the various error motion measurement examples. It is clear that the geometry errors in a reference sphere will cause erroneous error motion measurements, and it cannot always be assumed that the reference sphere has negligible errors. Annex B describes a method for separating the errors of the reference sphere from the synchronous error motion component of the axis of rotation.

A.10 Error motion versus run-out or TIR

It should be noted that error motion measurements differ from measurements of run-out or TIR (total indicator reading) in several respects. It is important to understand these differences, since run-out tests have been used extensively in the past in assessing the accuracy of rotational axes. Run-out is defined as “the total displacement measured by an instrument sensing against a moving surface or moved with respect to a fixed surface”. Under this definition, a radial run-out measurement includes both the roundness error and the centring error of the surface that the displacement sensor senses against, and hence radial run-out will be identical to radial error motion only if both of these errors are zero. As noted previously, neither of these conditions is easily accomplished. While centring error unavoidably makes the run-out larger than the error motion, it is possible for roundness errors to make the run-out either larger or smaller than the error motion. The latter situation can arise if the surface against which the displacement sensor is sensing was machined in place on the axis bearings, as discussed previously in A.7.3. Similar comments apply to face motion versus face run-out; the latter measurement includes non-squareness and circular flatness errors (see also A.7.6.)

A.11 Considerations on use of two displacement sensors system for fixed sensitive direction

Since the test method described by Bryan (see Figure 15) requires special equipment, it is natural to consider substituting the two-displacement sensor system described by Tlusty (see Figure 11) for measuring radial error motion with a fixed sensitive direction. If this substitution is made, the resulting radial error motion polar plot will not be representative of the potential part out-of-roundness as discussed in A.7.3. If $\theta = 0°$ is the fixed sensitive direction, then the polar plot reflects radial error motion in this direction only in the vicinity of $\theta = 0°$ and $\theta = 180°$. Moreover, if a given localized movement of the axis of rotation occurring at $\theta = 0°$ appears as a peak on the polar plot, the same movement occurring at $\theta = 180°$ will have an undesired sign reversal and will appear as a valley. At $\theta = 90°$ and $\theta = 270°$, the same movement will not register on the polar plot.

Despite the above observations, it still appears intuitively plausible that the radial error motion value should be roughly the same for both fixed and rotating sensitive directions, even if the details of the polar plot are different. This view appears reasonable if the factor of concern is asynchronous radial error motion. However, for synchronous radial error motion, an axis which exhibits an elliptical pattern when tested in a fixed sensitive direction can be free of radial error motion when tested in a rotating sensitive direction. The case occurs for the following error motions:

$$\Delta X(\theta) = A \cos 2\theta \tag{A.12}$$

$$\Delta Y(\theta) = A \sin 2\theta \tag{A.13}$$

where the coordinate system is that of Figure A.7 a). With a fixed sensitive direction along the X axis, the radial error motion polar plot has the formula

$$r(\theta) = r_0 + A \cos 2\theta \tag{A.14}$$

where r_0 is the basic circle radius. Formula (A.14) represents an elliptical shape, having a value $r_0 - A$ at $\theta = 0°$ and $\theta = 180°$ and a value of $r_0 + A$ at $\theta = 90°$ and $\theta = 270°$. The radial error motion value based on any of the polar profile centres is $2A$. If the sensitive direction rotates with angle θ, the radial error motion is given by Formula (A.15)

$$r(\theta) = r_0 + \Delta X(\theta) \cos\theta + \Delta Y(\theta) \sin\theta \tag{A.15}$$

Figure A.15 shows the resolution of $\Delta X(\theta)$ and $\Delta Y(\theta)$ into components along the rotating sensitive direction that leads to Formula A.(15). Combining Formulae (A.12) and (A.13) with Formula (A.15) and using the trigonometric identities

$$\cos\alpha \cos\beta = \frac{1}{2}\left[\cos(\alpha-\beta) + \cos(\alpha+\beta)\right] \tag{A.16}$$

and

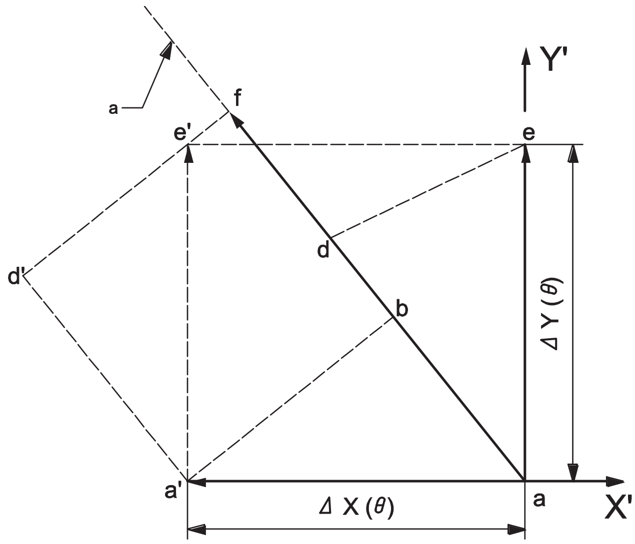
$$\sin\alpha \sin\beta = \frac{1}{2}\left[\cos(\alpha-\beta) - \cos(\alpha+\beta)\right] \tag{A.17}$$

the result is

$$r(\theta) = r_0 + \frac{A}{2}\left[\cos\theta + \cos 3\theta\right] + \frac{A}{2}\left[\cos\theta - \cos 3\theta\right] = r(\theta) = r_0 + A\cos\theta \tag{A.18}$$

