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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 230-7:2006(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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 230-7 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

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

The following part is under preparation:

- *Part 8: Determination of vibration levels* [Technical Report]

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. Spindles, 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 spindles:

- axis of rotation error motion;
- speed-induced axis shifts.

The other important properties of spindles, 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);
- runout of surfaces and components (see ISO 230-1);
- tool holder interface specifications;
- inertial vibration measurements (see ISO 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 drift (see ISO 230-3).

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 230-1:1996, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or finishing conditions*

ISO 230-2:2006, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes*

ISO 230-3:—[1], *Test code for machine tools — Part 3: Determination of thermal effects*

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

3 Terms and definitions

For the purposes of this document, the 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
device which provides an axis of rotation

NOTE Other devices such as rotary tables, trunnions and live centres are included within this definition.

3.1.2
spindle
rotor
rotating element of a spindle unit

3.1.3
spindle housing
stator
stationary element of a spindle unit

3.1.4
bearing
element of a spindle unit that supports the spindle (rotor) and enables rotation between the spindle and the spindle housing

3.1.5
axis of rotation
line segment about which rotation occurs

See Figure 1 a).

NOTE 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).

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1) To be published. (Revision of ISO 230-3:2001)

3.1.6
reference coordinate axes
mutually perpendicular X, Y, and Z-axes, fixed with respect to a specified object

See Figure 1 a).

NOTE The specified object can be fixed or rotating.

3.1.7
positive direction
in accordance with ISO 841, the direction of a movement that causes an increasing positive dimension of the workpiece

3.1.8
perfect spindle
spindle having no error motion of its axis of rotation relative to its axis average line

3.1.9
perfect workpiece
rigid body having a perfect surface of revolution about a centreline

3.1.10
axis average line
straight line segment located with respect to the reference coordinate axes representing the mean location of the axis of rotation

See Figure 1 a).

NOTE 1 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 2 Unless otherwise specified, the axis average line should be determined by calculating the least-squares centre of two data sets of radial error motion taken at axially separated locations (see 3.4).

NOTE 3 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.

3.1.11
axis shift
quasi-static relative displacement, between the tool and the workpiece, of the axis average line due to a change in conditions

See Figure 1 c).

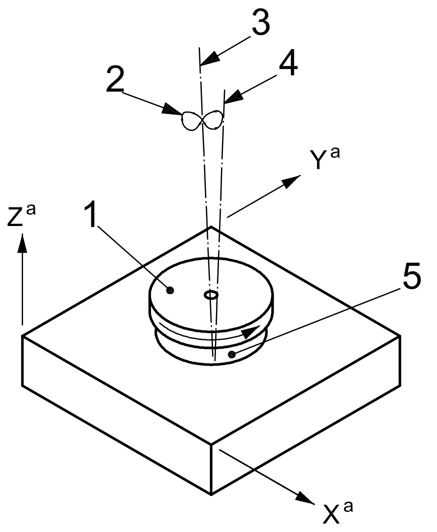
NOTE Causes of axis shift include thermal drift, load changes, and speed changes.

3.1.12
displacement sensor
device that measures displacement between two specified objects

EXAMPLE Capacitance gage, linear variable differential transformer (LVDTs), eddy current probe, laser interferometer, dial indicator.

3.1.13
structural loop
assembly of components which maintains the relative position between two specified objects

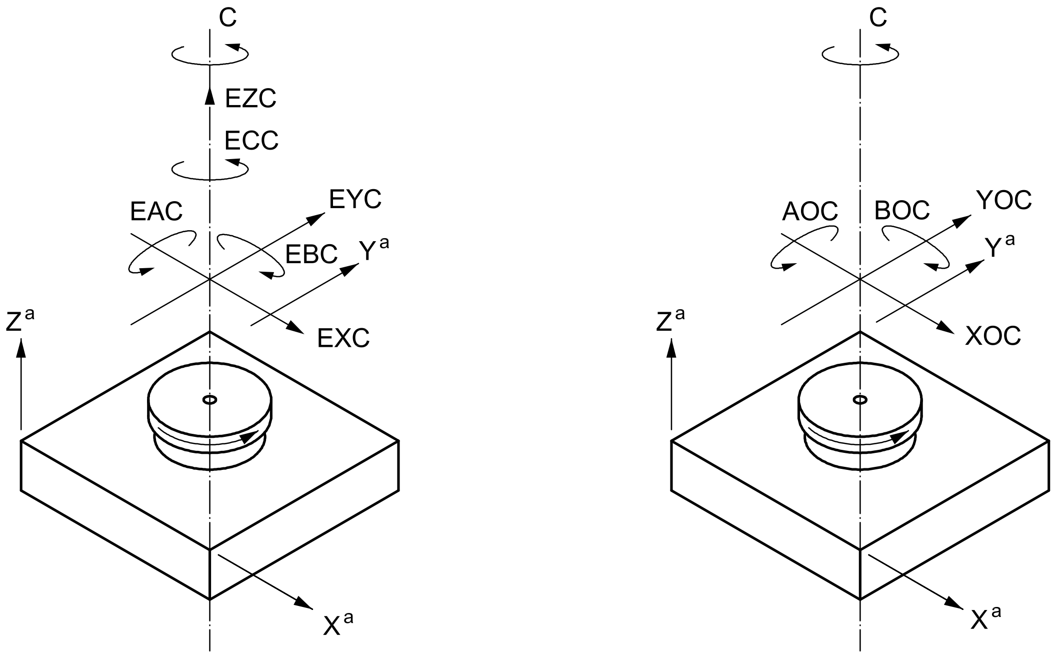
NOTE A typical pair of specified objects is a cutting tool and a workpiece: the structural loop would include the spindle, bearings and spindle housing, the machine head stock, the machine slideways and frame, and the tool and work holding fixtures.



Key

1	spindle (rotor)
2	error motion of axis of rotation (prior to angle C)
3	axis average line
4	axis of rotation (at angle C)
5	spindle housing (stator)

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



Key

EXC	radial motion in X direction
EYC	radial motion in Y direction
EZC	axial motion
EAC	tilt motion around X
EBC	tilt motion around Y axis
ECC	angular positioning error

Key

XOC	X position of C
YOC	Y position of C
AOC	squareness of C to Y
BOC	squareness of C to X

[a] Reference axis.

b) Error motions of axis of rotation

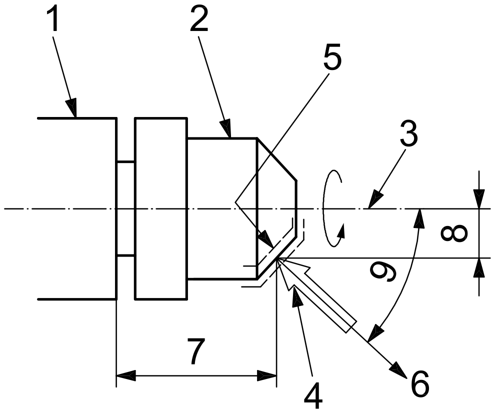
c) Location errors (axis shift) of axis average line

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

3.1.14
sensitive direction
direction perpendicular to the perfect workpiece surface through the instantaneous point of machining or measurement

See Figure 2.

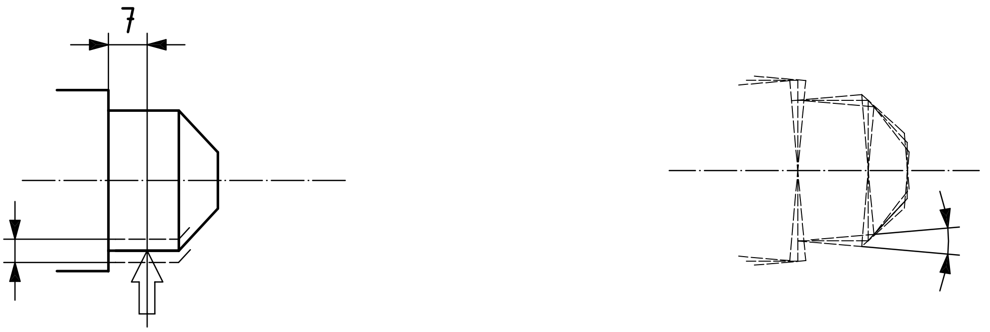
NOTE For a fixed sensitive direction, the results of the measurement of the relative displacement between the tool and the workpiece correspond to the shape error of the manufactured surface of a workpiece.



a) General case of error motion

b) Axial error motion

c) Face error motion



d) Radial error motion

e) Tilt error motion

Key

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

Figure 2 — General case of error motion and axial, face, radial and tilt error motions for fixed sensitive direction

3.1.15
non-sensitive direction
any direction perpendicular to the sensitive direction

3.1.16
fixed sensitive direction
sensitive direction where the workpiece is rotated by the spindle and the point of machining or measurement is fixed

3.1.17
rotating sensitive direction
sensitive direction where the workpiece is fixed and the point of machining or measurement rotates with the spindle

NOTE A lathe has a fixed sensitive direction, a jig borer has a rotating sensitive direction.

3.1.18
runout
total displacement measured by a displacement sensor sensing against a moving surface or moved with respect to a fixed surface

NOTE 1 For runout of a component at a given section, see ISO 230-1:1996, 5.611.4.

NOTE 2 The terms “TIR” (total indicator reading) and “FIM” (full indicator movement) are equivalent to runout.

3.1.19
stationary point runout
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

See Figure 3.

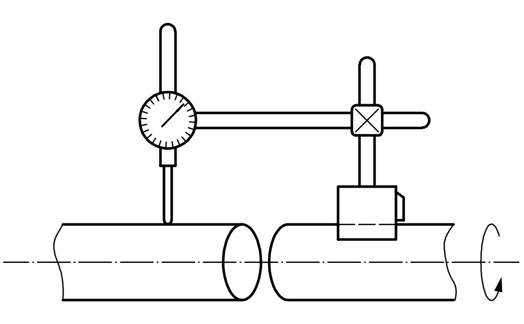


Figure 3 — Schematics of sample applications for use of stationary point runout (radial test for concentricity and face test for parallelism)

3.1.20
squareness
perpendicularity
angular relationship between two planes, two straight lines, or a straight line and a plane in which the angular deviation from 90 degrees does not exceed a given value

NOTE A plane surface is “square” to an axis of rotation if coincident polar profile centres are obtained for an axial and a face motion polar plot or for two face motion polar plots at different radii. *Perpendicularity of motion* refers, for machine tools, to the successive positions on the trajectory of a functional point on a moving part of the machine in relation to a plane (support or slideway), a straight line (axis or intersection of two planes) or the trajectory of a functional point on another moving part. See ISO 230-1:1996, 5.5.

3.1.21
play
condition of zero stiffness over a limited range of displacement due to clearance between elements of a structural loop

3.1.22
hysteresis
linear (or angular) displacement between two objects resulting from the sequential application and removal of equal forces (or moments) in opposite directions.

NOTE Hysteresis is caused by mechanisms, such as drive train clearance, guideway clearance, mechanical deformations, friction and loose joints.

3.1.22.1
setup hysteresis
hysteresis of various components in a test setup, normally due to loose mechanical connections

3.1.22.2
machine hysteresis
hysteresis of the machine structure when subjected to specific loads

3.2 Error motion

⟨axis of rotation⟩ unintended relative displacement in the sensitive direction between the tool and the workpiece

NOTE Error motions are specified as location and direction as shown in Figure 2 a) and do not include motions due to axis shifts associated with changes in temperature, load or rotational speed.

3.2.1
axis of rotation error motion
changes in position and orientation of axis of rotation relative to its axis average line as a function of angle of rotation of the spindle

NOTE 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.

