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**Test code for machine tools —**

Part 1:

**Geometric accuracy of machines  
operating under no-load or quasi-static  
conditions**

*Code d'essai des machines-outils —*

*Partie 1: Exactitude géométrique des machines fonctionnant à vide ou  
dans des conditions quasi-statiques*



Reference number  
ISO 230-1:2012(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 230-1 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This third edition cancels and replaces the second edition (ISO 230-1:1996), which has been technically revised.

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

- *Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*
- *Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*
- *Part 3: Determination of thermal effects*
- *Part 4: Circular tests for numerically controlled machine tools*
- *Part 5: Determination of the noise emission*
- *Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)*
- *Part 7: Geometric accuracy of axes of rotation*
- *Part 8: Vibrations [Technical Report]*
- *Part 9: Estimation of measurement uncertainty for machine tool tests according to series ISO 230, basic equations [Technical Report]*
- *Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools*

The following part is under preparation:

- *Part 11: Measuring instruments and their application to machine tool geometry tests [Technical Report].*

## Introduction

ISO/TC 39/SC 2 decided to revise and restructure this part of ISO 230 for the following reasons:

- a) some subclauses of the previous edition overlapped with other newly specified test codes;
- b) for practical reasons, it was necessary to modify the definitions of parallelism error and squareness error in order to exclude straightness error when looking at machine tool motion;

NOTE These definitions are not intended to be used for describing parallelism and perpendicularity errors of components and features. For components and features, this part of ISO 230 directly complies with the parallelism error and perpendicularity error definitions derived from other International Standards (e.g. ISO 1101).

- c) a clear separation was desired among error motions of a trajectory and imperfections of functional surfaces and workpieces;
- d) there was a need to address advances in machine tool technologies, measurement methods and measurement instruments.
- e) Annex A of the second edition became wider, as new measuring methods/apparatus have been developed and introduced for higher accuracy and faster measurements. Therefore, it was separated from the main body to become a future Part 11 (Technical Report).
- f) furthermore, to align this part of ISO 230 with ISO 14253 (all parts), subclauses related to the uncertainty of measurement have been introduced.

# Test code for machine tools —

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

### 1 Scope

This part of ISO 230 specifies methods for testing the accuracy of machine tools, operating either under no-load or under quasi-static conditions, by means of geometric and machining tests. The methods can also be applied to other types of industrial machines.

This part of ISO 230 covers power-driven machines, which can be used for machining metal, wood, etc., by the removal of chips or swarf material or by plastic deformation. It does not cover power-driven portable hand tools.

This part of ISO 230 relates to the testing of geometric accuracy. It is not applicable to the operational testing of the machine tool (vibrations, stick-slip motion of components, etc.) or to the checking of characteristics (speeds, feeds).

This part of ISO 230 does not cover the geometric accuracy of high-speed machine motions where machining forces are typically smaller than acceleration forces.

### 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 1, *Geometrical Product Specifications (GPS) — Standard reference temperature for geometrical product specification and verification*

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

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

ISO 230-6, *Test code for machine tools — Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)*

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

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

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

ISO 1101, *Geometrical Product Specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out*

ISO 12181-1:2011, *Geometrical product specifications (GPS) — Roundness — Part 1: Vocabulary and parameters of roundness*

ISO 12780-1:2011, *Geometrical product specifications (GPS) — Straightness — Part 1: Vocabulary and parameters of straightness*

ISO 12781-1:2011, *Geometrical product specifications (GPS) — Flatness — Part 1: Vocabulary and parameters of flatness*

ISO 14253-1, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 1: Decision rules for proving conformance or non-conformance with specifications*

### 3 Terms and definitions

#### 3.1 General

For the purposes of this document, the terms and definitions given in ISO 230-2, ISO 230-4, ISO 230-7, ISO 841, ISO 12181-1, ISO 12780-1 and ISO 12781-1 and the following apply.

This part of ISO 230 uses metrological definitions, which take into account actual motions, real lines and surfaces accessible to measurement taking into account the limitations introduced by the construction or the practicality of geometric verification.

NOTE 1 In some cases, geometric definitions (definitions of run-out, etc.) have been retained in this part of ISO 230, in order to eliminate any confusion and to clarify the language used. However, when describing test methods, measuring instruments and tolerances, metrological definitions are taken as the basis.

NOTE 2 For the alphabetical list of terms and definitions, see the index.

#### 3.2 Terms for machine coordinate system and motion nomenclature

##### 3.2.1

##### machine coordinate system

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

See Figure 1.

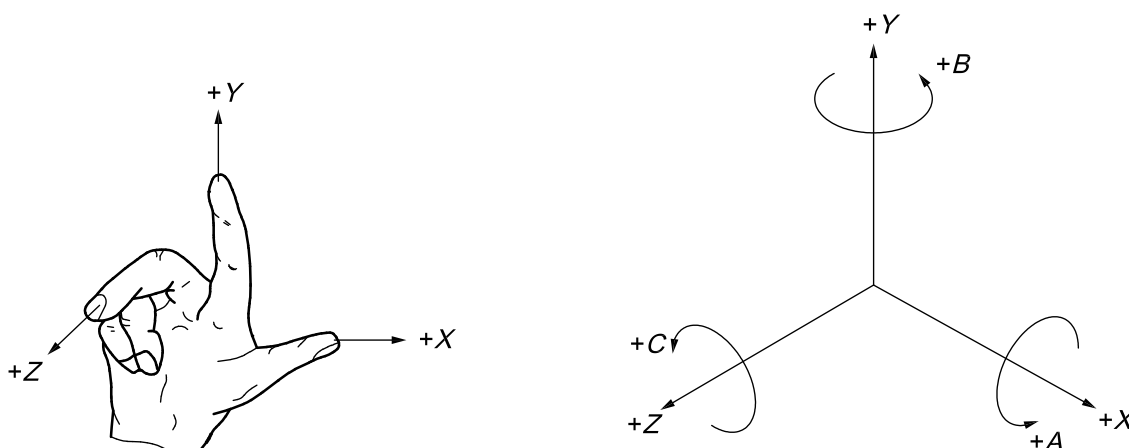


Figure 1 — Right-hand rectangular machine coordinate system

### 3.3 Terms for static compliance and hysteresis

#### 3.3.1

##### **structural loop**

assembly of components, which maintains the relative position between two specified objects

[ISO 230-7:2006, definition 3.1.13]

**NOTE** A typical pair of specified objects is a cutting tool and a workpiece, in which case the structural loop includes the spindle, bearings and spindle housing, the machine head stock, the machine slideways and frame, and the fixtures for holding the tool and workpiece. For large machines, the foundation can also be part of the structural loop.

#### 3.3.2

##### **static compliance**

linear (or angular) displacement per unit static force (or moment) between two objects, specified with respect to the structural loop, the location and direction of the applied forces, and the location and direction of the displacement of interest

**NOTE 1** Static compliance is reciprocal to static stiffness. Static compliance is preferred because of its additive properties.

**NOTE 2** The term “cross compliance” is used when displacement and force are not measured in the same direction.

#### 3.3.3

##### **play**

condition of zero stiffness over a limited range of displacement due to clearance between the components of a structural loop

[ISO 230-7:2006, definition 3.1.21]

#### 3.3.4

##### **hysteresis**

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

[ISO 230-7:2006, definition 3.1.22]

#### 3.3.5

##### **setup hysteresis**

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

[ISO 230-7:2006, definition 3.1.22.1]

#### 3.3.6

##### **machine hysteresis**

hysteresis of the machine structure when subjected to specific loads

[ISO 230-7:2006, definition 3.1.22.2]

### 3.4 Terms for linear axes

#### 3.4.1 General

In this part of ISO 230, many definitions and tests address errors in the relative motion between the component of the machine that carries the cutting tool and the component that carries the workpiece. These errors are defined and measured at the position or trajectory of the functional point.