Formula (A.18) is the equation of a circle, which is offset from the origin by a distance A, and hence the axis would be perfect if tested by the two-displacement sensor system.

Two additional comments can be made on the above finding. First, it can be argued that if the offset circle is assessed by concentric circles from the polar chart (PC) centre, then a value of 2*A* is obtained, as with the fixed sensitive direction. However, there is no way to carry out the initial electronic zeroing to locate the PC centre, since the base circle cannot be generated independently of the polar profile using the test method of Figure 10. Secondly, the view might be taken that the above example is a mathematical oddity, which is unlikely to occur in practice. In this regard, it can be noted that radial error motion polar plots commonly exhibit an elliptical pattern, and that to the extent that the overall patterns in the *x* and *y* directions contain components as given in Formulae (A.12) and (A.13), these components will not contribute to the measured radial error motion value.



ab = ΔX (θ) cos θ

ad = ΔY (θ) sin θ a′d′

af = ab + a′d′

= ΔX(θ) cos θ + ΔY (θ) sin θ

a Sensitive direction.

Figure A.15 — Vector diagram for rotating sensitive direction

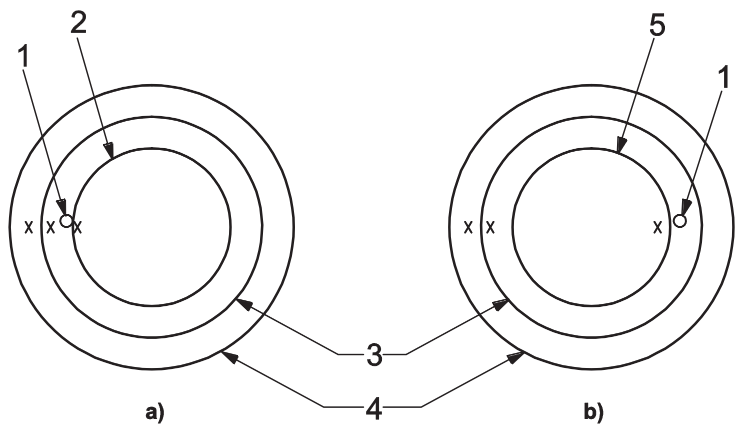
Annex B
(informative)

Elimination of reference sphere roundness error

B.1 Overview

Measurements of radial error motion are directly influenced by the out-of-roundness of the test sphere or circular reference against which the displacement sensor senses. This annex presents a method for separating the out-of-roundness of the reference sphere from the radial error motion of the axis of rotation as described by Donaldson.[12]

In the following description, the notation P(C) (for part) represents the out-of-roundness of the sphere and S(C) (for spindle) represents the radial error motion.



Key

1 displacement sensor

2 reference sphere

3 shaft

4 housing

5 reversed reference sphere

Figure B.1 — Schematic test setups for a) T1(C) [see Formula (B.1)] and b) T2P(C) [see Formula (B.2)], and T2S(C) [see Formula (B.4)]

B.2 Profile averaging method

B.2.1 General

It will be assumed in this clause that the axis of rotation is free of asynchronous radial error motion; means of dealing with asynchronous error motion will be discussed in B.4. The method can be divided into two procedures: Procedure P, which yields the roundness error of the sphere, and Procedure S, which yields the radial error motion.

B.2.2 Procedure P

Procedure P begins by recording an initial polar plot; the deviations from the base circle will be designated as T1(C). Figure B.1 a) shows a schematic diagram of the test arrangement, with the arbitrary initial angular positions being marked as C = 0° by coincident marks on the sphere, the displacement sensor, the shaft and the housing of the axis of rotation. The recorded value of T1(C) is the sum of the sphere roundness profile P(C) and the radial error motion S(C).