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

See 3.6

3.2.3
bearing error motion
error motion due to imperfect bearing

NOTE See Annex A.

3.2.4
total error motion

complete error motion as recorded, composed of the synchronous and asynchronous components of the spindle and structural error motions

3.2.5
static error motion

special case of error motion in which error motion is sampled with the spindle at rest at a series of discrete rotational positions

NOTE This is used to measure error motion exclusive of any dynamic influences.

3.2.6
synchronous error motion

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

NOTE It is the mean contour of the total error motion polar plot averaged over the number of revolutions.

3.2.7
fundamental error motion

portion of the total error motion that occurs at the rotational frequency of the spindle

3.2.8
residual synchronous error motion

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

3.2.9
asynchronous error motion

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

NOTE 1 Asynchronous error motion is the deviations of the total error motion from the synchronous error motion.

NOTE 2 Asynchronous error motion comprises those components of error motion that are

a) not periodic,

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

c) periodic at frequencies that are subharmonics of the spindle rotational frequency.

3.2.10
radial error motion

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

See Figure 2 d).

NOTE 1 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 2 The term “radial runout” has an accepted meaning, which includes errors due to centring and workpiece out-of-roundness, and hence is not equivalent to radial error motion.

3.2.11
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 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.

3.2.12
tilt error motion
error motion in an angular direction relative to the axis average line

See Figure 2 e).

NOTE 1 This motion may be evaluated by simultaneous measurements of the radial error motion in two radial planes separated by a distance along the axis average line.

NOTE 2 “Coning,” “wobble,” “swash”, “tumbling” and “towering” errors are non-preferred terms for tilt error motion.

NOTE 3 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.

3.2.13
axial error motion
error motion coaxial with the axis average line

See Figure 2 b).

NOTE 1 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 2 “Axial slip”, “end-camming”, “pistoning” and “drunkenness” are non-preferred terms for axial error motion.

3.2.14
face error motion
error motion parallel to the axis average line at a specified radial location

See Figure 2 c).

NOTE Face error motion is a combination of axial and tilt error motions. The term “face runout” has an accepted meaning analogous to “radial runout” and hence is not equivalent to face error motion.

3.2.15
error motion measurement
measurement record of error motion, which includes all pertinent information regarding the machine, instrumentation and test conditions

3.3 Error motion polar plot

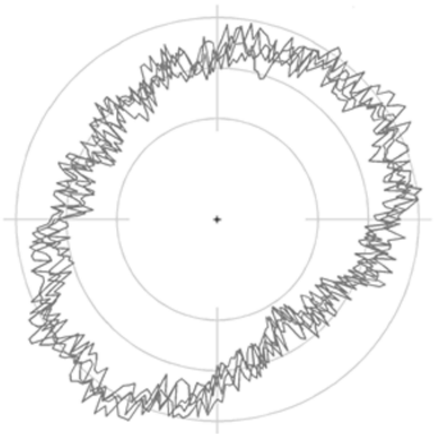
representation of error motions of axes of rotation generated by plotting displacement versus the angle of rotation of the spindle

See Figure 4.

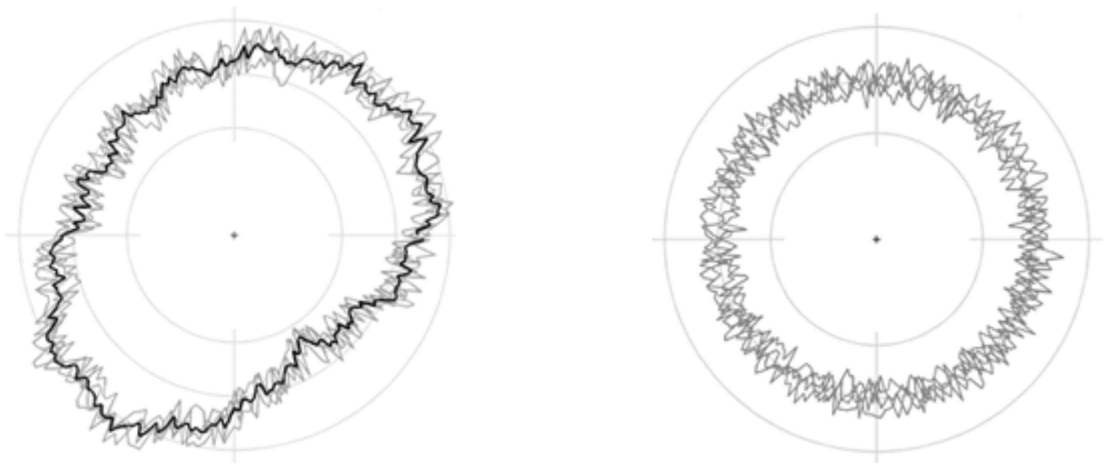
3.3.1
total error motion polar plot
polar plot of the complete error motion as recorded

3.3.2
synchronous error motion polar plot
polar plot of the error motion components having frequencies that are integer multiples of the rotation frequency

NOTE It is acceptable to create the synchronous error polar plot by averaging the total error motion polar plot.

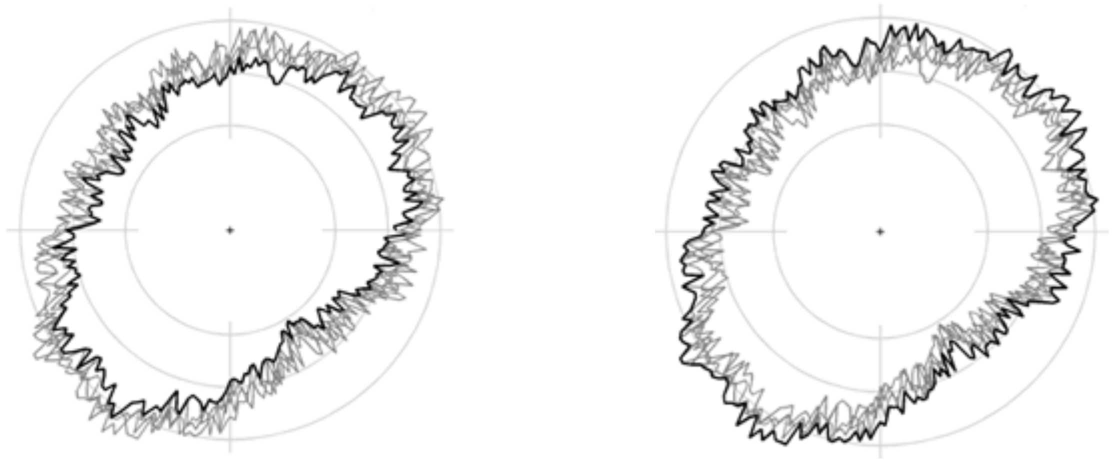


a) Total error motion



b) Synchronous error motion

c) Asynchronous error motion



d) Inner error motion

e) Outer error motion

Figure 4 — Error motion polar plots

3.3.3
asynchronous error motion polar plot

polar plot of that portion of the total error motion that occurs at frequencies that are not integer multiples of the rotational frequency

3.3.4
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

3.3.5
axial error motion polar plot

polar plot of the axial error motion, including the fundamental, synchronous residual and asynchronous axial error motions

3.3.6
residual synchronous error motion polar plot

polar plot of the portion of the synchronous error motion that occurs at frequencies other than the fundamental

NOTE The division of synchronous error motion into fundamental and residual components is only applicable to axial and face error motions. In the radial and tilt directions, fundamental error motion does not exist — the measured value that occurs at the fundamental frequency is not a characteristic of the axis of rotation.

3.3.7
inner error motion polar plot

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

3.3.8
outer error motion polar plot

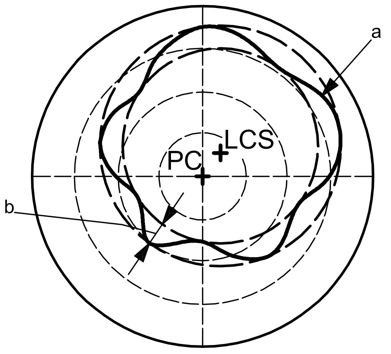
contour of the outer boundary of the total error motion polar plot

3.4 Error motion centre

centre defined for the assessment of error motion polar plots

See Figure 5.

NOTE Table 1 provides the preferred centres for the assessment of error motion values. If the centre is not specified, the preferred centre is to be assumed.



[a] Error motion polar plot.

[b] Error motion value for LSC centre.

Figure 5 — Error motion polar plot, PC (polar chart) centre and LSC (least-square circle) centre and error motion value for LSC centre

Table 1 — Error motion type preferred centre

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

3.4.1
polar chart centre
PC centre
centre of the polar chart

3.4.2
polar profile centre
centre derived from the polar profile by a mathematical or graphical technique

3.4.3
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

3.4.4
minimum radial separation centre
MRS centre
centre that minimizes the radial difference required containing the error motion polar plot between two concentric circles

3.4.5
maximum inscribed circle centre
MIC centre
the centre of the largest circle that can be inscribed within the error motion polar plot

3.4.6
minimum circumscribed circle centre
MCC centre
centre of the smallest circle that will just contain the error motion polar plot

NOTE 1 Unless otherwise specified, the polar profile centre is determined using the synchronous error motion polar plot.

NOTE 2 A workpiece is centred with *zero centring error* when the polar chart centre coincides with the chosen polar profile centre.

3.5 Error motion value

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

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 3.5.1 to 3.5.7 are presented in terms of polar plots to aid in understanding the phenomena and the computations. Mathematical analysis allows values to be calculated without constructing polar plots.

3.5.1
total error motion value

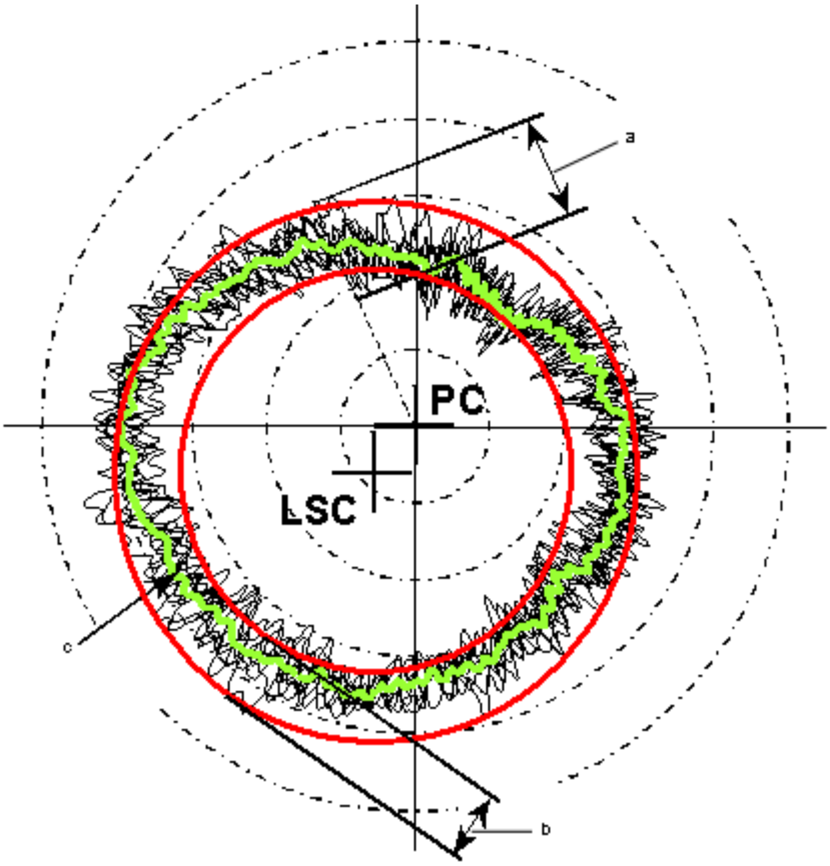
scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the total error motion polar plot

NOTE Four total error motion values are defined: total radial error motion, total tilt error motion, total axial error motion and total face error motion.