#### 3.4.2

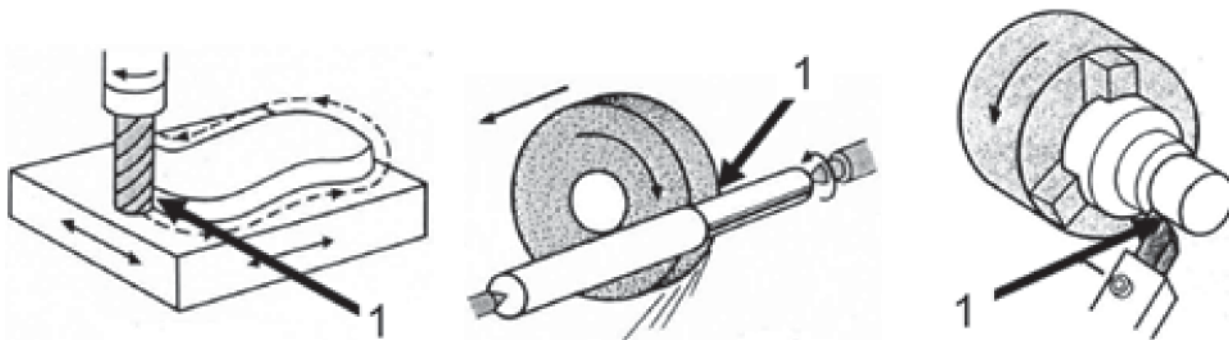
##### functional point

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

See Figure 2.

**NOTE 1** The functional point is a single point that can move within the machine tool working volume. This part of ISO 230 and related machine tool-specific standards, typically recommend to perform tests of geometrical characteristics applying test setups that are representative of the relative position between a (moving) tool of estimated average length and the hypothetical centre of a (moving) workpiece assumed to be located near the centre travel of the machine tool axes.

**NOTE 2** To improve readability, definitions and tests of this part of ISO 230 use the expression: “functional point on a moving component” instead of the formally more accurate expression: “moving point representing the relative position between a (moving) tool and a (moving) workpiece”.



#### Key

1 functional point

**Figure 2 — Examples of functional points**

#### 3.4.3

##### error motions of a linear axis

unwanted linear and angular motions of a component commanded to move along a (nominal) straight-line trajectory

See Figure 3.

**NOTE 1** Error motions are identified by the letter *E* followed by a subscript, where the first letter is the name of the axis corresponding to the direction of the error motion and the second letter is the name of the axis of motion (see Figure 3 and Annex A).

**NOTE 2** Linear error motions are defined in 3.4.4; angular error motions are defined in 3.4.16.

### 3.4.4

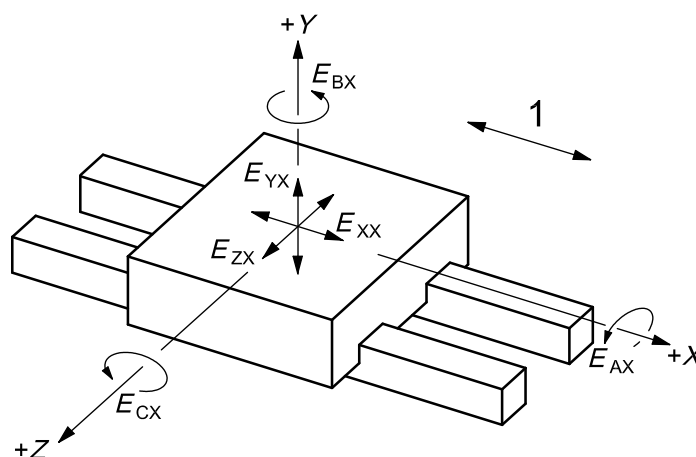
#### linear error motions of a linear axis

three translational error motions of the functional point of a moving component commanded to move along a (nominal) straight-line trajectory, the first one being along the direction of the (nominal) motion and the other two being along two directions orthogonal to this direction

NOTE 1 The linear error motion along the direction of motion is called **linear positioning error motion** (3.4.5). The other two translational error motions are called **straightness error motions** (3.4.8).

NOTE 2 The linear error motions measured at the functional point include the effects of angular error motions. The effects of these angular error motions are different when the location of a measurement point on the moving component is different from the functional point. In such cases, angular error motions are taken into account to determine the deviations of the trajectory of the functional point.

NOTE 3 If the moving component cannot be regarded as a rigid body, e.g. in the case of a large moving table, tests are carried out for more than one point on the moving component.



#### Key

- 1 X-axis commanded linear motion
- $E_{AX}$  angular error motion around A-axis (roll)
- $E_{BX}$  angular error motion around B-axis (yaw)
- $E_{CX}$  angular error motion around C-axis (pitch)
- $E_{XX}$  linear positioning error motion of X-axis; positioning deviations of X-axis
- $E_{YX}$  straightness error motion in Y-axis direction
- $E_{ZX}$  straightness error motion in Z-axis direction

**Figure 3 — Angular and linear error motions of a component commanded to move along a (nominal) straight-line trajectory parallel to the X-axis**

### 3.4.5

#### linear positioning error motion

unwanted motion along the direction of motion that results in the actual local position reached by the moving component at the functional point differing from the local commanded position along the direction of motion

See Figure 4.

NOTE 1 The positive sign of the positioning error motion is in the direction of the positive direction of the motion (according to ISO 841).

NOTE 2 Linear positioning error motion is associated with imperfections of the moving component and its guiding system. It is not associated with the dynamic response of the moving component and its positioning servo control system.

### 3.4.6

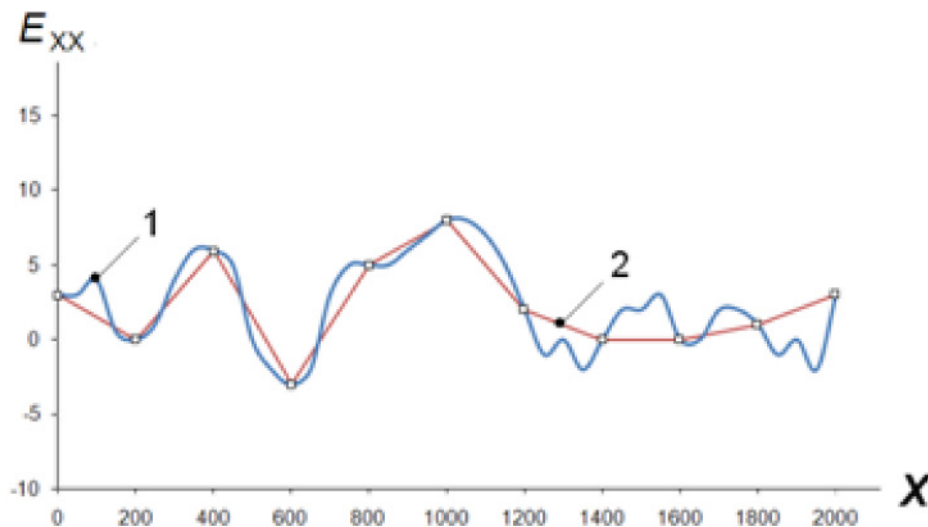
#### linear positioning deviation

position reached by the functional point on the moving component minus the target position

NOTE 1 Adapted from ISO 230-2:2006, definition 2.5.

NOTE 2 Positioning deviations are measured at specified discrete intervals in accordance with the requirements of ISO 230-2, to determine positioning accuracy and repeatability of numerically controlled axes.

NOTE 3 Positioning deviations, measured in accordance with the requirements of ISO 230-2, constitute a limited representation of positioning error motion (see Figure 4).



#### Key

- $X$  X-axis coordinates (mm)
- $E_{xx}$  X-axis positioning deviation and positioning error motion ( $\mu\text{m}$ )
- 1 plot of the actual positioning error motion of the X-axis
- 2 plot of the measured positioning deviations of the X-axis

**Figure 4 — Example of linear positioning error motion and measured linear positioning deviations of the linear motion of a functional point along the X-axis**

### 3.4.7

#### linear positioning error

#### linear positioning accuracy

#### accuracy of linear positioning

value of the largest positive linear positioning deviation added to the absolute value of the largest negative positioning deviation, evaluated in accordance with specified conventions

NOTE 1 This definition only applies to axes that are not continuously numerically controlled. Accuracy of linear positioning of continuous numerically controlled axes is established and determined in accordance with the requirements of ISO 230-2.

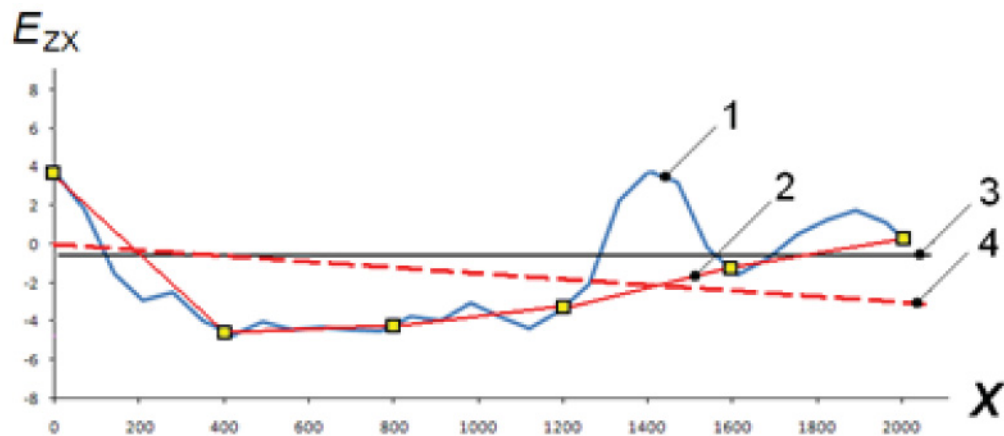
NOTE 2 A convention for linear positioning error evaluation can be to position a linear axis manually over 100 mm, ten times forward, ten times backward and evaluate for each positioning the linear positioning deviation.