$$T_1(C) = P(C) + S(C) \tag{B.1}$$

It is assumed that the sign convention for roundness measurement is used, so that hills and valleys on the polar plot correspond to hills and valleys on the sphere. The second step of Procedure P is to make a second polar plot $T_{2P}(C)$ using the arrangement of Figure B.1 b), in which the shaft and housing marks are coincident at C = 0°, but the sphere and displacement sensor positions are reversed (rotated 180° about the axis of rotation). For the second step [Figure B.1 b)], the relation between the angular position of the polar plot and the angular position of the shaft should be identical. The same sign convention should be used as for $T_1(C)$. Comparison of Figure B.1 a) and Figure B.1 b) shows that the out-of-roundness of the sphere is recorded in the same manner, since the relative position of the displacement sensor and the sphere is unchanged. However, radial error motion is recorded with a reversed sign in Figure B.1 b), because a movement of the spindle toward the displacement sensor in Figure B.1 a) becomes a movement away from the displacement sensor in Figure B.1 b). Expressed as an equation:

$$T_{2P}(C) = P(C) - S(C) \tag{B.2}$$

Adding Formulae (B.1) and (B.2) and solving for P(C) gives

$$P(C) = \frac{\left[T_1(C) + T_{2P}(C)\right]}{2} \tag{B.3}$$

Formula (B.3) states that the out-of-roundness profile of the sphere, P(C), is the average of the first and second polar plots. If $T_1(C)$ and $T_{2P}(C)$ are recorded on the same polar chart, P(C) can be obtained by drawing a third polar plot halfway between the first two as shown in Figure B.2 a).

B.2.3 Procedure S

Procedure S begins by recording an initial profile $T_1(C)$ as in Procedure P. The second step of Procedure S is also identical to the second step of Procedure P except that the sign convention should be reversed. Calling the second polar plot $T_{2S}(C)$ it follows that

$$T_{2S}(C) = -T_{2S}(C) = -P(C) + S(C) \tag{B.4}$$

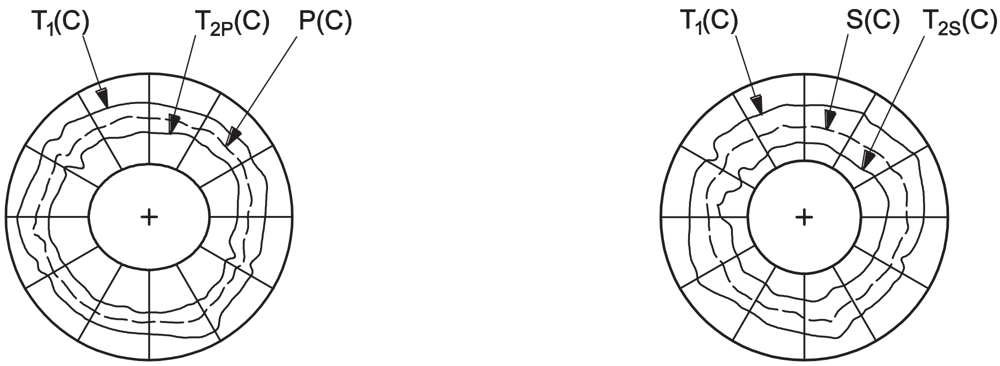
Adding Formulae (B.1) and (B.4) and solving for S(C) gives

$$S(C) = \frac{\left[T_1(C) + T_{2S}(C)\right]}{2} \tag{B.5}$$

Formula (B.5) states that a third polar plot drawn halfway between $T_1(C)$ and $T_{2S}(C)$ will be the radial error motion polar plot S(C).

Procedure	**Reverse for record 2**	**Average**
P	Sphere, displacement sensor	Sphere, out-of-roundness
S	Sphere, displacement sensor, sign	Radial error motion

No mention was made of whether the sphere or the displacement sensor rotated with the axis of rotation, and hence the above procedures are equally valid with either a fixed or a rotating sensitive direction.



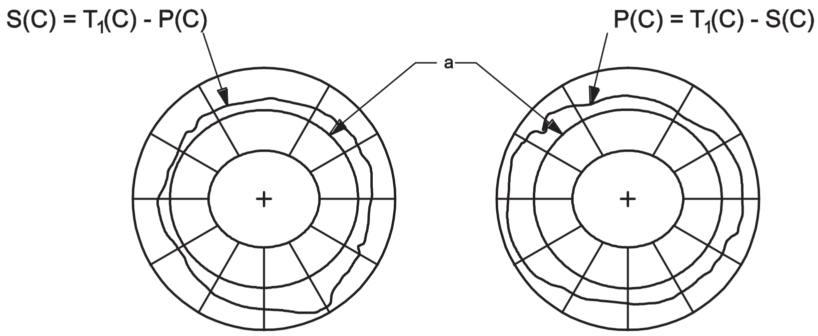
a) Sphere out-of-roundness P (C)

b) Radial error motion S (C)

Figure B.2 — Error separation profile averaging for a) sphere out-of-roundness P(C), b) radial error motion S(C)

B.3 Profile subtraction method

In some instances, it might be reasonable to obtain only one of the polar plots T2P(C) and T2S(C). If either P(C) or S(C) has been obtained by averaging, the other of the two can be obtained by subtraction of the known profile from T1(C), as shown by Formula (B.1). Graphically, it is necessary to construct a new polar plot by laying out relative to a new base circle a sufficient number of radial differences transferred from the original chart. Figure B.3 a) and Figure B.3 b) illustrate this procedure using the profiles of Figure B.2 a) and Figure B.2 b), respectively. Being more difficult and error prone, the subtraction method is not recommended if the profile averaging method can be used.



a)

b)

a Base circle.