3.5.2
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

See Figure 6.



[a] Asynchronous error motion value.

[b] Synchronous error motion value.

[c] Synchronous error motion plot.

Figure 6 — Error motion polar plot, asynchronous error motion and synchronous error motion values

3.5.3
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

See Figure 6.

NOTE 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 6.)

3.5.4
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 Alternatively, it is the amplitude of the rotational frequency component.

NOTE 2 There is no fundamental radial error motion value — in the radial direction, motion that occurs at the rotational frequency is caused by an off-centre reference artefact and is not a property of the axis of rotation.

3.5.5
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

3.5.6
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.

3.5.7
outer error motion value
the scaled difference in radii of two concentric circles from a specified error motion centre just sufficient to contain the outer error motion polar plot.

3.6 Structural error motion

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

NOTE Structural error motion can be reaction to the rotation of the spindle that can influence the measurements.

3.6.1
structural error motion with rotating spindle
motion of one element of a structural loop relative another element, measured while the spindle is rotating

NOTE In some machines the spindle drive system may transmit large deflections to the structure.

3.6.2
structural error motion with non-rotating spindle
motion of one or more elements of a structural loop relative to the axis of rotation, measured while the spindle is not rotating

NOTE 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.

3.6.3
structural error motion plot
time-based rectilinear displacement plot is the most common method of recording structural motion

NOTE However, a polar plot may be desired in order to resolve structural error motion, which is synchronous to spindle rotation.

3.6.4
structural motion value
range (max. – min.) of displacement measured over a defined time and specified operating conditions

3.7 Axis shift caused by speed change

3.7.1
radial shift
axis shift in the direction perpendicular to the axis average line

3.7.2
tilt shift
axis shift in an angular direction relative to the axis average line

3.7.3
axial shift
axis shift in the direction parallel to the axis average line

3.7.4
face shift
combination of axial and tilt shifts in the axis of rotation measured at a specified radial location

3.7.5
speed-induced axis shift plot
rectilinear graph of the shift in the axis of rotation as rotational speed is varied

3.7.6
speed-induced axis shift value
difference between the maximum and minimum displacement measurements of 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 are expressed in millimetres, all linear deviations (error motions) are expressed in micrometres. Furthermore, all angular dimensions are expressed in degrees and all angular deviations (error motions) in microradians or arcseconds.

4.2 Reference to ISO 230-1

To apply this part of ISO 230, reference should be made to ISO 230-1, especially for the installation of the machine before testing, warming up of moving parts and recommended accuracy 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 greater accuracy may be used.

a) Non-contact displacement (proximity) measuring system 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. Proportionally higher bandwidths are required for higher spindle speeds.

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, overhead heaters.

4.5 Axis of rotation to be tested

The axis of rotation 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. Tests of the same spindle unit in different machines might generate different results due to mounting, thermal effects and vibration conditions.

4.6 Axis of rotation 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.

5 Error motion test methods

5.1 General

Error motions in the 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 perpendicular to the sensitive direction are considered to be in the non-sensitive direction and are not evaluated. However, there could be second order effects that are significant in some cases (such as turning very small parts.)

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 Structural motion, spindle off

5.3.1 General

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

5.3.2 Test procedure

The test setup is the same as for the ETVE test as described in ISO 230-3:—, 5.2.

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

5.3.3 Analysis of results

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

5.4 Spindle tests — Rotating sensitive direction

5.4.1 General

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

5.4.2 Radial error motion

5.4.2.1 Test setup

Figure 7 schematically represents a test setup for the measurement. In this setup, a precision test ball or other suitable artefact such as a cylinder, is mounted in the machine spindle. Displacement sensors are mounted to the table of the machine in orthogonal orientations. The ball is centred on the axis of rotation to minimize eccentricity. 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 ball 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. The setup for this latter case is shown in Figure 8.

5.4.2.2 Test procedure

Radial error motion measurements shall be carried out at three spindle speeds 2):

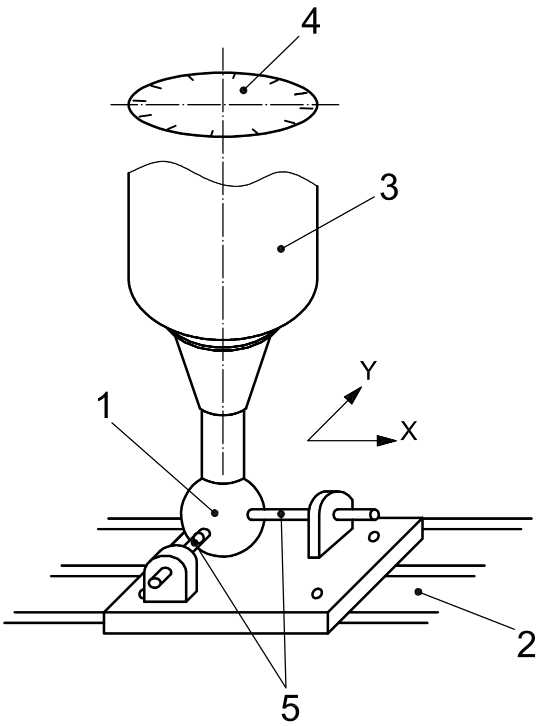
a) rotate spindle at 10 % of maximum speed or at minimum speed and record both displacement sensors readings as a function of spindle angular position;

b) rotate spindle at 50 % of maximum speed and record both displacement sensors readings as a function of spindle angular position;

c) rotate spindle at 100 % of maximum speed and record both displacement sensors readings as a function of spindle angular position.

---

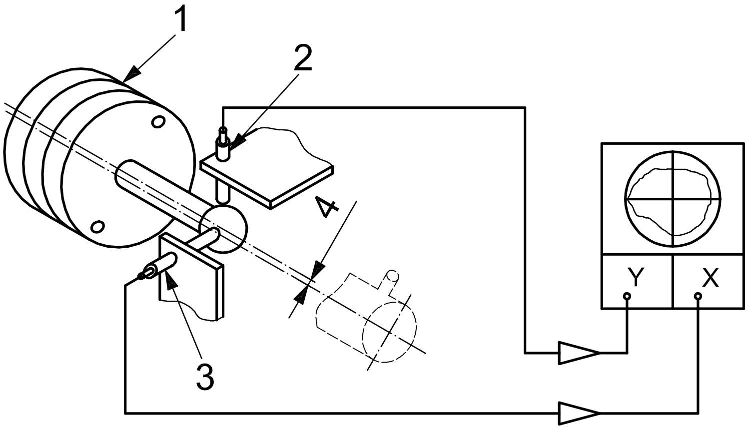
2) It is recommended that the machine user simply observe the output of the error-indicating system while changing the spindle speed slowly throughout its total speed range. Speeds could be observed where excessive error motion results due to structural error motion. Where such speeds exist, they should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



Key

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

Figure 7 — Schematic of test setup for radial error motion with rotating sensitive direction using angular position measuring device and centred reference artefact (ball) (Vanherck/Peters method)



Key

1 wobble plate
2 vertical sensor
3 horizontal sensor
4 master ball offset in direction of tool

Figure 8 — Test method for radial motion with rotating sensitive direction and ball mounted eccentric to the spindle (Tlusty method)

5.4.2.3 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 displacement sensors located perpendicular to each other and by computing and displaying the error motion polar plot according to the following formula:

$$r(\theta) = r_0 + \Delta \mathrm{X}(\theta) \cos\theta + \Delta \mathrm{Y}(\theta) \sin\theta$$

where

θ is the angular position of the spindle;

$r(\theta)$ is the radial error motion at angular position θ;

$\Delta \mathrm{X}(\theta)$ is the output of the displacement sensor oriented with the X axis;

$\Delta \mathrm{Y}(\theta)$ is the output of the displacement sensor oriented with the Y axis;

r_0 is the value of the radius set by the alignment of the displacement sensors and the test artefact.

At each speed a polar plot of the spindle error motion shall be made for a sufficient number of revolutions [3]. A typical plot for a single spindle speed is shown in Figure 4 a). 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 4 c) and Figure 6. Next, 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 4 b) and Figure 6. 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 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 speeds shall be reported.

5.4.3 Tilt error motion

5.4.3.1 Test setup

Measurement of the tilt error motion requires measurements of the radial error motion at two spatially separated points, as shown in Figure 9. A test artefact with two balls spaced some distance apart or a cylindrical mandrel may be attached to the spindle and aligned to the axis of spindle rotation. The recommended minimum distances between the balls/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 sensors and Method 2 describes using four sensors for measuring tilt. Both procedures are acceptable.

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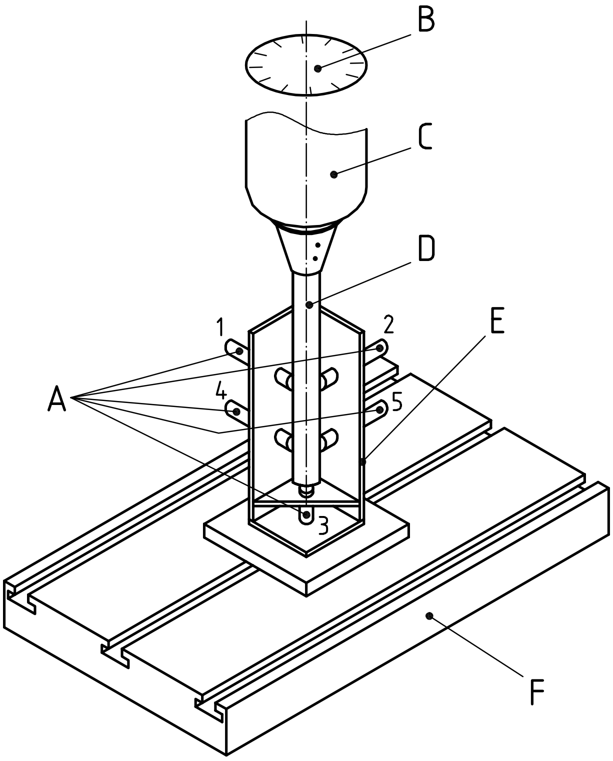
3) For spindles the minimum is 20 revolutions, for rotary tables the minimum is four revolutions in the clockwise and four in the anticlockwise (counter-clockwise) direction; for rotary heads and swivelling tables the minimum is two rotations in the clockwise and two in the anticlockwise (counter-clockwise) direction.



Key

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

Figure 9 — Five-sensor test system for measurement of rotating sensitive direction spindle error motions

Table 2 — Recommended minimum axial separation between balls/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

5.4.3.2 Test procedure — Method 1

First, mount a test ball or other artefact and displacement sensors according to 5.4.2.1, and carry out radial error motion measurements at three spindle speeds:

a) rotate the spindle at 10 % of maximum speed[4] (or at minimum speed, whichever is higher) and record both displacement sensor readings as a function of spindle angular position;

b) rotate the spindle at 50 % of maximum speed and record both displacement sensor readings as a function of spindle angular position;

c) rotate the spindle at 100 % of maximum speed and record both displacement sensor readings as a function of 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 10 % (or at minimum speed, whichever is higher), 50 % and 100 % of maximum speed.

5.4.3.3 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 5.4.2.3. 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.