### 3.4.8

#### straightness error motion

unwanted motion in one of the two directions orthogonal to the direction of a linear axis commanded to move along a (nominal) straight-line trajectory

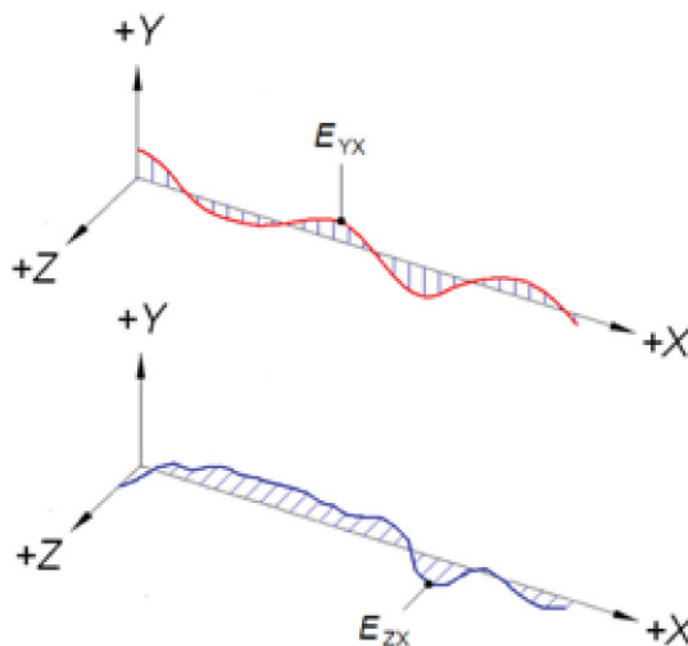
See Figures 5 and 6.



### Key

- $X$  X-axis coordinates (mm)
- $E_{ZX}$  straightness deviations of X in Z-axis direction ( $\mu\text{m}$ )
- 1 plot of the actual linear error motion of X in Z-axis direction
- 2 plot of the measured straightness error motion
- 3 mean minimum zone reference straight line associated with actual linear error motion
- 4 mean minimum zone reference straight line associated with measured straightness error motion

**Figure 5 — Example of straightness error motion in Z-direction and measured straightness error motion of the functional point trajectory for X-axis motion**



### Key

- $E_{YX}$  straightness deviations of X in Y-axis direction
- $E_{ZX}$  straightness deviations of X in Z-axis direction

**Figure 6 — Representation of straightness deviations of X-axis in Y- and Z-axis direction**

### 3.4.9

#### **straightness deviation**

distance of the functional point from the **reference straight line** (3.4.12) fitting its trajectory, measured in one of the two directions orthogonal to the direction of a commanded (nominal) straight-line trajectory

See Figure 6.

NOTE 1 Straightness deviations are measured at low speed (or when the axis under test has stopped) in order to avoid dynamic cross-talk.

NOTE 2 Straightness deviations, measured at discrete intervals (400 mm in the example of Figure 5), constitute a limited representation of the actual straightness error motion.

NOTE 3 The positive sign of the straightness deviation is in the positive direction of the associated principal axis according to ISO 841.

### 3.4.10

#### **straightness error of a linear axis**

value of the largest positive straightness deviation added to the absolute value of the largest negative straightness deviation (with respect to any previously defined reference straight line)

NOTE The minimum straightness error is obtained by using the minimum zone reference straight line.

### 3.4.11

#### **straightness**

property of a straight line

[ISO 12780-1:2011, definition 3.1.1]

NOTE The actual trajectory of the functional point of a moving component, commanded to move along a nominal straight-line trajectory, is not a straight line.

### 3.4.12

#### **reference straight line**

general direction of the line

associated straight line fitting the measured trajectory of a functional point in accordance with specified conventions, to which the straightness deviations and the straightness error are referred

NOTE 1 The reference straight line is computed from the measured deviations in two orthogonal planes (see Figure 6), within the boundary of the measurement being performed.

NOTE 2 The previous edition of this part of ISO 230 used the expressions “representative line”; it is a non-preferred expression for “reference straight line”.

NOTE 3 The mean minimum zone **reference straight line** (3.4.13), or the **least squares reference straight line** (3.4.14), or the **end-point reference straight line** (3.4.15) can be used (see Figures 7, 8 and 9).

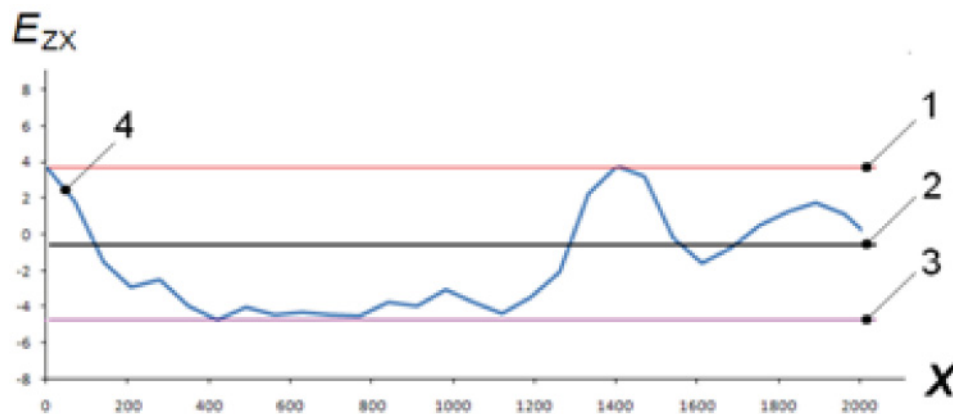
NOTE 4 The minimum straightness error is typically evaluated by using the mean minimum zone reference straight line. However, since software for minimum zone calculation has limited availability, straightness error is evaluated as the minimum error resulting from using the least squares reference straight line or using the end-point reference straight line.

### 3.4.13

#### **mean minimum zone reference straight line**

arithmetic mean of two parallel straight lines in the straightness plane enclosing the measured straightness deviations and having the least separation

See Figure 7.

**Key**

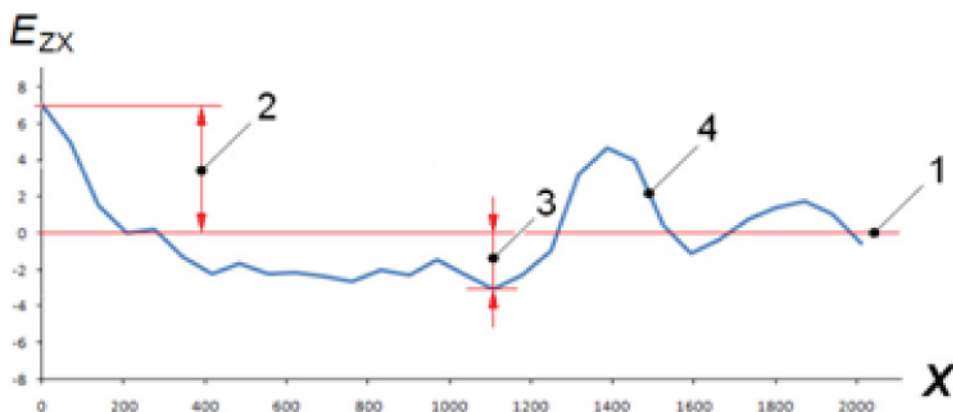
- $X$  X-axis coordinates (mm)
- $E_{ZX}$  straightness deviations of X in Z-axis direction ( $\mu\text{m}$ )
- 1 upper minimum zone reference straight line at positive  $E_{ZX}$
- 2 mean minimum zone reference straight line
- 3 lower minimum zone reference straight line at negative  $E_{ZX}$
- 4 measured straightness deviations

**Figure 7 — Example of minimum zone reference straight lines for straightness of X in the ZX plane**

**3.4.14****least squares reference straight line**

straight line, where the sum of the squares of the measured straightness deviations is minimum

See Figure 8.