Figure B.3 — Error separation by profile subtraction using data of Figure B.2

B.4 Practical considerations

Several practical considerations arise in obtaining accurate results. A crucial assumption in the equations is that both P(C) and S(C) repeat themselves between the first and second measurements. Regarding the repeatability of the roundness profile of the sphere, this involves attention to details such as reversing both the sphere and the displacement sensor by 180° without axial shift or tilt of the two tracks followed by the displacement sensor around the part. Sensitivity to track location can be tested by examining the repeatability of T1(C) as the track is shifted by small amounts in the first setup.

In the presence of asynchronous radial error motion, S(C) shall be interpreted as the synchronous radial error motion polar plot, and the resulting accuracy depends upon being able to obtain a repeatable average radial error motion in the two setups. This can be tested by successive recordings of T1(C) in the first setup. Repeatability over a single revolution is sometimes improved by turning the axis backward to the same starting point, particularly with rolling element bearings.

Synchronizing the reading of a series of error motions with respect to the angular position of the spindle greatly simplifies the elimination of reference sphere roundness error. Synchronization can be achieved by attaching an angular encoder, with an angular reference, to the back end of the spindle. With such a synchronized data acquisition, a reading of a series of error motions over one revolution starts always at exactly the same angular position. Simply averaging the data over several revolutions will filter out the asynchronous error motion. The polar plot can be centred by numerically removing the fundamental harmonic. The reference circle can be created by adding a fundamental to the signal. The sum or the difference between two signals can easily be computed.

Annex C
(informative)

Terms and definitions for compliance properties of axis of rotation

C.1

compliance

displacement per unit force between two objects, specified as to the structural loop, the location and direction of the applied force, and the location and direction of the displacement

C.2

stiffness

reciprocal of compliance

C.3

radial compliance

compliance applicable when the force and displacement directions are perpendicular to the Z reference axis

C.4

tilt compliance

compliance applicable for a pure moment and a tilt displacement in a plane containing the Z reference axis

C.5

axial compliance

compliance applicable when the force and displacement directions are coaxial with the Z reference axis

C.6

face compliance

compliance applicable when the force and displacement directions are coaxial and parallel with the Z reference axis and at a specified radial location

C.7

compliance plot

rectilinear plot showing displacement versus force

C.8

compliance value

slope of the compliance plot at a designated displacement or force

Annex D
(informative)

Terms and definitions for thermally-induced errors associated with rotation of spindle and rotary tables/heads

D.1

thermally-induced radial error

shift in the axis measured perpendicular to the Z reference axis

D.2

thermally-induced tilt error

tilt shift of the axis relative to the Z reference axis caused by the thermal effects

D.3

thermally-induced axial error

shift of the axis coaxial with or parallel to the Z reference axis

D.4

thermally-induced face error

combination of axial and tilt shifts of the axis measured at a specified radial location

D.5

thermal error plot

time-based record of thermally-induced error

D.6

thermal error value

difference between the maximum and minimum values over a specified period of time, at a specified speed (or speeds) and with a measured temperature change

Annex E
(informative)

Static error motion tests

E.1 General

The purpose of these tests is to separate spindle-bearing errors from spindle error motion caused by dynamic effects of the spindle drive system. It is important to isolate the errors caused by spindle bearings. They are often blamed for problems caused by the spindle drive system.

E.2 Test procedure

The test setup is similar to the ones described in 5.3 and 5.4.

Put the spindle drive into neutral. If the spindle has a non disengageable belt drive, the belt tension should be removed, if possible, so that the spindle is free of all external forces.

Rotate the spindle by hand at a minimum of two revolutions, stopping at a minimum of eight points per revolution.

Release all hand forces and record the average sensor reading at each point. Averaging the readings eliminates the effect of structural motion with the spindle stopped.

E.3 Data analysis

The data are analysed for the radial, tilt and axial error motion using methods described in 5.3 and 5.4.

Annex F
(informative)

Measurement uncertainty estimation for axis of rotation tests

F.1 Estimation of the measurement uncertainty

The estimation of the measurement uncertainty follows the procedures and equations of ISO/TR 230-9. The measurement uncertainties U are calculated for a coverage factor of $k = 2$.

The measurement uncertainty should be stated for linear measurements (i.e. for radial and axial movements) in micrometres (µm) and for angular measurements (i.e. for tilt movements) in micrometres per metre (µm/m).