5.4.3.4 Test procedure — Method 2

Mount the test artefact and displacement sensors according to 5.4.3.1, and carry out measurements at three spindle speeds:

a) rotate the spindle at 10 % of maximum speed[5] (or at minimum speed, whichever is higher) and record all displacement sensor readings as a function of spindle angular position;

b) rotate the spindle at 50 % of maximum speed and record all displacement sensor readings as a function of spindle angular position;

c) rotate the spindle at 100 % of maximum speed and record all displacement sensor readings as a function of spindle angular position.

5.4.3.5 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 5.4.2.3. 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 5.4.2.3 and r_0 is set equal to zero (note that sensor No. 3 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 5.4.2.3. The asynchronous error motion, in radians, is obtained by dividing the asynchronous error by the distance between the sensors in the test setup.

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[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.

5.4.4 Axial error motion

5.4.4.1 Test setup

Figure 10 schematically represents a test setup for the measurement. In this setup, a precision test ball is mounted in the machine spindle. A displacement sensor is mounted to the table of the machine axially against the test ball. The ball is centred on the axis of rotation to minimize eccentricity. The angular position of the spindle is measured using an angle-measuring device such as a rotary encoder mounted on the spindle.

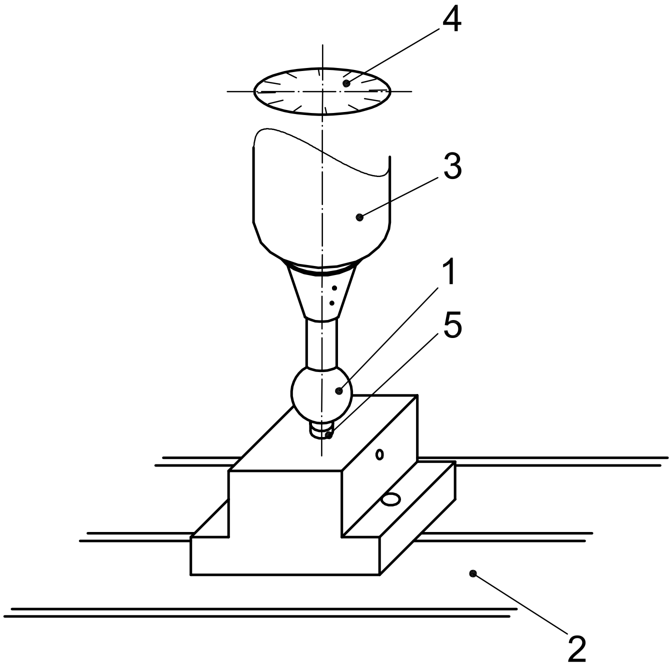
5.4.4.2 Test procedure

Position the displacement sensor as indicated in the axial position as shown in Figure 10.

Rotate the spindle at 10 % (or at minimum speed, whichever is higher), 50 % and 100 % of maximum speed [5] and record the displacement sensor readings as a function of spindle angular position.

5.4.4.3 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 (eccentricity) should not be removed analytically. The axial error motion may be presented on a linear plot of error motion versus spindle angular orientation. The asynchronous axial error motion shall be the maximum range of the displacement over a sufficient number of revolutions [5] of the spindle. The synchronous axial error motion shall be the range of the synchronous error motion values, defined with respect to the least-squares centre.



Key

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

Figure 10 — Setup for axial error motion measurement

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[5] For spindles the minimum is 20 revolutions, for rotary tables the minimum is four revolutions in the clockwise and four in the anticlockwise (counter-clockwise) direction; for rotary heads and swivelling tables the minimum is two rotations in the clockwise and two in the anticlockwise (counter-clockwise) direction.

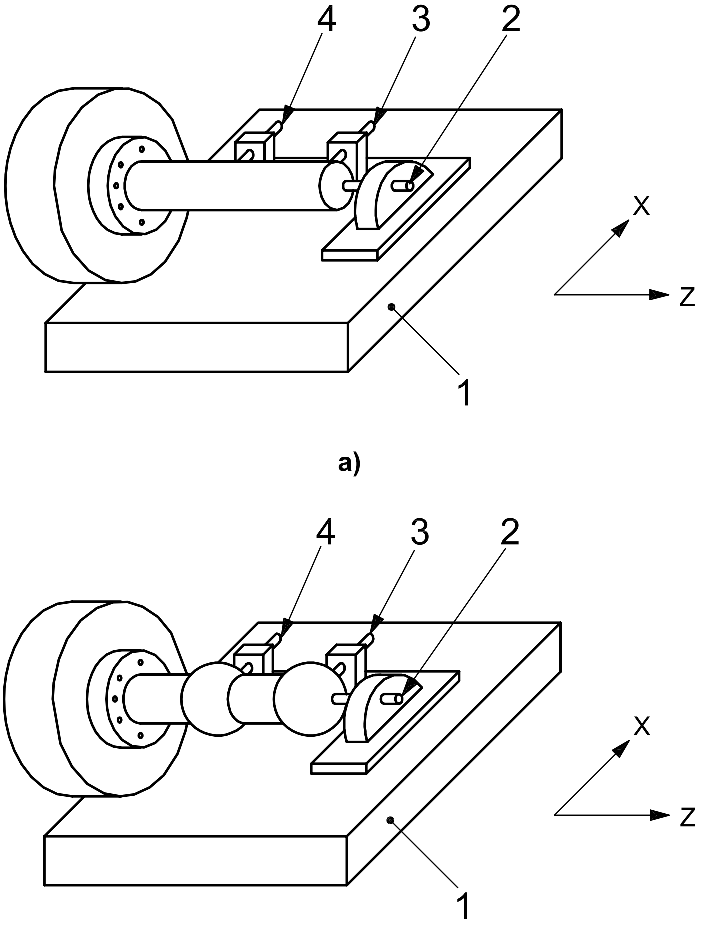
5.5 Spindle tests — Fixed sensitive direction

5.5.1 General

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

5.5.2 Test setup

Figure 11 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 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 either in a computer or on an oscilloscope.) A precision test ball, 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 ball or artefact should be centred around the axis of rotation so as to minimize eccentricity. Note that eccentricity can be mistaken for fundamental axial error motion.



a)

b)

Key

1 cross slide

2 axial sensor

3 radial sensor 2

4 radial sensor 1

Figure 11 — Test setups used for measuring spindle fixed sensitive direction error motion

5.5.3 Radial error motion

5.5.3.1 Test procedure

The radial error motion shall be measured by positioning the displacement sensor in the radial direction, as shown in Figure 11.

Radial error motion measurements shall be made at three spindle speeds after the spindle has been allowed a warm-up period at half maximum revolutions per minute for a period of 10 min. The spindle speeds chosen for this test shall be 10 % (or at minimum speed, whichever is higher), 50 %, and 100 % of the recommended maximum spindle speed 6). At each speed a polar plot of the spindle error motion shall be made for a sufficient number of revolutions 7).

5.5.3.2 Data analysis

At each speed a polar plot of the spindle error motion shall be made for a sufficient number of revolutions 8). A typical plot for a single spindle speed is shown in Figure 4 a). It must 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 6. Next, 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 4 (b) and Figure 6. 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.

5.5.4 Axial error motion

5.5.4.1 Test procedure

The axial error motion shall be measured by positioning the displacement sensor in the axial direction, as shown in Figure 11. 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 5.4.4.1.

5.5.4.2 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 (eccentricity) should not be removed analytically. The axial error motion may be presented on a linear plot of error motion versus spindle angular orientation. The asynchronous axial error motion shall be the maximum range of the displacement over a sufficient number of revolutions 8) of the spindle. The synchronous axial error motion shall be the range of the synchronous error motion values, defined with respect to the least-squares centre.

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6) 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.

7) For ball and roller bearing spindles a higher number of revolutions — up to several hundred — is recommended for properly assessing error motions.

8) For spindles the minimum is 20 revolutions, for rotary tables the minimum is four revolutions in the clockwise and four in the anticlockwise (counter-clockwise) direction; for rotary heads and swivelling tables the minimum is two rotations in the clockwise and two in the anticlockwise (counter-clockwise) direction.

5.5.5 Tilt error motion

5.5.5.1 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 11, using radial sensors 1 and 2. A test artefact with two balls with their centres spaced some distance apart (see Table 2) or a precision test mandrel may be attached to the spindle and precisely aligned to the axis of spindle rotation in order to minimize eccentricity.

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.

5.5.5.2 Test procedure — Method 1

Mount the test ball or mandrel and a displacement sensor in accordance with 5.5.2 and carry out radial error motion measurements at three different spindle speeds:

a) rotate the spindle for a sufficient number of revolutions [10)] at 10 % of maximum speed (or at minimum speed, whichever is higher) and record the displacement sensor readings as a function of spindle angular position;

b) rotate the spindle at 50 % of maximum speed and record the displacement sensor readings as a function of spindle angular position;

c) rotate the spindle at 100 % of maximum speed and record the displacement sensor readings as a function of spindle angular position.

Next, remount the ball or mandrel and sensor at a distance of 50 mm to 100 mm away from the previous location and perform a second set of measurements.

5.5.5.3 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 5.5.3.2. The difference in the radial error motion measurements divided by the distance between them is defined as the synchronous tilt motion error. The difference in the asynchronous radial error motion divided by the length is defined as the asynchronous tilt motion error in radians.

5.5.5.4 Test procedure — Method 2

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

The spindle shall be run for a sufficient number of revolutions [10)] at the three spindle speeds selected, as in 5.5.4.2, and the differences between the two readings (sensor 1 and sensor 2) plotted on a polar plot.

5.5.5.5 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 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:

$$\beta(\theta) = \left[r_2(\theta) - r_1(\theta)\right] / L_\mathrm{d}$$

where

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

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

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

L_d is the distance between the centres of the two displacement sensors;

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

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

Annex A
(informative)

Discussion of general concepts

A.1 Introduction

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 will use 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 or measuring device components — rotary tables, trunnion bearings, live centres and so on.

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 may 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 must be 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, a term that will refer to the mechanical components which maintain the relative position between the workpiece and the tool (the chuck, spindle shaft, spindle bearings, headstock, frame, slides and tool post in the present example).

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 A.1 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 contrast to a machine such as a lathe, another basic type of machine exists in which the workpiece is fixed and the cutting tool rotates, such as a boring machine. Since the sensitive direction is always parallel to a line through the point of machining, the sensitive direction rotates with the tool (Figure A.2). As will be discussed in A.11 and A.12, 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.

A.2.5 Displacement sensors versus tools

The above examples all referred to cutting tools. The term “tool” must 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 or a measuring device:

“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)”.