**Key**

- $X$  X-axis coordinates (mm)
- $E_{ZX}$  straightness deviations of X in Z-axis direction ( $\mu\text{m}$ )
- 1 least squares reference straight line
- 2 largest positive straightness deviation  $E_{ZX}$
- 3 largest negative straightness deviation  $E_{ZX}$
- 4 measured straightness deviations

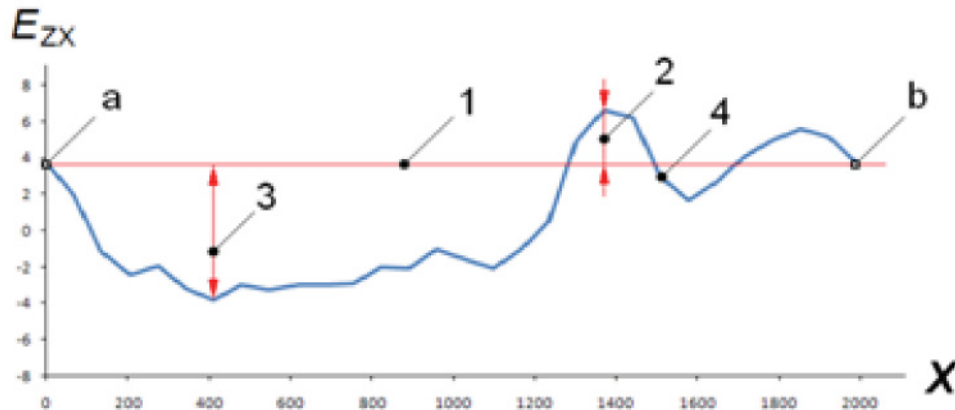
**Figure 8 — Example of least squares reference straight line for straightness of X in ZX plane**

### 3.4.15

#### end-point reference straight line

straight line connecting the first and the last point of the measured straightness deviations

See Figure 9.



#### Key

- $X$  X-axis coordinates (mm)
- $E_{ZX}$  straightness deviations of X in Z-axis direction ( $\mu\text{m}$ )
- 1 end-point reference straight line
- 2 largest positive straightness deviation  $E_{ZX}$
- 3 largest negative straightness deviation  $E_{ZX}$
- 4 measured straightness deviations
- a First measurement point.
- b Last measurement point.

**Figure 9 — Example of end-point reference straight line for straightness of X in ZX plane**

### 3.4.16

#### angular error motions of a linear axis

three unwanted rotational movements of a moving component commanded to move along a (nominal) straight-line trajectory

NOTE 1 The positive sign of the angular error motions follows the right-hand rule described in ISO 841 (see Figure 3).

NOTE 2 There are three rotations around the three orthogonal directions: one around the axis of motion and one around each of the two axes square to the axis of motion (see Figure 3). The rotation around the moving direction can be called roll. The rotations around axes, which are perpendicular to the moving direction, are called tilt. There are two tilts. For a horizontally moving axis, tilt around the vertical axis can be called yaw, tilt around the horizontal axis can be called pitch.

NOTE 3 The linear error motions of the functional point include the effects of angular error motions. The effects of these angular error motions are different when the location of a measurement point on the moving component is different from the functional point (see Figure 10). In such cases, angular error motions are taken into account to estimate the deviations of the trajectory of the functional point (see Figure 10).

NOTE 4 The terms “pitch” and “yaw” are used for horizontal axes only. These terms are not relevant to vertical axes.

### 3.4.17

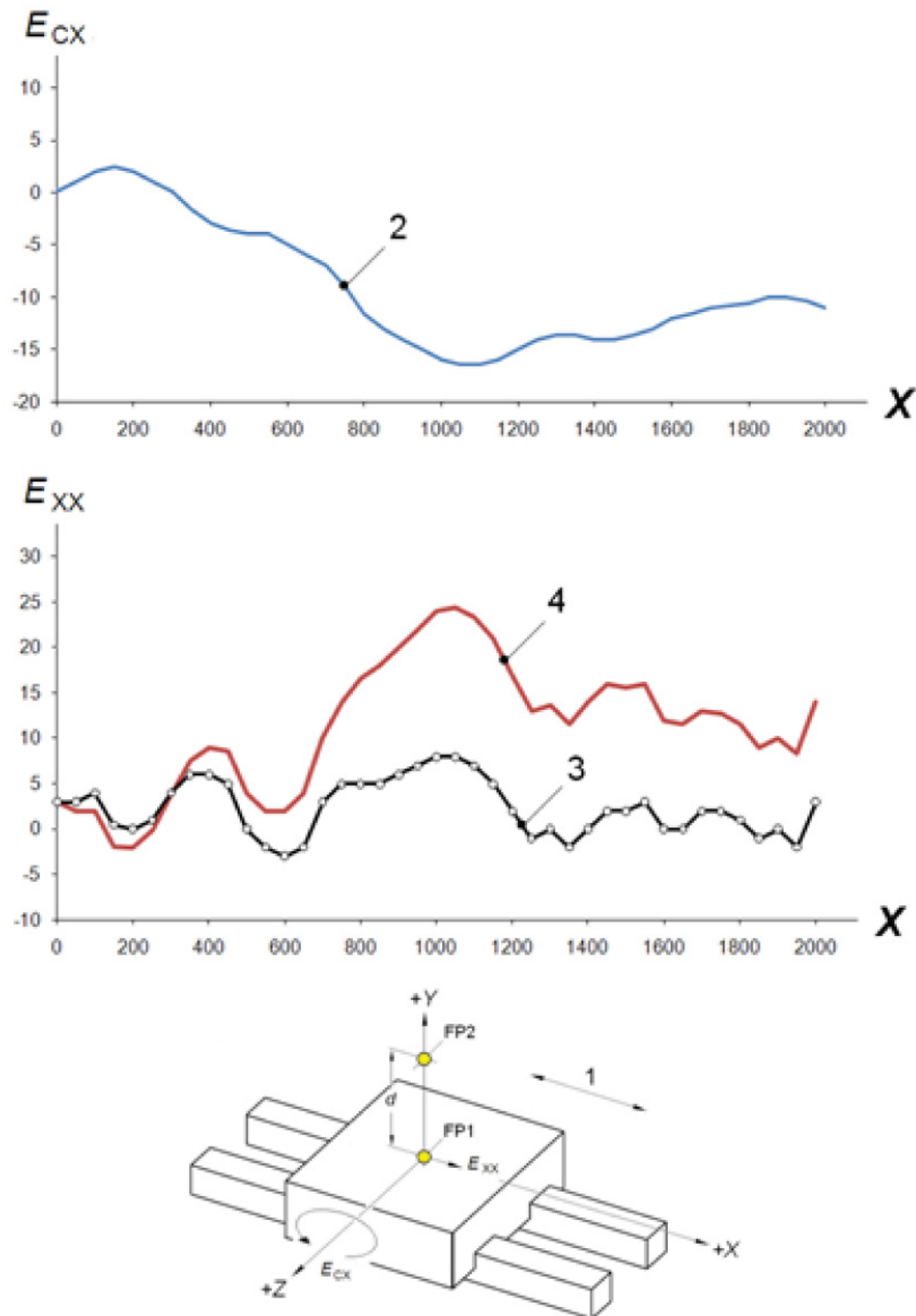
#### angular deviation

reading of an angular measuring instrument in the direction around any of the three orthogonal directions, measured during a complete traverse of the moving component

### 3.4.18

#### angular error of a linear axis

value of the largest positive angular deviation added to the absolute value of the largest negative angular deviation measured during a complete traverse of the moving component, evaluated in each one of the three orthogonal directions

**Key**

- |          |                                                  |     |                                                                                        |
|----------|--------------------------------------------------|-----|----------------------------------------------------------------------------------------|
| $X$      | X-axis coordinates (mm)                          | 3   | $E_{XX}$ deviations measured at FP1                                                    |
| $E_{CX}$ | angular error motion (pitch) ( $\mu\text{rad}$ ) | 4   | $E_{XX}$ deviations at FP2 (assumed to be affected by $E_{CX}$ only)                   |
| $E_{XX}$ | positioning error motion ( $\mu\text{m}$ )       | $d$ | Y-axis coordinate difference between FP2 and FP1 (1 000 mm, for the depicted diagrams) |
| 1        | X-axis motion                                    | FP1 | functional point 1                                                                     |
| 2        | measured $E_{CX}$ deviations                     | FP2 | functional point 2                                                                     |

**Figure 10 — Example of  $E_{CX}$  effect on  $E_{XX}$**

### 3.5 Terms for axes of rotation

#### 3.5.1 General

The complete set of definitions related to the geometric accuracy of axes of rotation (i.e. spindles, rotary tables and other rotary axes) are given in ISO 230-7. Some important definitions are repeated in this subclause.