Measurement uncertainties for radial and axial movements may differ. Measurement uncertainties can also differ for different frequency ranges, i.e. for different spindle speed ranges.

F.2 Contributors to the measurement uncertainty

F.2.1 General

In general, the main contributors to the measurement uncertainty for axis of rotation tests are the measurement device and the environmental variation error (E_{VE}).

The following assumptions are made:

— the measurement device is used correctly according to the guideline of the equipment manufacturer/supplier;

— all necessary alignment and adjustment procedures are carried out correctly;

— any length measurement devices, if applicable, are aligned square to the surface touched;

— the measurement equipment is mounted statically und dynamically stiff and without any backlash;

— the machine components holding the measurement equipment behave as rigid bodies;

— the measurement equipment is placed on the machine tool with a maximum deviation of 10 mm from the position stated on the test report,

— the measurement equipment is used within the allowable frequency range stated by the equipment manufacturer/supplier;

— the uncertainty of the software evaluation is included in the measurement uncertainty of the measurement equipment.

If these assumptions are not fulfilled, additional contributions to the measurement uncertainty have to be taken into account.

F.2.2 Uncertainty due to the measurement device, U_{DEVICE}

The use of a calibrated measurement device is recommended. If the calibration certificate states the uncertainty in [µm] for linear and in [µm/m] for angular measurements, Formula (F.1) applies.

$$U_{\mathrm{DEVICE}} = U_{\mathrm{CALIBRATION}} \tag{F.1}$$

where

U_{DEVICE} is the uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;

$U_{CALIBRATION}$ is the uncertainty of the calibration according to the calibration certificate in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurements with coverage factor k = 2.

If no calibration certificate is available and the manufacturer states an error range in micrometres (µm) and in micrometres per metre (µm/m), then Formula (F.2) should be used. The influence of the resolution of the measurement device is in general negligible and can be checked according to ISO/TR 230-9:2005, Formula (C.3).

$$U_{\mathrm{DEVICE}} = 0{,}6 R_{\mathrm{DEVICE}} \tag{F.2}$$

where

U_{DEVICE} is the uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement, coverage factor k = 2;

R_{DEVICE} is the error range given by manufacturer of device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement.

If the measurement equipment is assembled from different components, at least the following contributors should be used for the estimation of the measurement uncertainty of the device:

— roundness and surface finish of the mechanical artefact;

— alignment of the artefact on the spindle under test, if relevant;

— measurement uncertainty of the linear displacement sensor;

— resolution of the linear displacement sensor;

— distance between the radial or facial measurements for evaluating the uncertainty of tilt movement measurements;

— alignment of the linear displacement sensor to the surface of the artefact;

— evaluation of the measurement read out (parameters from mean values, centre definition, etc.).

— All other assumptions as listed in F.2 should be fulfilled. The estimation of the measurement uncertainty of the device can use ISO/TR 230-9:2005, Formulae (1) to (7) and should use a coverage factor of k = 2. This estimation can differ for different speed ranges of the axis under test.

F.2.3 Uncertainty due to the environmental variation error (E_{VE}, or thermal drift), U_{EVE}

During most measurements, temperature changes and vibrations can be observed that might influence the machine tool and the measurement device. These effects, and especially any drift, need to be kept to a minimum.

The effects are checked by a simple test, a drift test.

Before starting the measurements according to this part of ISO 230, the axis of rotation under test is stopped. During the approximate time needed for an axis of rotation measurement the readout of the measurement device is recorded. The range of the readout, E_{VE}, is the remaining environmental variation error that is used to estimate the corresponding uncertainty according to Formula (F.3), based on ISO/TR 230-9:2005, Formula (C.9).

$$U_{EVE} = 0{,}6 E_{VE} \quad \text{(F.3)}$$

where

U_{EVE} is the measurement uncertainty due to environmental variation in micrometres (μm) for linear and in micrometres per metre (μm/m) for angular measurement, coverage factor $k = 2$;

E_{VE} is the range from drift test in micrometres (μm) for linear and in micrometres per metre (μm/m) for angular measurement.

F.3 Uncertainty estimation for error motion plots and error motion values

F.3.1 General

Asynchronous error motion, inner error motion, and outer error motion [see Figure 4 b) and c)] are based on maxima or minima of single measurement, synchronous error motion [see Figure 4 a)] is based on mean values of several error motion plots.

For error motion values two extreme values of an error motion plot are used, as shown in Figure 6.

The following assumptions are made:

— the evaluation of error motion centres is executed correctly,

— the correct error motion centre is used for the evaluation of error motion values,

— the main contributors to the measurement uncertainty are the measurement device and the environmental variation error,

— the environmental variation error is uncorrelated for different plots and for different angles,

— the plots are available over a 360° rotation of the axis under test.

If these assumptions are fulfilled, ISO/TR 230-9:2005, Formulae (1), (3), and (A.7) can be applied to estimate the uncertainty of error motion plots and error motion values.