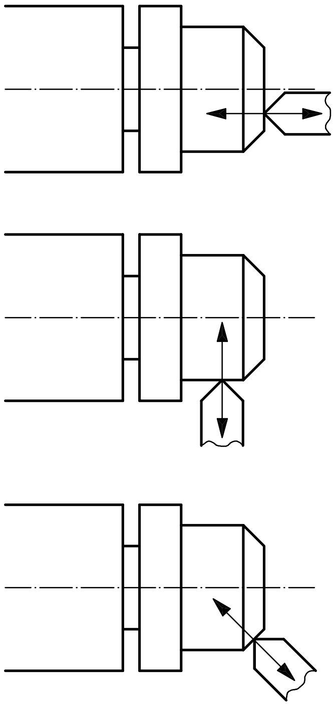


Figure A.1 — Illustration of sensitive direction in facing, turning and chamfering

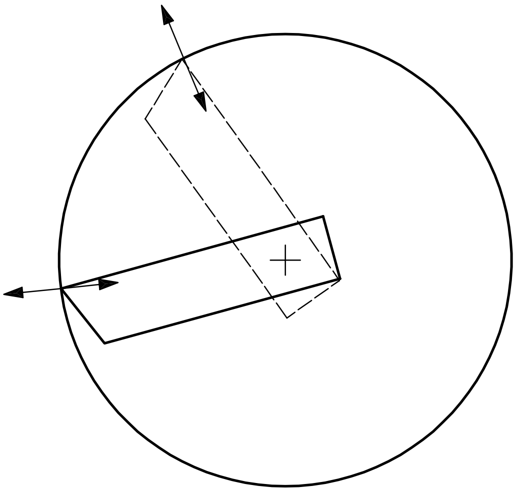


Figure A.2 — Illustration of rotating sensitive direction at two instants in time in jig-boring a hole

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.3. 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. The following formula is useful in estimating this error. Let

E_N = motion in the non-sensitive direction

E_s = error in the sensitive direction due to E_N

R = part radius

Then

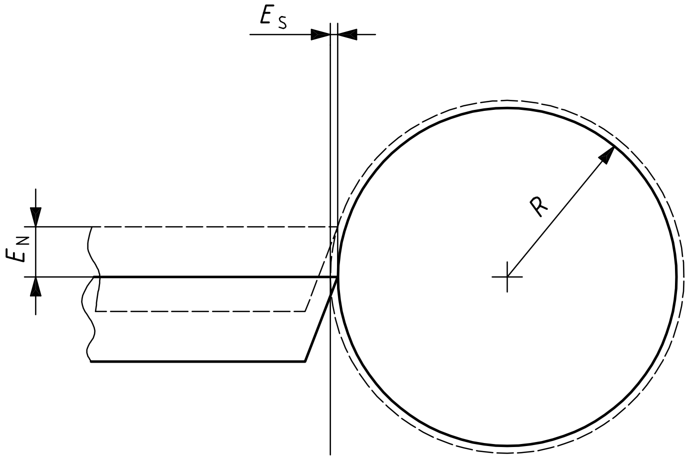
$$E_S = \frac{(E_N)^2}{2R} \quad \text{(if } E_N \text{ is small compared to } R\text{)} \qquad \text{(A.1)}$$

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 (20 nm) 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.



Non-sensitive direction

Figure A.3 — 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" will be 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 subsequently 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 micrometer. 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 drift

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 drift. Thermal drift 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 drift 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.4. 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.

In general, the workpiece has six degrees of freedom, consisting of three linear motions and three angular motions as shown individually in Figure A.5, 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, shown in Figure A.1, it can be concluded that the sensitive direction always lies in the plane of 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 and measuring devices where the workpiece rotates shows that in virtually all 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 EYC(t) and EAC(t) are always in a non-sensitive direction and can be ignored. In other words, the only motions of concern are the motions EXC(t), EZC(t) and EBC(t) which appear in the X′-Z′ projection plane. The terms given in A.6.2 to A.6.4 will be used [9].

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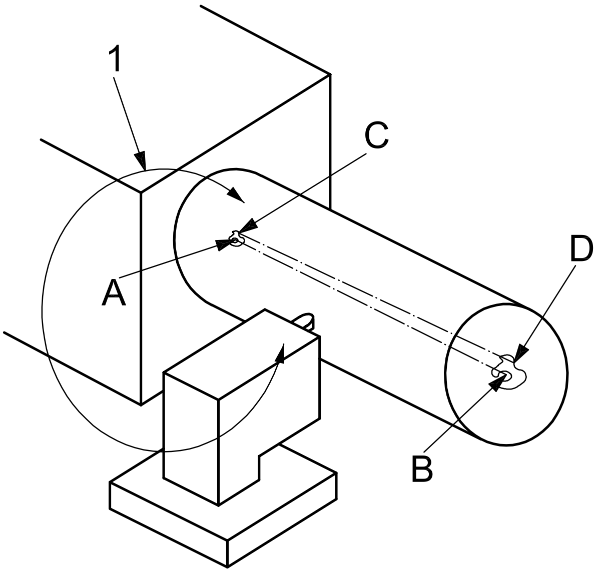
[9] For a lathe, the coordinate system shown in Figure A.5 is in accordance with ISO 841. According to ISO 841, “The positive direction of movement of a component is that which causes an increasing positive dimension of the workpiece [see Fig. A.5 b)]. On the schematic drawings of the machines, an unprimed 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 document, in order to simplify the reading, these motions are represented without prime (′) notations.



Key

1 structural loop

AB axis average line

CD axis of rotation at time *t*

Figure A.4 — Axis of rotation example: AB fixed relative to tool, CD imbedded in workpiece

A.6.2 Pure radial error motion

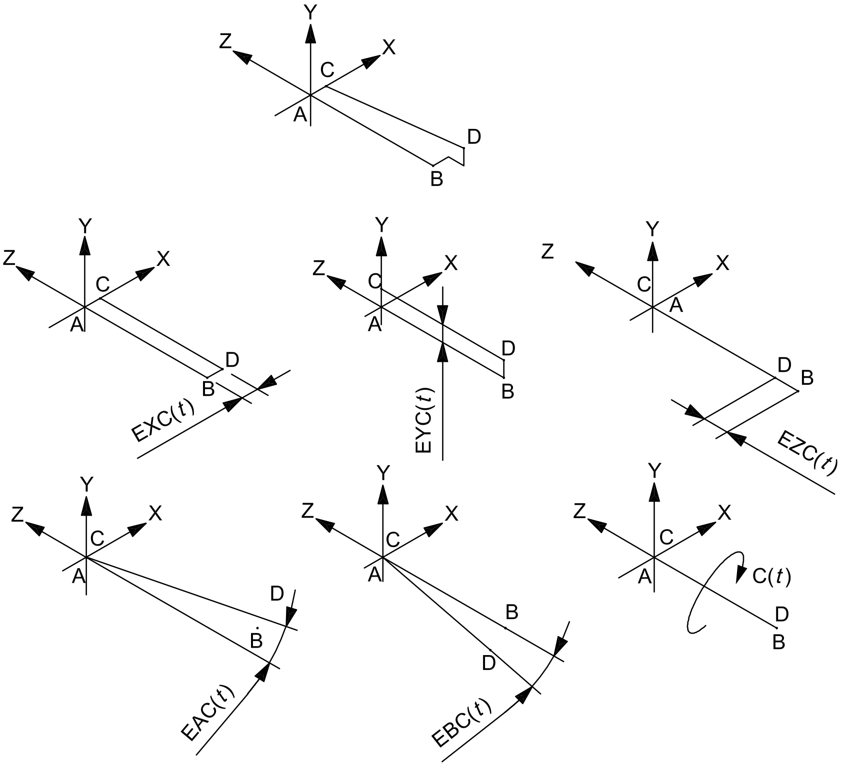
Motion EXC(*t*) in Figure A.5 a), in which the axis of rotation remains parallel to the axis average line and moves perpendicular to it in the sensitive direction.

A.6.3 Axial error motion

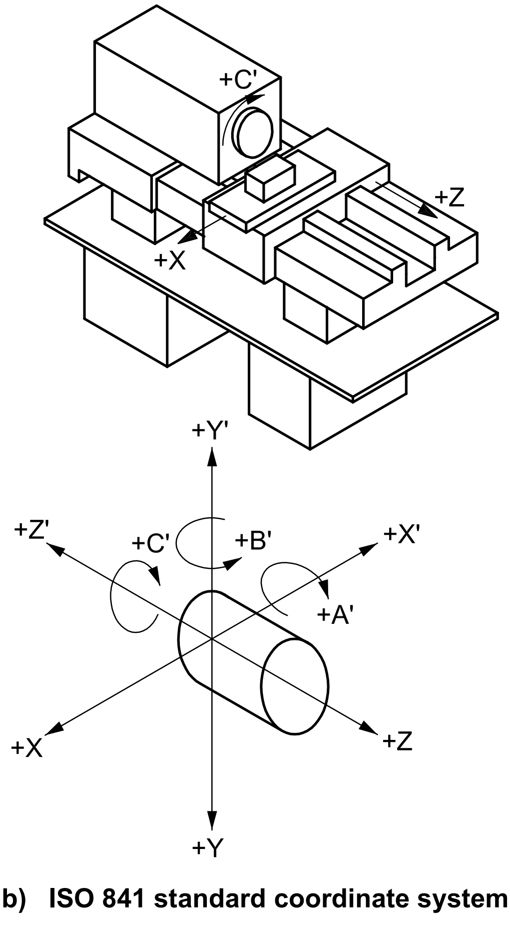
Motion EZC(*t*) in Figure A.5 a), in which the axis of rotation remains co-axial with the axis average line and moves axially with respect to it.

A.6.4 Tilt error motion

Motion EBC(*t*) in Figure A.5 a), in which the axis of rotation moves angularly with respect to the axis average line and in the plane of the axial and pure radial error motions.



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.5 — Designation of axis of rotation error motion for a lathe

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 $\mathrm{EX_0C}(t)$ at one axial position and tilt error motion $\mathrm{EBC}(t)$ allows the radial error motion $r(t)$ at another axial position to be predicted as shown in Figure A.6 a),

$$\mathrm{EXC}(t) = \mathrm{EX_0C}(t) + L \times \mathrm{EBC}(t) \quad [\text{assuming } \mathrm{EXC}(t) \ll L] \tag{A.2}$$

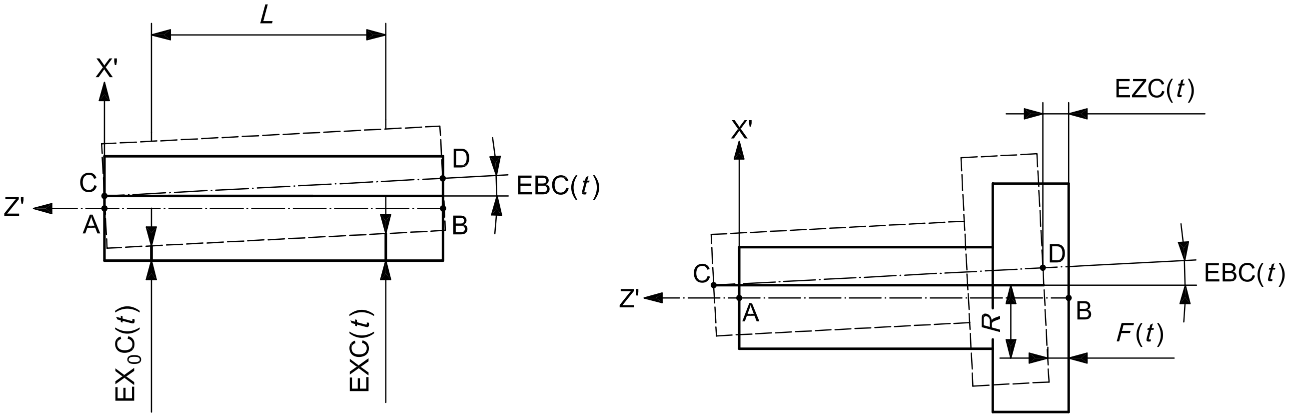
where L is the distance between the two axial locations. Since radial error motion varies with axial position, it is necessary to specify the axial location of a radial error motion measurement.