#### 3.5.2

##### **axis of rotation**

line segment about which rotation occurs

See Figure 11.

[ISO 230-7:2006, definition 3.1.5]

#### 3.5.3

##### **axis average line**

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

[ISO 230-7:2006, definition 3.1.10]

#### 3.5.4

##### **axis of rotation error motion**

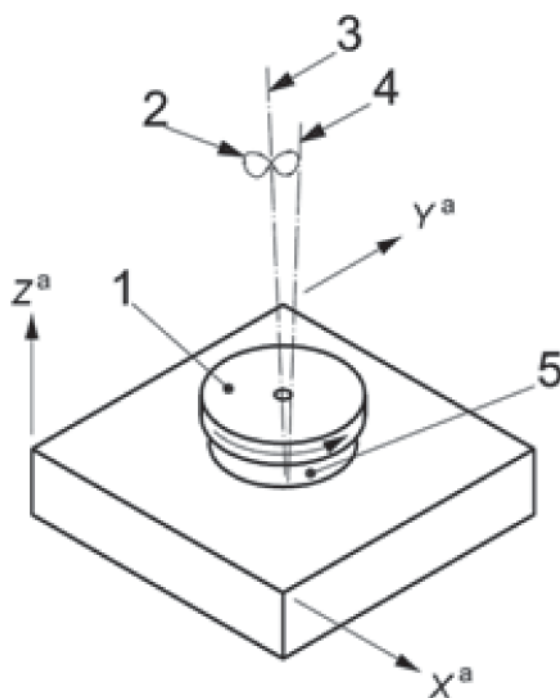
changes in position and orientation of axis of rotation relative to its axis average line as a function of angle of rotation of the rotary axis

See Figure 11 and Figure 12.

NOTE 1 The positive direction of linear (error) motion is that which increases the positive position values and decreases the negative position values (see ISO 841:2001, 5.2.1). The positive direction for the angular error motion is in the direction to advance right-hand screws in the positive direction of linear motion (see Figure 1).

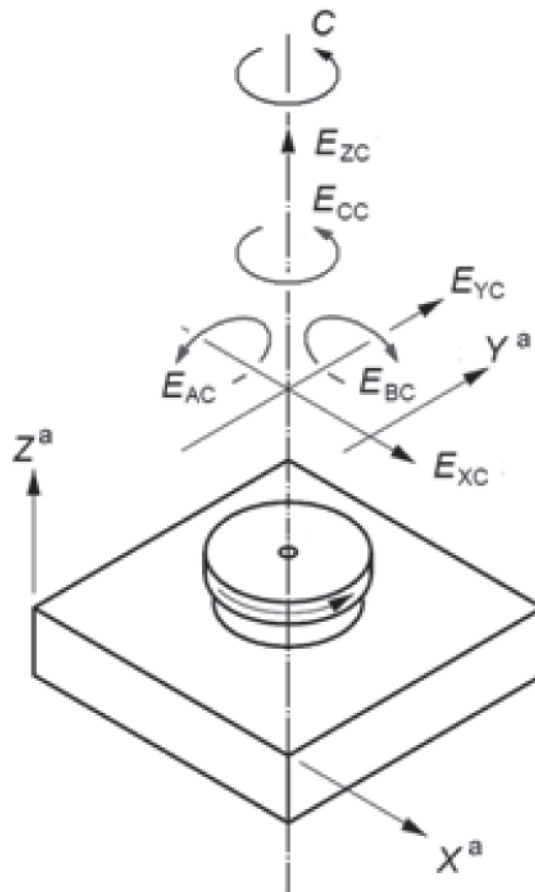
NOTE 2 Error motions are identified by the letter *E* followed by a subscript, where the first letter is the name of the axis corresponding to the direction of the error motion and the second letter is the name of the axis of motion (see Figure 12 and Annex A).

NOTE 3 Adapted from ISO 230-7:2006, definition 3.2.1.

**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)
- <sup>a</sup> Reference axis.

**Figure 11 — Reference coordinate axes, axis of rotation, axis average line and error motion for a rotary axis (C-axis)**



**Key**

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

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

$E_{ZC}$  axial error motion of C

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

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

$E_{CC}$  angular positioning error motion of C; measured angular positioning deviations of C-axis

<sup>a</sup> Reference axis.

NOTE See ISO 230-7.

**Figure 12 — Error motions of an axis of rotation**

**3.5.5**

**axial error motion**

error motion coaxial with the axis average line

[ISO 230-7:2006, definition 3.2.13]

**3.5.6**

**radial error motion**

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

[ISO 230-7:2006, definition 3.2.10]

**3.5.7****tilt error motion**

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

[ISO 230-7:2006, definition 3.2.12]

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

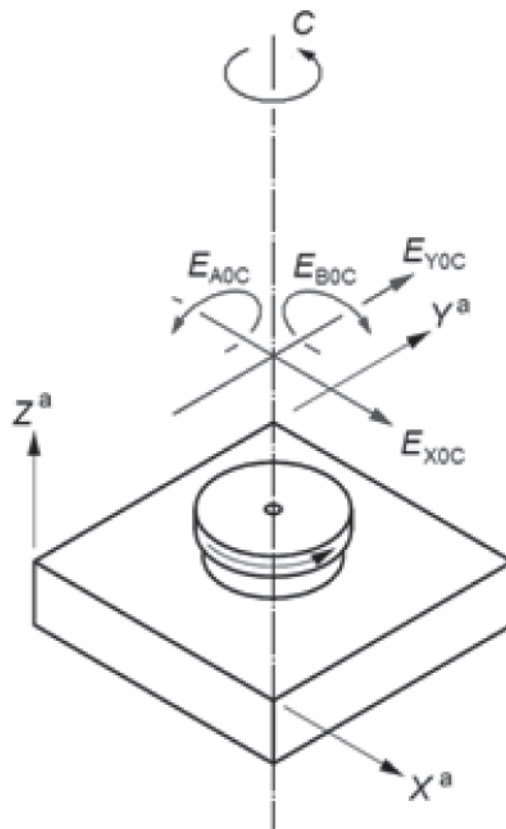
**3.5.8****axis shift**

⟨axes of rotation⟩ quasi-static change in location and orientation of the axis average line due to a change in conditions

See Figure 13.

NOTE 1 Causes of axis shift include temperature changes, load changes and speed changes (see ISO 230-7:2006, 3.7).

NOTE 2 Location and orientation errors are identified by the letter *E* followed by a subscript where the first character is the name of the axis corresponding to the direction of the error, the second character is the numeral 0 (zero) and the third character is the name of the axis of motion (see Figure 13); see Annex A.

**Key**

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

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

$E_{A0C}$  error of the orientation of C in the A-axis direction; squareness of C to Y

$E_{B0C}$  error of the orientation of C in the A-axis direction; squareness of C to X

<sup>a</sup> Reference axis.

**Figure 13 — Location and orientation errors of axis average line**

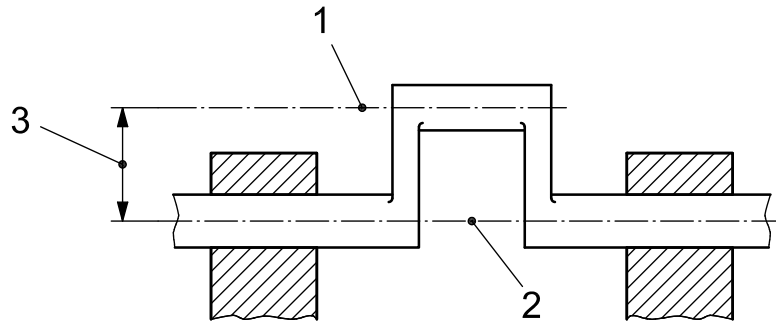
### 3.5.9

#### **eccentricity of a driven axis**

distance between a driven axis and an axis of rotation when the first is rotated around the second and is nominally parallel to it

See Figure 14.

NOTE Eccentricity is not an error, but a dimension subject to tolerances.