F.3.2 Uncertainty estimation for total error motion plot, asynchronous error motion polar plot, inner error motion polar plot, outer error motion polar plot, $U_{(\text{single plot})}$

All plots, except the synchronous error motion plot, are based on maxima of several single plots. Therefore just the uncertainties of the two main contributors, which are assumed to be uncorrelated, are summed according to ISO/TR 230-9:2005, Formula (1):

$$U_{(\text{single plot})} = \sqrt{U_{\text{DEVICE}}^2 + U_{EVE}^2} \tag{F.4}$$

where

$U_{(\text{single plot})}$	is the uncertainty of total error motion plot, asynchronous error motion polar plot, inner error motion polar plot, outer error motion polar plot, coverage factor k = 2, in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular error motion plots;
U_{DEVICE}	is the uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
U_{EVE}	is the measurement uncertainty due to environmental variation in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement.

F.3.3 Uncertainty estimation for synchronous error motion plots, $U_{(\text{synchronous plot})}$

For synchronous error motion plots, several plots are used to calculate a mean plot. Therefore, the influence of the environmental variation error can be reduced according to ISO/TR 230-9:2005, Formulae (A.7) and (1) together, this results in Formula (F.5):

$$U_{(\text{synchronous plot})} = \sqrt{U_{\text{DEVICE}}^2 + \frac{U_{EVE}^2}{n}} \tag{F.5}$$

where

$U_{(\text{synchronous plot})}$	is the uncertainty of synchronous error motion polar plot, coverage factor k = 2, in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
U_{DEVICE}	is the uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
U_{EVE}	is the measurement uncertainty due to environmental variation in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
n	is the number of polar plots to calculate synchronous error motion polar plot.

If a large number of plots are taken to calculate the synchronous error motion polar plot, the environmental variation error should be taken from a drift test lasting for at least as long as the measurement time for the plots taken.

F.3.4 Uncertainty of total error motion value, asynchronous error motion value, inner error motion value, outer error motion value, $U_{(\text{single plot value})}$

The error motion values are based on the difference of the maximum and the minimum radial deviation of a polar plot. As maximum and minimum generally appear at different angles of the axis of rotation, the contributors to the uncertainty are regarded as not correlated. With ISO/TR 230-9:2005, Formula (1), this results in Formula (F.6):

(F.6)

where

$U_{(\text{single plot value})}$	is the uncertainty of total error motion plot value, asynchronous error motion plot value, inner error motion plot value, outer error motion plot value, coverage factor $k = 2$, in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
$U_{(\text{single plot})}$	is the uncertainty of total error motion plot, asynchronous error motion polar plot, inner error motion polar plot, outer error motion polar plot.

F.3.5 Uncertainty of synchronous error motion value, $U_{(\text{synchronous plot value})}$

The synchronous error motion values are based on the difference of the maximum and the minimum radial deviation of a synchronous polar plot. As maximum and minimum generally appear at different angles of the axis of rotation, the contributors to the uncertainty are regarded as not correlated. With ISO/TR 230-9:2005, Formula (1), this results in Formula (F.7):

$$U_{(\text{synchronous plot value})} = 1{,}4 U_{(\text{synchronous plot})} \quad \text{(F.7)}$$

where

$U_{(\text{synchronous plot value})}$	is the uncertainty of synchronous error motion value, coverage factor $k = 2$, in micrometres (µm) for linear and in in micrometres per metre (µm/m) for angular measurement;
$U_{(\text{synchronous plot})}$	is the uncertainty of synchronous error motion plot.

Annex G
(informative)

Alphabetical cross-reference of terms and definitions

Term	No.
2D effect of axis of rotation error motion	3.3.6
asynchronous error motion	3.5.5
asynchronous error motion polar plot	3.6.4
asynchronous error motion value	3.8.4
axial error motion	3.4.4
axial shift	3.10.3
axis average line	3.1.12
axis of rotation	3.1.7
axis of rotation error motion	3.2.1
axis shift	3.1.13
bearing	3.1.6
bearing error motion	3.2.3
error motion polar plot	3.6.1
error motion polar plot centre	3.7.1
error motion value	3.8.1
face error motion	3.4.5
face shift	3.10.4
fixed sensitive direction	3.3.3
functional point	3.1.11
fundamental axial error motion value	3.8.5
fundamental error motion	3.5.3
fundamental error motion polar plot	3.6.5
hysteresis	3.1.21
inner error motion polar plot	3.6.7
inner error motion value	3.8.7
least-squares circle (LSC) centre	3.7.4
maximum inscribed circle (MIC) centre	3.7.6
minimum circumscribed circle (MCC) centre	3.7.7
minimum radial separation (MRS) centre	3.7.5
non-sensitive direction	3.3.2
outer error motion polar plot	3.6.8
outer error motion value	3.8.8
perfect spindle	3.1.9
perfect workpiece	3.1.10
play	3.1.20