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.6 b). Face motion $F(t)$ is related to axial and tilt error motion:

$$F(t) = \mathrm{EZC}(t) - R \times \mathrm{EBC}(t) \qquad [\text{assuming } F(t) \ll R] \tag{A.3}$$

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



a) Radial error motion variation with axial distance

b) Face motion variation with radius

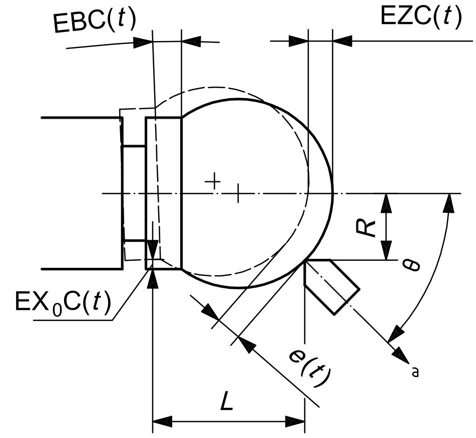
Figure A.6 — Geometry of radial error and face motion

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.7. The error motion depends on both the axial and radial locations, which must be specified together with θ. The Equation for error motion $e(t)$ in terms of axial, radial and tilt motion is

$$e(t) = \mathrm{EXC}(t)\ \sin\theta + F(t)\ \cos\theta$$

$$\mathrm{EX_0C}(t)\ \sin\theta + \mathrm{EZC}(t)\ \cos\theta + \mathrm{EBC}(t)\ (L\ \sin\theta - R\ \cos\theta) \qquad \text{(A.4)}$$



a Sensitive direction.

Figure A.7 — General case of error motion

It can be seen from Equations (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 EZC(t), tilt error motion EBC(t), and radial error motion $\mathrm{EX_0C}(t)$ at a known axial position.

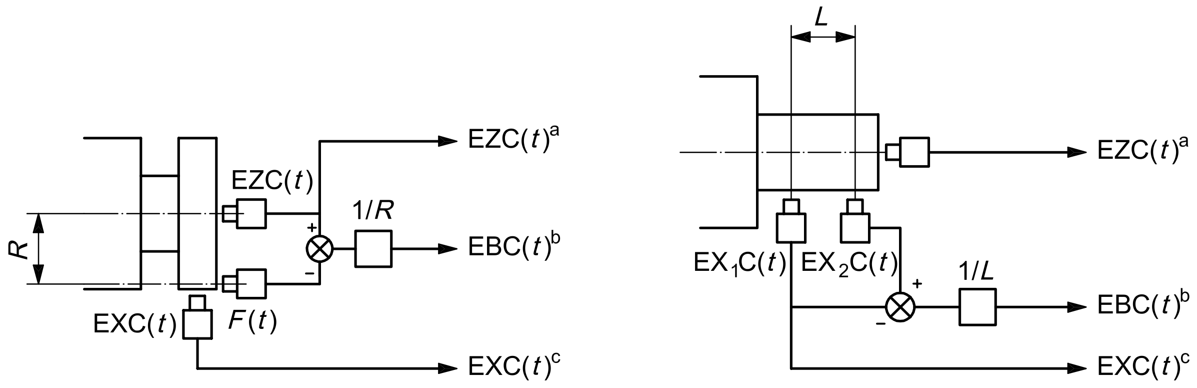
Figure A.8 shows schematic diagrams of two test arrangements, which can be used to measure the necessary error motions. In both cases, the radial and axial error motions are measured directly using non-contact displacement sensors. In Figure A.8 a), tilt error motion is derived from face motion by use of Equation (A.3),

$$\mathrm{EBC}(t) = (1/R)\ [\mathrm{EZC}(t) - F(t)] \qquad \text{(A.5)}$$

In Figure A.8 b), a second radial error motion measurement is used to obtain tilt error motion from Equation (A.2),

$$\mathrm{EBC}(t) = (1/L)\ [\mathrm{EX_2C}(t) - \mathrm{EX_1C}(t)] \qquad \text{(A.6)}$$

It should be noted that pure radial error motion EXC(t) does not appear in any of the above Equations. 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) Test arrangement using radial, face and axial error motion measurements

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

a Axial.

b Tilt.

c Radial.

Figure A.8 — 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*) [see Figure A.5 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 master test ball;

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.9 a) shows a test arrangement involving a master test ball (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.9 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.9 c) shows a rectilinear plot of the radial error motion measured by the displacement sensor versus angle of rotation as a result of the figure-eight pattern, which motion of the ball from the displacement sensor being positive (for the normal convention, see ISO 841). Figure A.9 d) shows the same data as Figure A.9 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.7.3 Average radial error motion and part roundness

If the displacement sensor in Figure A.9 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.9 d) as shown in Figure A.10. The out-of-roundness of the two charts is identical, and hence the radial error motion polar plot of a machine tool 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 runout 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.10).

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 A.11 a) shows a more typical case of error motion, which is non-repetitive. Figure A.11 a) is known as a total error motion polar plot. Figure A.11 b) shows a synchronous error motion polar plot, which is obtained from Figure A.11 a) by averaging the radial error motion at each angular position over the number of revolutions recorded. Figure A.11 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 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.

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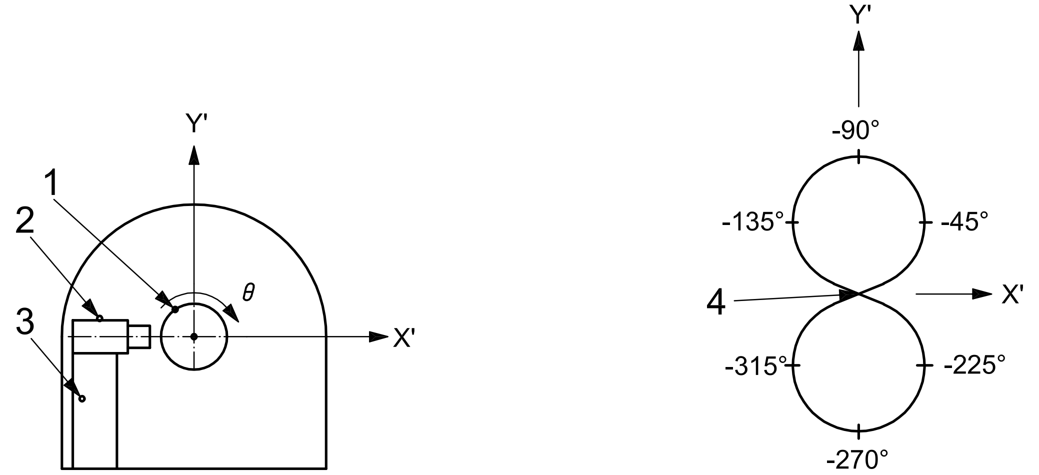
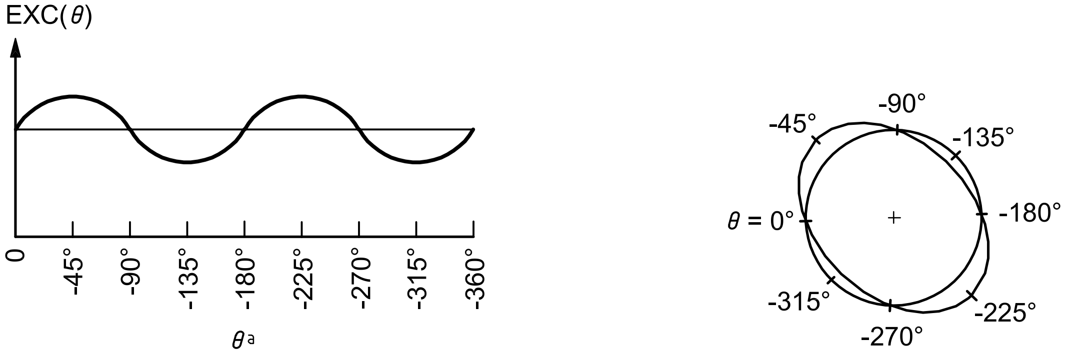
[10] It is important to note that for a lathe the normal rotation of the spindle is in the negative sense of θ.



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 masterball

2 displacement sensor

3 tool post

4 X, Z reference axis

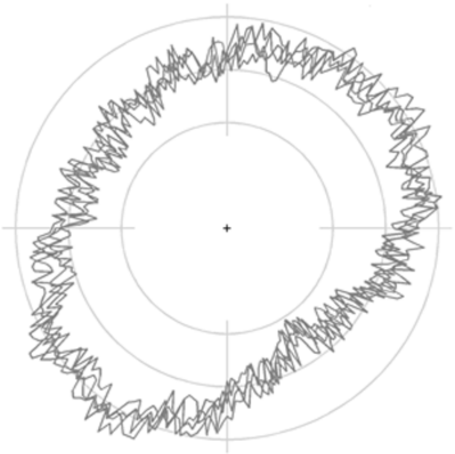
[a] Angle of rotation.

Figure A.9 — Hypothetical example of radial error motion measurement and plotting

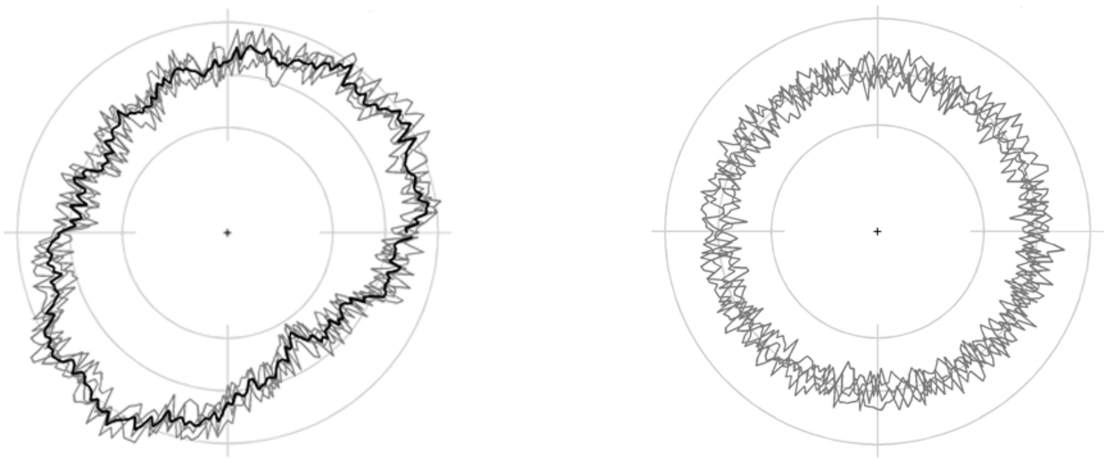
a) Radial error motion polar plot

b) Part roundness profile

Figure A.10 — Relationship of radial error motion to part roundness for example of Figure A.9

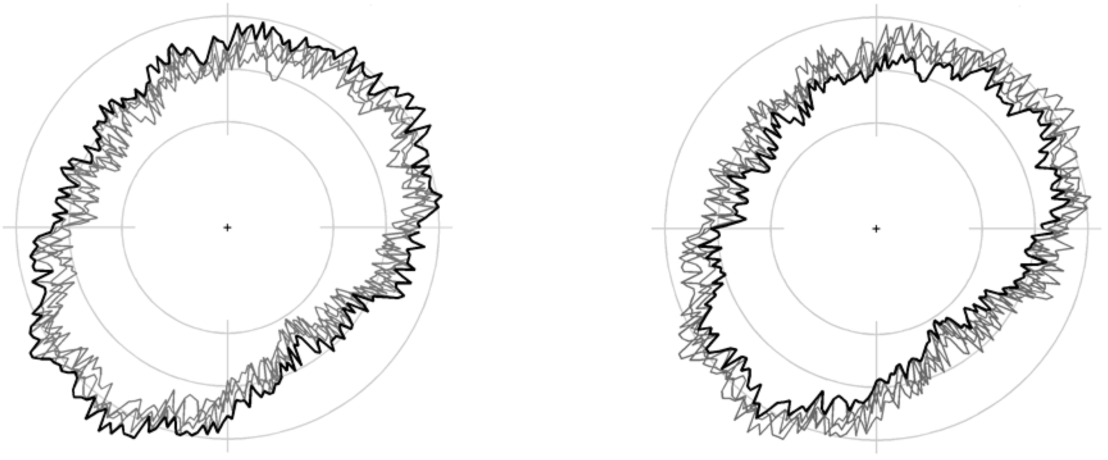


a) Total error motion



b) Synchronous error motion

c) Asynchronous error motion



d) Outer error motion

e) Inner error motion

Figure A.11 — Total, synchronous, asynchronous, inner and outer error motion polar plots