#### **Key**

- 1 axis of rotation
- 2 driven axis
- 3 specified eccentricity

**Figure 14 — Eccentricity between a driven axis and an axis of rotation**

### 3.5.10

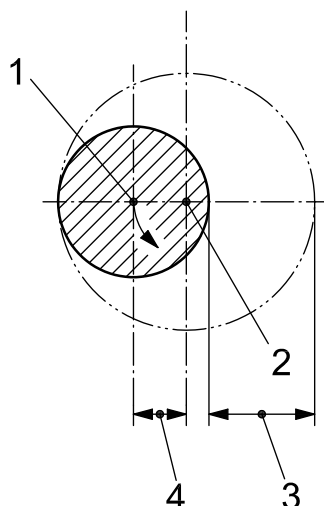
#### **radial throw of a rotary axis at a given point**

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

See Figure 15.

NOTE 1 The geometric axis of the part (or test artefact) is derived from part (or test artefact) measurements conducted at different axial locations.

NOTE 2 Where the part (or test artefact) form error and the radial error motion are negligible, the radial throw of the axis at a given point is half the **run-out** (3.9.7) measured at such a point.

**Key**

- 1 geometric axis
- 2 axis of rotation
- 3 run-out
- 4 radial throw

**Figure 15 — Radial throw and run-out of an axis at a given point**

**3.5.11****angular positioning error motion**

unwanted motion along the direction of rotary motion that results in the actual local angular position reached by the rotating component at the functional point differing from the local commanded position

See Figure 16.

NOTE 1 The positive sign of the angular positioning error motion is in the direction of the positive angular motion (according to ISO 841).

NOTE 2 Angular positioning error motion is associated with imperfections of the rotating component angular positioning and its guiding system. It is not associated with the dynamic response of the rotating component and its positioning servo control system.

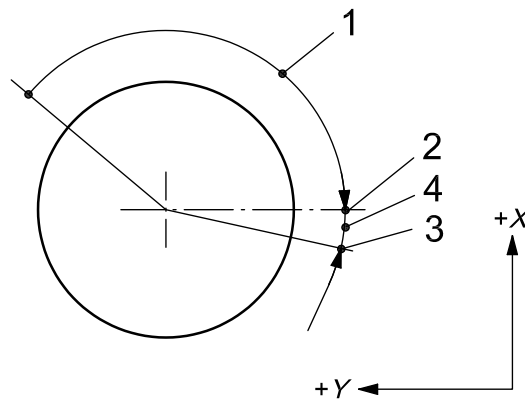
**3.5.12****angular positioning deviation**

actual angular position reached by the moving component minus the commanded angular position in the plane perpendicular to the axis average line

NOTE 1 The positive sign of the angular positioning deviation is in the direction of positive angular motion (see Figure 16).

NOTE 2 ISO 230-2 defines parameters and test procedures for the positioning accuracy and repeatability of continuous numerically controlled axes.

NOTE 3 Angular positioning deviations, measured in accordance with the requirements of ISO 230-2, constitute a limited representation of angular positioning error motion.



**Key**

- 1 C-axis negative motion direction
- 2 target position
- 3 actual position
- 4 angular positioning deviation (negative)

**Figure 16 — Angular positioning deviation of the C-axis**

**3.5.13**

**angular positioning error**

**angular positioning accuracy**

**accuracy of angular positioning**

value of the largest positive angular positioning deviation added to the absolute value of the largest negative angular positioning deviation, evaluated in accordance with specified conventions

**NOTE** This definition only applies to axes that are not continuously numerically controlled. Accuracy of angular positioning of continuous numerically controlled axes is established and determined in accordance with ISO 230-2.

**3.5.14**

**unidirectional repeatability of angular indexing**

range of angular positioning deviations resulting from a series of trials when approaching any one angular target position under the same conditions of direction and speed of approach

**NOTE 1** This parameter includes the effects of clamping at each target position, where applicable, and angular play.

**NOTE 2** The repeatability of continuous numerically controlled angular positioning is established and determined in accordance with ISO 230-2.

**3.5.15**

**bidirectional repeatability of angular indexing**

range of angular positioning deviations resulting from a series of trials when approaching any one angular target position from both directions of motion for the same speed of approach

**NOTE 1** This parameter includes the effects of clamping at each target position, where applicable, and angular play.

**NOTE 2** The repeatability of numerically controlled angular positioning is established and determined in accordance with ISO 230-2.

### 3.6 Terms for parallelism error and squareness error of axes of motion

#### 3.6.1 General

The orientations of axis of motion with respect to each other are generally affected by geometric imperfections of assembly of machine components (e.g. alignment of guideways, bearing surfaces). However, linear and angular error motions of the moving components also affect the orientation of these axes by introducing local perturbations/deviations.

Therefore, specification and measurement of the relative orientation between the trajectory of the functional point of a linear moving component and

- a) a functional surface (support or slideway),
- b) a straight line (axis average line or intersection of planes), or
- c) the trajectory of a functional point on another linear moving component

require disregarding (avoiding) the effects of local perturbations on the trajectory itself and the effects of local perturbations on the reference (datum) element. These objectives are reached by associating the relevant reference straight lines to linear motion trajectories and by associating the reference straight line or the reference plane to datum elements; thus, new definitions for squareness error and parallelism error related to axes of motion (as opposed to the definitions contained in the previous edition of this part of ISO 230) do not include straightness and flatness deviations.

Definitions (as opposed to the previous edition of this part of ISO 230) for parallelism error, related to linear and rotary axes of motion, consider the term “parallelism” as the property of two straight lines that have the same angle of inclination to the abscissa of a common coordinate plane.

Definitions (as opposed to the previous edition of this part of ISO 230) for squareness error, related to linear and rotary axes of motion, consider the term “squareness” as the property of two straight lines where the angle between the two is 90°.

Error parameters for orientation of coordinate axes are identified by the following notations: The first character after *E* (for error) is the name of the axis corresponding to the direction of deviation, the second character is the numeral 0 (zero) accompanied with the chosen reference (datum) axis, the last character is the name of the coordinate axis of concern (see Annex A).

EXAMPLE 1 Squareness error of Z relative to X:  $E_{B(0X)Z}$ ; if X is primary or secondary axes the notation may be simplified as  $E_{B0Z}$ .

EXAMPLE 2 Parallelism error (in ZX plane) of Z relative to W:  $E_{B(0W)Z}$ .

NOTE The actual trajectory of the functional point of a moving component, commanded to move along a nominal straight-line trajectory, is not a straight line. Measurements constitute a sampling of the actual trajectory and a limited representation of it. Parallelism error and squareness error, related to linear and rotary axes of motion, are defined considering the angular relationship between the reference straight lines associated with the measured deviations of the actual trajectories.

These new definitions in this edition shall not be confused with parallelism error and perpendicularity error of components and machine functional surfaces addressed in 3.9, where direct compliance to parallelism error and perpendicularity error definitions derived from other International Standards (e.g. ISO 1101) is specified.

#### 3.6.2 parallelism error between two axes of linear motion

angle between (orientation of) the reference straight line of the trajectory of the functional point of a linear moving component and (in relation to) that of another linear (datum) component, measured on two common orthogonal planes

See Figure 17.

NOTE 1 The sign of the angle of inclination follows the right-hand rule for a rotation around an axis of the machine coordinate system, as described in ISO 841.

NOTE 2 Parallelism error has a positive sign when the difference between the inclination of the reference straight line associated with the referred axis and the inclination of the reference line associated with the datum axis yields a positive result. Parallelism error sign is reversed when the referred axis and the datum axis are swapped; for example, parallelism error between Z-axis (referred axis) and W-axis (datum axis) has an opposite sign to parallelism error between W-axis (referred axis) and Z-axis (datum axis).

NOTE 3 Referred axis straightness deviations and datum axis straightness deviations are measured with respect to a common physical straightness reference. For each one of the two coordinate planes, parallelism error between Z-axis and W-axis is typically measured by recording the readings of a linear displacement sensor fixed to the spindle housing, sensing a (stationary) point on the table while Z-axis and W-axis are commanded to move simultaneously in opposite directions. The angle of inclination of the reference straight line associated with the recorded readings represents the parallelism error.

NOTE 4 For the example of Figure 17, Equations (1) and (2) apply:

$$E_{B(0W)Z} = \theta_{Z,ZX} - \theta_{W,ZX} \quad (1)$$

and

$$E_{A(0W)Z} = \theta_{Z,YZ} - \theta_{W,YZ} \quad (2)$$

NOTE 5 Parallelism error evaluation over short measurement lengths can tend to lose significance.

### 3.6.3

#### parallelism error between two axes of rotation

angle between (orientation of) the axis average line of a rotating component and (in relation to) the axis average line of another (datum) rotating component, evaluated in two orthogonal planes

NOTE 1 The common reference for the determination of inclinations is the positive direction of the machine principal axis associated with the axes of rotation.