Term	No.
polar chart (PC) centre	3.7.2
polar profile centre	3.7.3
positive direction	3.1.8
pure radial error motion	3.4.2
radial error motion	3.4.1
radial shift	3.10.1
radial throw of a rotary axis at a given point	3.1.15
residual synchronous error motion	3.5.4
residual synchronous error motion polar plot	3.6.6
residual synchronous error motion value	3.8.6
rotary (or swivelling) table	3.1.2
rotary (or swivelling) head	3.1.3
rotating sensitive direction	3.3.4
run-out of a functional surface at a given section	3.1.16
sensitive direction	3.3.1
speed-induced axis shift value	3.10.6
speed-induced axis shift plot	3.10.5
spindle	3.1.4
spindle housing	3.1.5
spindle unit	3.1.1
Squareness error between a linear axis of motion and an axis average line	3.1.19
squareness error between two axis average lines	3.1.18
static error motion	3.2.4
stationary point run-out	3.1.17
structural error motion	3.2.2
structural error motion plot	3.9.3
structural error motion with non-rotating spindle	3.9.2
structural error motion with rotating spindle	3.9.1
structural loop	3.1.14
structural error motion value	3.9.4
synchronous error motion	3.5.2
synchronous error motion polar plot	3.6.3
synchronous error motion value	3.8.3
tilt error motion	3.4.3
tilt shift	3.10.2
total error motion	3.5.1
total error motion polar plot	3.6.2
total error motion value	3.8.2
varying sensitive direction	3.3.5

Annex H
(informative)

Linear displacement sensor bandwidth and rotational speed

H.1 General

Machine tool spindle axis of rotation error motion measurements are made with non-contact linear displacement sensors such as capacitive or inductive displacement transducers. Such sensors measure displacements of a rotating target along one direction as the target moves towards and away from the sensor as it rotates. The bandwidth of the measurement system should be capable of accommodating the frequency of the motion of the target along that direction. This annex provides some background information and guidance in selecting the displacement sensor with adequate bandwidth.

H.2 Bandwidth of linear displacement sensors

In general, many displacement sensors respond to changing target position by varying output voltage corresponding to the amount of motion. However, as the frequency of the target motion increases, the response of the sensor starts decreasing beyond a frequency threshold. This behaviour is shown in Figure H.1. In this example, the sensor output is considered "flat" up to 10 kHz. The bandwidth specification of any sensor is the frequency at which the output voltage is reduced to 70,7 % (−3 db) of lower frequency (or DC) output levels. In the example given in Figure H.1, the sensor bandwidth is 15 kHz. This means that a target moving at 15 kHz with a displacement of 10 µm will only be measured as 7 µm.

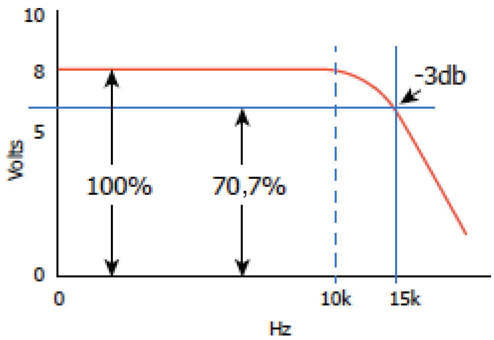


Figure H.1 — Example frequency response of a linear displacement sensor with a bandwidth of 15 kHz, having a flat response up to 10 kHz

H.3 Considerations for the frequency of target motion

H.3.1 The fundamental frequency

Due to radial throw, all rotating targets will exhibit one cycle of error motion per revolution. This establishes a "fundamental frequency." A linear displacement sensor that has a flat frequency response up to 10 kHz can accurately measure fundamental error motions of targets at speeds up to 600 000 r/min. A sensor with 15 kHz bandwidth can measure rotational speeds of 900 000 r/min at 70 % of the actual displacement amplitude.

H.3.2 Non-fundamental frequencies

Frequencies other than the fundamental frequency are also present in the error motions of a spindle. Imperfections in bearing components, mounts, motors, drives, structural vibration, and other factors each contribute a unique frequency. These error motions occur at integer and non-integer multiples of the fundamental frequency.

H.3.3 Stator and rotor shape errors

Stators and rotors are not perfectly round. These imperfections create additional frequencies in the spindle error motion, which are always synchronous with the fundamental frequency. Two- and three-lobe shapes are common out-of-roundness errors. These form errors create error motion frequencies two and three times higher than the fundamental frequency. Higher number of lobes require sensor with higher bandwidth for accurate measurements, otherwise, spindle speeds have to be reduced. For example, to accurately measure a three lobed error motion, sensor with a flat response to 10 kHz can only be used at spindle speeds of up to 200 000 r/min.