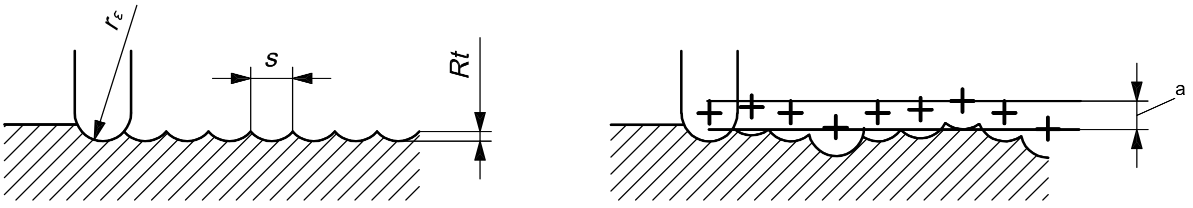
A.7.4 Asynchronous error motion and surface roughness

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.12 a), which is referred to as the "theoretical finish". The peak-to-valley height Rt 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 Rt can easily be made quite small, e.g. if $s = 0{,}02$ mm/rev and $r_\varepsilon = 5$ mm, then $Rt = 0{,}01$ µm.

However, if asynchronous error motion is present, then the surface is cut to varying levels on successive revolutions as in Figure A.12 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 Rt from Equation (A.7) represents the potential peak-to-valley surface roughness for the machine under ideal cutting conditions, with the Ra (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.9) 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 A.11 e). For operations inside a cylindrical bore, the outer error motion polar plot has a similar significance [see Figure A.11 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 Asynchronous error motion.

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

Figure A.12 — 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 machine, 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 axis bearings and the axis 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 frequencies present can be determined more easily by polar plots of one or a few revolutions to avoid overlapping traces. Rectilinear time base records are also useful for determining frequencies, but can complicate the separation of synchronous and asynchronous error motion components.

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 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.

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 term, which will be used to refer to the once-per-revolution sinusoidal component of an error motion polar plot, is fundamental error motion. Since a test ball is perfectly centred when this component vanishes, it follows that fundamental radial error motion of an axis of rotation does not exist.

Similarly, fundamental tilt error motion does not exist. 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”,

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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: $x = 2 R_b/R_i$.

“wobble” and “swash” suggest a once-per-revolution component, they are inappropriate names for tilt error motion.

In contrast, fundamental axial error motion does exist, and is not caused by a master ball mounting-error as with centring error. 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.

Reference to Equation (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 in 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 existence of 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 Equation 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 may 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.12 a)].

Asynchronous error motion, on the other hand, is motion of the tool with respect to the spindle at frequencies other than whole number 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.12 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 Test master errors

Thus far it has been assumed that a geometrically perfect master test ball or equivalent was being used in the various error motion measurement examples. It is clear that the geometry errors in a master will cause erroneous error motion measurements, and it cannot always be assumed that the master has negligible errors, since high quality axes of rotation may have error motions of the order of 0,02 µm. Appendix B describes a method for separating the errors of the master from the synchronous error motion component of the axis of rotation.

A.10 Error motion versus runout or TIR

It should be noted that error motion measurements differ from measurements of runout or TIR (total indicator reading) in several respects. It is important to understand these differences, since runout tests have been used extensively in the past in assessing the accuracy of rotational axes. Runout 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 runout 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 runout larger than the error motion, it is possible for roundness errors to make the runout 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 runout; the latter measurement includes non-squareness and circular flatness errors (see also A.7.6.)

A.11 Rotating sensitive direction measurements

As noted in A.2.4, the sensitive direction rotates with respect to the machine frame in those cases in which the workpiece is supported from the machine frame and the tool is supported from the axis of rotation. Boring machines are examples of machines having a rotating sensitive direction.

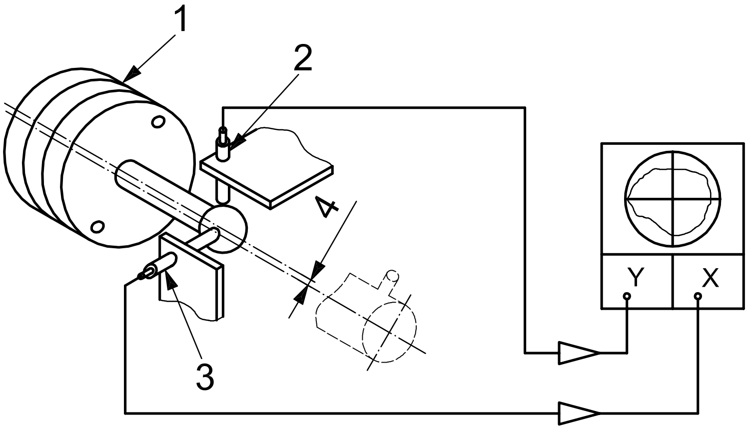
In principle, the same concepts regarding error motion of an axis of rotation apply for a rotating sensitive direction as for a fixed sensitive direction. This clause will deal with the differences involved in measuring and displaying the error motion polar plot.

Axial error motion is the only measurement which is independent of whether the sensitive direction is fixed or rotating, and hence is most easily measured by a fixed displacement sensor sensing along the axis average line.

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 master test ball 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 or their equivalent are necessary.

For high-speed axes, the frequency response of polar recorders is usually inadequate, since the polar plot may contain frequencies orders of magnitude higher than the axis rotational frequency. The oscilloscope with a camera attachment is a more suitable instrument, but since it employs rectilinear rather than polar coordinates, means must be provided to generate a base circle and to cause the error motion to appear as a radial deviation from the base circle.

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 A.13 is a schematic diagram showing horizontal and vertical displacement sensors which sense radially against a master test ball. The sensor signals are amplified and fed to the respective horizontal and vertical axes of the oscilloscope. By use of a wobble plate, the master ball 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 master ball eccentricity alters the shape of the oscilloscope display. Motion at right angles to the master ball 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 master ball. If the tool or sensor can be mounted on the axis in only one angular orientation, the master ball must be eccentric in this direction. If the orientation is arbitrary, then the axis should be tested with the ball eccentric in a number of different directions.



Key

1 wobble plate

2 vertical sensor

3 horizontal sensor

4 master ball offset in direction of tool

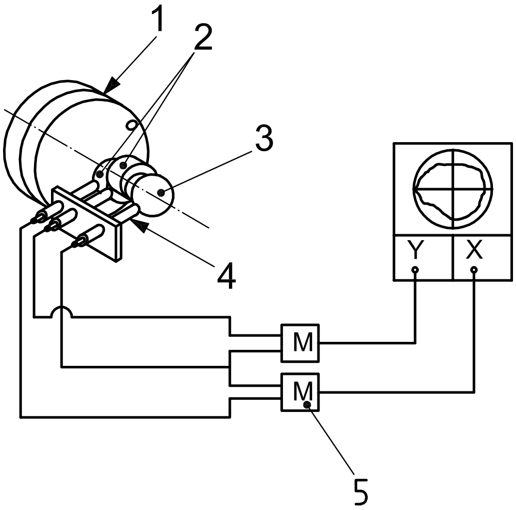
Figure A.13 — Test method for radial error motion with a rotating sensitive direction (Tlusty method)

A.12 Fixed sensitive direction measurements

Use of an oscilloscope for radial error motion measurement with a fixed sensitive direction requires a separate means for generating the base circle. Figure A.14 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 master test ball, 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. Vanherck[11] replaced the eccentric cams and low magnification sensors with a small commercial angular measuring device physically attached to the axis of rotation. The advantages are lower cost, less difficulty in obtaining an accurately round base circle and simplification of the test set-up, with negligible influence on the axis from the angular measuring device attachment except in the most exacting situations.

A.13 Considerations on use of two-displacement sensors system for fixed sensitive direction

Since the test method described by Bryan (see Figure A.14) requires special equipment, it is natural to consider substituting the two-displacement sensor system described by Tlusty (see Figure A.13) 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.



Key

1 wobble plate
2 circle generating cams
3 spherical master
4 displacement sensor
5 multiplier

Figure A.14 — Test method for radial error motion with fixed sensitive direction (Bryan method)

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 may be free of radial error motion when tested in a rotating sensitive direction. The case occurs for the following error motions:

$$\Delta \mathrm{X}(\theta) = -A \cos 2\theta \tag{A.8}$$

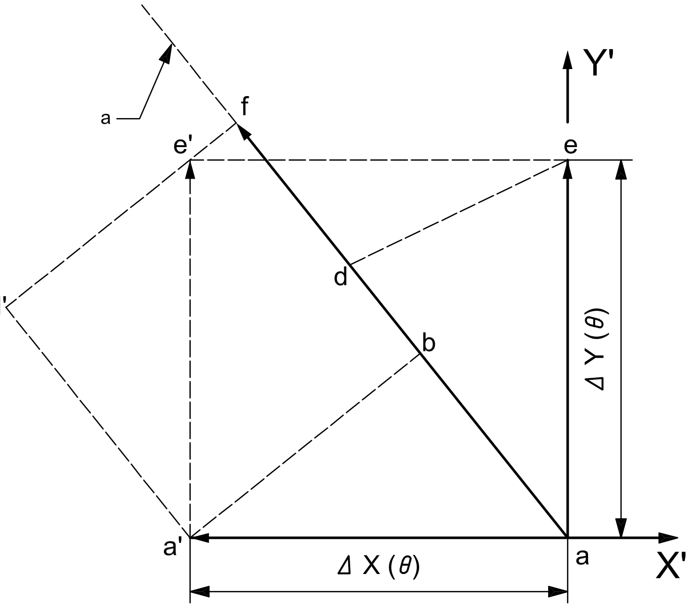
$$\Delta \mathrm{Y}(\theta) = A \sin 2\theta \tag{A.9}$$

where the coordinate system is that of Figure A.9 a). With a fixed sensitive direction along the X axis, the radial error motion polar plot has the Equation

$$r(\theta) = r_0 - A \cos 2\theta \tag{A.10}$$

where r_0 is the basic circle radius. Equation (A.10) 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 the Equation

$$r(\theta) = r_0 + \Delta\mathrm{X}(\theta)\ \cos\theta + \Delta\mathrm{Y}(\theta)\sin\theta \qquad \text{(A.11)}$$



$$\mathrm{ab} = \Delta\mathrm{X}(\theta)\cos\theta$$

$$\mathrm{ad} = \Delta\mathrm{Y}(\theta)\sin\theta = \mathrm{a'd'}$$

$$\begin{aligned}\mathrm{af} &= ab + \mathrm{a'd'} \\ &= \Delta\mathrm{X}(\theta)\cos\theta + \Delta\mathrm{Y}(\theta)\sin\theta\end{aligned}$$

[a] Sensitive direction.