NOTE 2 Parallelism error has a positive sign when the difference between the inclination of the average line associated with the referred axis (spindle axis in Figure 18) and the inclination of the average line associated with the datum axis (C-axis in Figure 18) yield a positive result.

NOTE 3 For the example of Figure 18, Equations (3) and (4) apply:

$$E_{B(0C)C1} = \theta_{C1,ZX} - \theta_{C,ZX} \quad (3)$$

and

$$E_{A(0C)C1} = \theta_{C1,YZ} - \theta_{C,YZ} \quad (4)$$

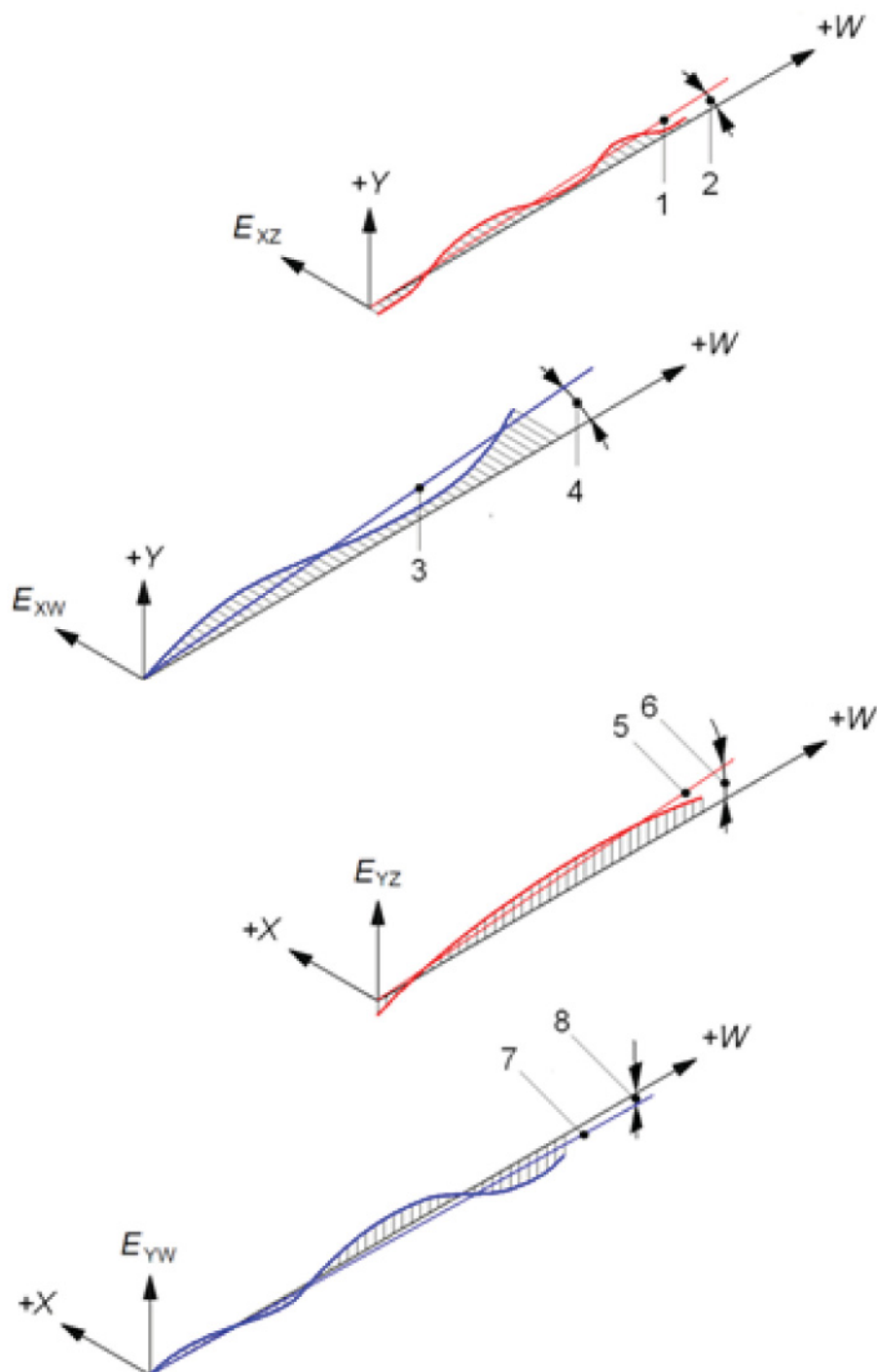
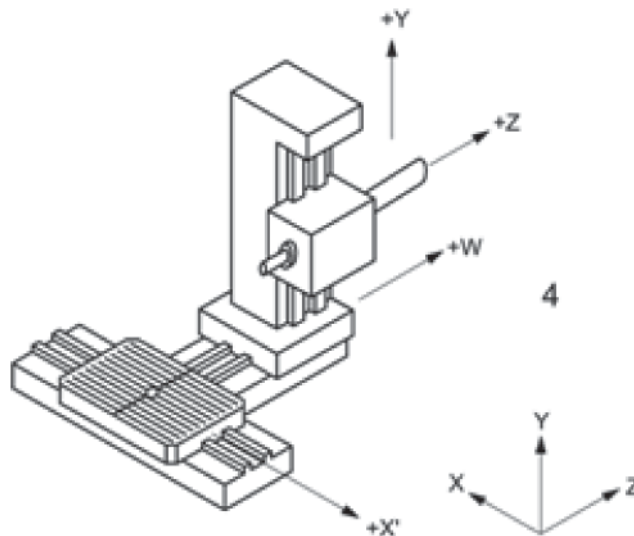


Figure 17 — Example of parallelism error between Z-axis and W-axis in ZX and YZ planes (*continued*)

**Key**

- $E_{XZ}$  Z-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis
- $E_{XW}$  W-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis
- 1 reference straight line associated to  $E_{XZ}$
- 2  $E_{XZ}$  reference straight line inclination;  $\theta_{Z,ZX}$  (positive value, as shown)
- 3 reference straight line associated to  $E_{XW}$
- 4  $E_{XW}$  reference straight line inclination;  $\theta_{W,ZX}$  (positive value, as shown)
- $E_{YZ}$  Z-axis straightness deviations, measured in the YZ plane, with respect to a physical straightness reference aligned with the W-axis
- $E_{YW}$  W-axis straightness deviations, measured in the YZ plane, with respect to a physical straightness reference aligned with the W-axis
- 5 reference straight line associated to  $E_{YZ}$
- 6  $E_{YZ}$  reference straight line inclination;  $\theta_{Z,YZ}$  (negative value, as shown)
- 7 reference straight line associated to  $E_{YW}$
- 8  $E_{YW}$  reference straight line inclination;  $\theta_{W,YZ}$  (positive value, as shown)

NOTE See Note 4 of 3.6.2.

**Figure 17 — Example of parallelism error between Z-axis and W-axis in ZX and YZ planes**

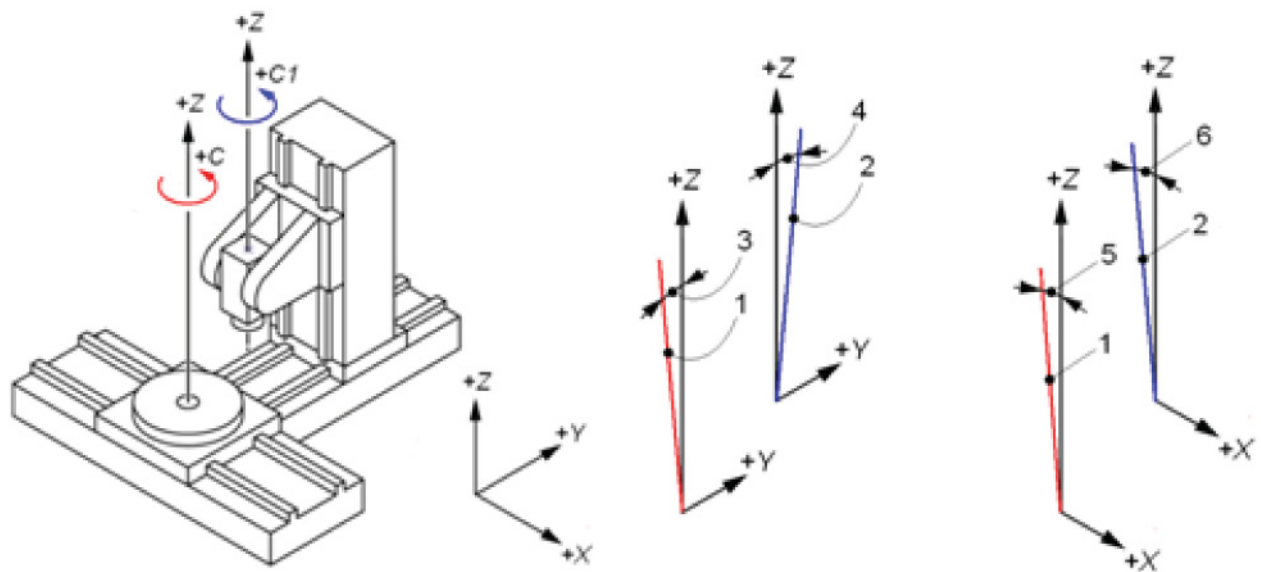
**3.6.4****parallelism error between an axis of linear motion and an axis of rotation**

angle between (orientation of) the reference straight line of the trajectory of the functional point of a linear moving component and (in relation to) the axis average line of a (datum) rotating component, evaluated in two orthogonal planes

**3.6.5****parallelism error between an axis of linear motion and a surface**

angle between (orientation of) the reference straight line of the trajectory of the functional point of a linear moving component and (in relation to) a (datum) machine functional surface

NOTE The common reference for the determination of inclinations is the positive direction of the (common) associated machine principal axis.