H.3.4 Mounting induced errors

Mounting of the spindle can create stresses in the bearing structure resulting in slight deformities. These create synchronous error motions and are essentially the same as stator and rotor shape errors. Theoretically, each mounting fastener could add another lobe to the synchronous error motion.

H.3.5 Motor pole print-through

The magnetic poles in motors create a normal force on the motor’s rotor that is different at the poles than between the poles. This varying force cycles on every rotation. Depending on the stiffness of the spindle bearing, this changing force can appear as error motions in the spindle. This motion is synchronous with the fundamental frequency.

The number of poles in the drive motor determines the shape of the print-through error. For example, an eight-pole motor creates an 8-lobe pattern and would be accurately measured at speeds up to 75 000 r/min by a sensor with a flat response to 10 kHz. A typical drive motor has 4, 6, or 8 poles. Very large motors can have more poles, but due to their size, they run at much slower speeds keeping the error motion frequencies comparatively low.

H.3.6 Structural vibration

The machine structure itself will have natural resonant frequencies that can appear in the spindle error motion. Because of the size and mass of the machine structure, these frequencies are usually low (10 Hz – 30 Hz) and might or might not be synchronous with the fundamental frequency.

H.3.7 Rolling-element bearings

Rolling-element bearings have four basic components: the rolling element itself (ball or roller), inner race, the outer race, and the cage. As the bearing turns, these components interact mechanically; their inherent imperfections cause deviations in bearing forces and the axis of rotation which result in spindle error motions.

Each bearing component has its own shape errors which produce error motions in the spindle. The ratio of the diameters of the bearing components and the contact angle of the rolling element determine the relationships to the fundamental frequency. To prevent resonances within the spindle, bearings are intentionally selected so that these frequencies are not synchronous with the spindle rotor; therefore, these errors occur at non-integer multiples of the fundamental frequency.

H.3.8 Bearing frequencies

The frequency distribution of a bearing consists of cage frequency, inner and outer race (ballpass) frequencies and ball spin frequency and their harmonics. They are represented as the multiples of the fundamental frequency. Table H.1 shows an example of typical bearing frequencies shown as the multiples of the fundamental frequency. The highest frequency shown is 8,32 times the fundamental frequency. Accurate measurements of error motions can be made with spindle speeds up to 70 000 r/min using a sensor with a flat response to 10 kHz.

Table H.1 — Example bearing frequencies for a typical rolling-element bearing

Number of balls	Ball diameter [mm]	Pitch diameter [mm]	BallPass outer [multiples of fundamental frequency]	BallPass inner [multiples of fundamental frequency]	Cage [multiples of fundamental frequency]	Ball spin [multiples of fundamental frequency]
15	8	72,5	6,68	8,32	0,45	4,52

Bibliography

[1] ISO 230-2, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes*

[2] ISO 230-5, *Test code for machine tools — Part 5: Determination of the noise emission*

[3] ISO/TR 230-8, *Test code for machine tools — Part 8: Vibrations*

[4] ISO/TR 230-9:2005, *Test code for machine tools — Part 9: Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations*

[5] ISO 1940-1, *Mechanical vibration — Balance quality requirements for rotors in a constant (rigid) state — Part 1: Specification and verification of balance tolerances*

[6] ISO 6103, *Bonded abrasive products — Permissible unbalances of grinding wheels as delivered — Static testing*

[7] ISO 10791-6, *Test conditions for machining centres — Part 6: Accuracy of feeds, speeds and interpolations*

[8] ISO 13041-6, *Test conditions for numerically controlled turning machines and turning centres — Part 6: Accuracy of a finished test piece*

[9] Unification Document Axes of Rotation, ME Annals of the CIRP, 2/1976

[10] TLUSTY J. System and Methods of Testing Machine Tools. Microtechnic. 1959, **13** p. 162

[11] BRYAN J., CLOUSER R., HOLLAND E. Spindle Accuracy, American Machinist, Spec. Rpt. No. 612, Dec 4, 1967

[12] PETERS J, & VANHERCK P An Axis of Rotation Analyser, Proceedings of the 14th International MTDR Conference, Manchester 1973

[13] DONALDSON R. A Simple Method for Separating Spindle Error from Test Ball Roundness Error. CIRP Ann. 1972, **21** (1) p. 125

[14] Lu X., & Jamalian A. A new method for characterizing axis of rotation radial error motion: Part 1. Two-dimensional radial error motion theory. Precis. Eng. 2011, v35

[15] ISO/TR 230-11, *Test code for machine tools — Part 11: Measuring Instruments and their application to machine tool geometry tests*

[16] ISO 230-3, *Test code for machine tools — Part 3: Determination of thermal effects*

[17] ISO 841, *Industrial automation systems and integration — Numerical control of machines — Coordinate system and motion nomenclature*

ICS 25.080.01
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