Figure A.15 — Vector diagram for rotating sensitive direction

Figure A.15 shows the resolution of $\Delta\mathrm{X}(\theta)$ and $\Delta\mathrm{Y}(\theta)$ into components along the rotating sensitive direction that leads to Equation A.11. Combining Equations (A.8) and (A.9) with Equation (A.11) and using the trigonometric identities

$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha-\beta) + \cos(\alpha+\beta)] \qquad \text{(A.12)}$$

and

$$\sin\alpha\sin\beta = \frac{1}{2}[\cos(\alpha-\beta) - \cos(\alpha+\beta)] \qquad \text{(A.13)}$$

the result is

$$r(\theta) = r_0 + \frac{A}{2}\ [\cos\theta + \cos 3\theta] + \frac{A}{2}\ [\cos\theta - \cos 3\theta] = r(\theta) = r_0 + A\cos\theta \qquad \text{(A.14)}$$

Equation (A.14) 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 $2A$ 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 A.13. Secondly, the view might be taken that the above example is 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 Equations (A.8) and (A.9), these components will not contribute to the measured radial error motion value.

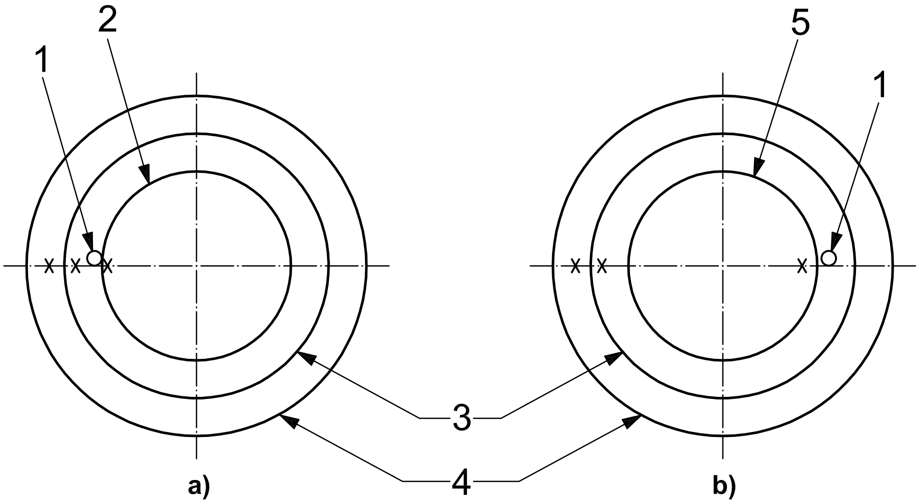
Annex B
(informative)

Elimination of master ball roundness error

B.1 Introduction

Measurements of radial error motion are directly influenced by the out-of-roundness of the test ball or circular master against which the displacement sensor senses. This annex presents a method for separating the out-of-roundness of the master 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 master and S(C) (for spindle) represents the radial error motion.



Key

1 displacement sensor
2 master
3 shaft
4 housing
5 reversed master

Figure B.1 — Schematic test setups for a) $T_1(C)$ [see Equation (B.1)] **and b) $T_{2P}(C)$** [see Equation (B.2)] **and $T_{2S}(C)$** [see Equation (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 master, 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 $T_1(C)$. 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 master, the displacement sensor, the shaft and the housing of the axis of rotation. The recorded value of $T_1(C)$ is the sum of the master 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 master. 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 master 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 must 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 master is recorded in the same manner, since the relative position of the displacement sensor and the master is unchanged. However, radial error motion is recorded with a reversed sign in Figure B.1b, 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 Equations (B.1) and (B.2) and solving for P(C) gives

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

Equation (B.3) states that the out-of-roundness profile of the master, 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 must 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 Equations (B.1) and (B.4) and solving for S(C) gives

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

Equation (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).

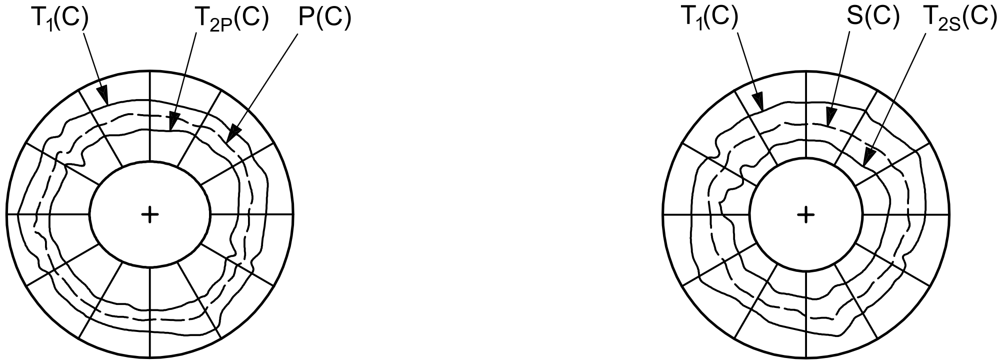
The following summarizes the above two procedures:

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

No mention was made of whether the master 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.

B.3 Profile subtraction method

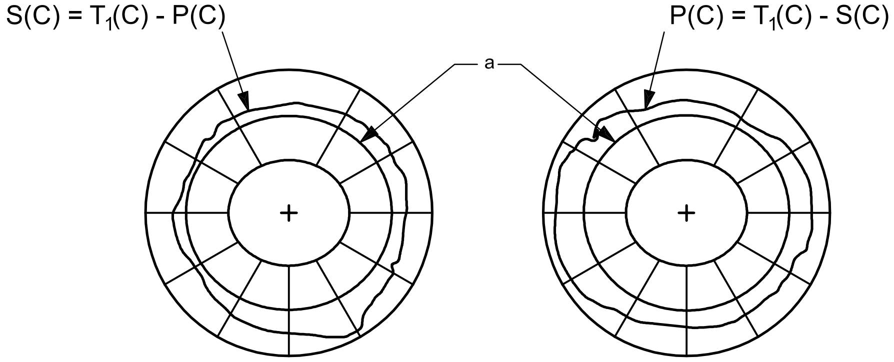
In some instances it may be reasonable to obtain only one of the polar plots $T_{2P}(C)$ and $T_{2S}(C)$. If either P(C) or S(C) has been obtained by averaging, the other of the two can be obtained by subtraction of the known profile from $T_1(C)$, as shown by Equation (B.1). Graphically, it is necessary 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) Master out-of-roundness P (C)

b) Radial error motion S (C)

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



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 master, this involves attention to details such as reversing both the master 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 $T_1(C)$ as the track is shifted by small amounts in the first setup.

In the presence of asynchronous radial error motion, S(C) must 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 $T_1(C)$ 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 master ball 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 thermal drift associated with rotation of spindle

D.1
radial thermal drift
drift applicable when the shift in the axis is measured perpendicular to the Z reference axis

D.2
tilt thermal drift
drift applicable to a tilt shift in the axis relative to the Z reference axis

D.3
axial thermal drift
drift applicable when the shift in the axis is coaxial with or parallel to the Z reference axis

D.4
face thermal drift
drift applicable to a combination of axial and tilt shifts in the axis measured at a specified radial location

D.5
thermal drift plot
time-based record of thermal drift

D.6
thermal drift 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

NOTE The specific thermal drift values are defined in ISO 230-3.

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

E.2.1 The test setup is similar to the ones described in 5.4 and 5.5.

E.2.2 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.

E.2.3 Rotate the spindle, by hand, a minimum of two revolutions, stopping at a minimum of eight points per revolution.

E.2.4 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 is analysed for the radial, tilt and axial error motion using methods described in 5.4 and 5.5.

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 may 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, Equation (F.1) applies.

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

where

U_{DEVICE}	uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
$U_{\text{CALIBRATION}}$	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 Equation (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, Equation (C.3).

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

where

U_{DEVICE}	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}	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 of ISO/TR 230-9:2005 Equations (1) to (7) and should use a coverage factor of $k = 2$. This estimation may 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), $U_{E\mathrm{VE}}$

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, shall 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 Equation (F.3), based on of ISO/TR 230-9:2005, Equation (C.9).

$$U_{E\mathrm{VE}} = 0{,}6 E_{\mathrm{VE}} \tag{F.3}$$

where

$U_{E\mathrm{VE}}$	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}	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, Equations (1), (3) and (A.7) of 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 of ISO/TR 230-9:2005, Equation (1):

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

where

$U_{\text{(single plot)}}$	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}	uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
$U_{E\text{VE}}$	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, Equations (A.7) and (1) together, this results in Equation (F.5):

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

where

$U_{\text{(synchronous plot)}}$	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}	uncertainty due to the measurement device in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
$U_{E\text{VE}}$	measurement uncertainty due to environmental variation in micrometres (µm) for linear and in micrometres per metre (µm/m) for angular measurement;
n	number of polar plots to calculate synchronous error motion polar plot.

NOTE 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, Equation (1), this results in Equation (F.6):

$$U_{\text{(single plot value)}} = 1{,}4U_{\text{(single plot)}} \tag{F.6}$$

where

$U_{\text{(single plot value)}}$	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;
$U_{\text{(single plot)}}$	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, Equation (1), this results in Equation (F.7):

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

where

$U_{\text{(synchronous plot value)}}$	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;
$U_{\text{(synchronous plot)}}$	uncertainty of synchronous error motion plot.

Annex G
(informative)

Alphabetical cross-reference of terms and definitions

Term	No.
asynchronous error motion	3.2.9
asynchronous error motion polar plot	3.3.3
asynchronous error motion value	3.5.3
axial error motion	3.2.13
axial error motion polar plot	3.3.5
axial shift	3.7.3
axis average line	3.1.10
axis of rotation	3.1.5
axis of rotation error motion	3.2.1
axis shift	3.1.11
bearing	3.1.4
bearing error motion	3.2.3
displacement sensor	3.1.12
error motion measurement	3.2.15
face error motion	3.2.14
face shift	3.7.4
fixed sensitive direction	3.1.16
fundamental axial error motion value	3.5.4
fundamental error motion	3.2.7
fundamental error motion polar plot	3.3.4
hysteresis	3.1.22
inner error motion polar plot	3.3.7
inner error motion value	3.5.6
least-squares circle (LSC) centre	3.4.3
maximum inscribed circle (MIC) centre	3.4.5
minimum circumscribed circle (MCC) centre	3.4.6
minimum radial separation (MRS) centre	3.4.4
non-sensitive direction	3.1.15
outer error motion polar plot	3.3.8
outer error motion value	3.5.7
perfect spindle	3.1.8

Term	No.
perfect workpiece	3.1.9
play	3.1.21
polar chart (PC) centre	3.4.1
polar profile centre	3.4.2
positive direction	3.1.7
pure radial error motion	3.2.11
radial error motion	3.2.10
radial shift	3.7.1
reference coordinate axes	3.1.6
residual synchronous error motion	3.2.8
residual synchronous error motion polar plot	3.3.6
residual synchronous error motion value	3.5.5
rotating sensitive direction	3.1.17
runout	3.1.18
sensitive direction	3.1.14
speed-induced axis shift value	3.7.6
speed-induced axis shift plot	3.7.5
spindle	3.1.2
spindle housing	3.1.3
spindle unit	3.1.1
squareness	3.1.20
static error motion	3.2.5
stationary point runout	3.1.19
structural error motion	3.2.2
structural error motion plot	3.6.3
structural error motion with non-rotating spindle	3.6.2
structural error motion with rotating spindle	3.6.1
structural loop	3.1.13
structural motion value	3.6.4
synchronous error motion	3.2.6
synchronous error motion polar plot	3.3.2
synchronous error motion value	3.5.2
tilt error motion	3.2.12
tilt shift	3.7.2
total error motion	3.2.4
total error motion polar plot	3.3.1
total error motion value	3.5.1

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