**Key**

- |     |                                             |   |                                                                                           |
|-----|---------------------------------------------|---|-------------------------------------------------------------------------------------------|
| +C1 | spindle axis (referred axis)                | 3 | C-axis average line inclination in YZ plane; $\theta_{C,YZ}$ (positive value, as shown)   |
| +C  | rotary table (datum axis)                   | 4 | C1-axis average line inclination in YZ plane; $\theta_{C1,YZ}$ (negative value, as shown) |
| +Z  | common reference for inclination evaluation | 5 | C-axis average line inclination in ZX plane; $\theta_{C,ZX}$ (negative value, as shown)   |
| 1   | C-axis average line                         | 6 | C1-axis average line inclination in ZX plane; $\theta_{C1,ZX}$ (negative value, as shown) |
| 2   | C1-axis (spindle axis) average line         |   |                                                                                           |

NOTE See Note 3 of 3.6.3.

**Figure 18 — Example of parallelism error between C-axis and spindle axis**

**3.6.6****parallelism error between an axis of rotation and a surface**

angle between (orientation of) the axis average line of a rotating component and (in relation to) the reference plane associated to a machine functional surface

NOTE The common reference for the determination of inclinations is the positive direction of the (common) associated machine principal axis.

**3.6.7****squareness error between two axes of linear motion**

difference between the inclination of the reference straight line of the trajectory of the functional point of a linear moving component with respect to its corresponding principal axis of linear motion and (in relation to) the inclination of the reference straight line of the trajectory of the functional point of another linear moving component with respect to its corresponding principal axis of linear motion

See Figure 19.

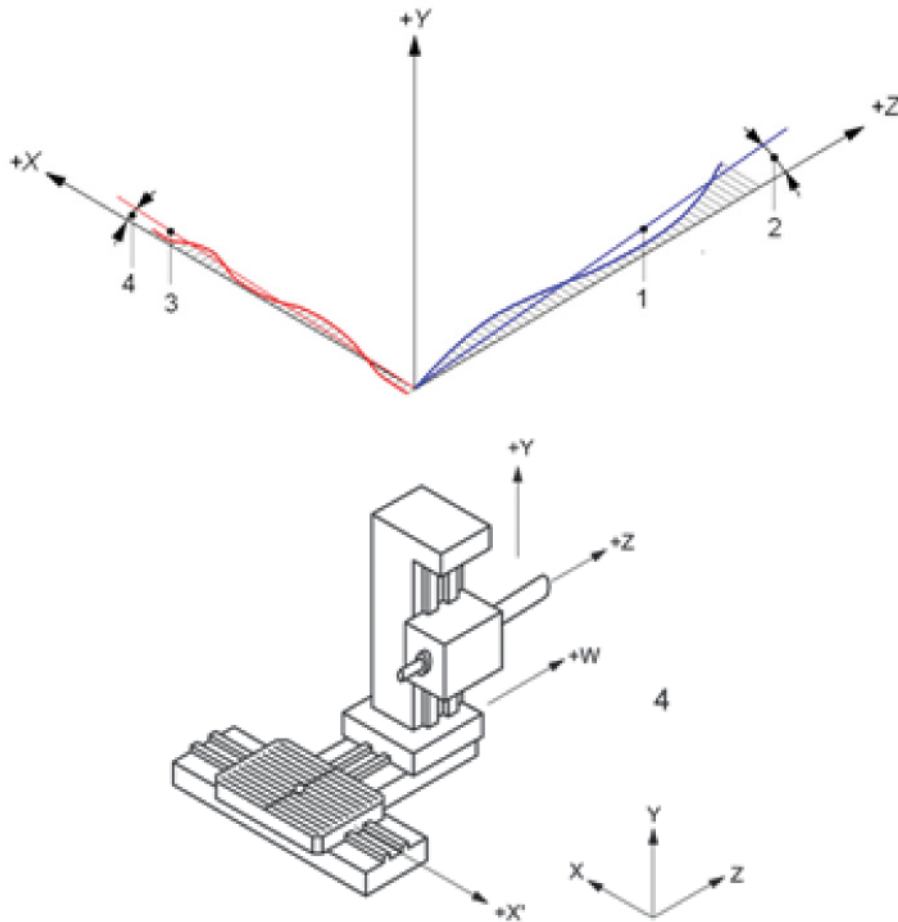
NOTE 1 This definition is conceptually different from the definition for **perpendicularity error between two functional lines** (3.9.5).

NOTE 2 A positive squareness error corresponds to a positive angular error in the orientation of the referred axis relative to the datum axis, following the right-hand rule for rotations as described in ISO 841. The squareness error sign is reversed when the referred axis and the datum axis are swapped; for example, the squareness error between the X-axis (referred axis) and Y-axis (datum axis) has an opposite sign to the squareness error between the Y-axis (referred axis) and X-axis (datum axis). To avoid confusion, squareness errors may also be accompanied with additional text like "larger than 90°" or "smaller than 90°".

NOTE 3 For the example of Figure 19, Equation (5) applies:

$$E_{B(0Z)X} = E_{B0X} = \theta_{X,ZX} - \theta_{Z,ZX} \quad (5)$$

NOTE 4 Squareness error evaluation over short measurement lengths can tend to lose significance.



#### Key

- 1 reference straight line associated to  $E_{XZ}$
- 2  $E_{XZ}$  reference straight line inclination;  $\theta_{Z,ZX}$  (positive value, as shown)
- 3 reference straight line associated to  $E_{ZX}$
- 4  $E_{ZX}$  reference straight line inclination;  $\theta_{X,ZX}$  (negative value, as shown)

NOTE See NOTE 3 of 3.6.7.

**Figure 19 — Example of squareness error between X- and Z-axis of linear motion**

#### 3.6.8

##### **squareness error between an axis of linear motion and an axis average line**

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

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

**3.6.9****squareness error between two axis average lines**

angular deviation from  $90^\circ$  between the axis average line of a rotating component of the machine and (in relation to) the axis average line of another rotating component of the machine

**3.7 Terms for other relationships between axis average lines****3.7.1****offset between two axis average lines**

distance, in the radial direction, between two nominally parallel axis average lines at a specified position in the axial direction

**3.7.2****coaxiality error of axis average lines**

offset at a specified location and angle between two nominally coaxial axis average lines, evaluated in two orthogonal planes

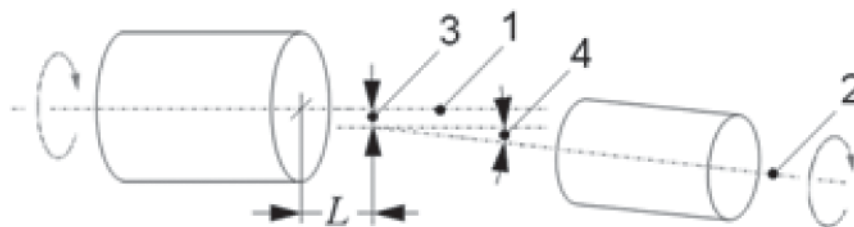
See Figure 20.

NOTE 1 This definition considers the term “coaxiality” as the property of two straight lines, where the two lines are parallel with zero offset.

NOTE 2 Coaxiality error is represented by two offsets at a specified location and two angles of parallelism evaluated in two orthogonal planes.

NOTE 3 Coaxiality error is measured in two perpendicular planes similar to parallelism error measurements.

NOTE 4 The terms “coincidence” and “alignment” are not preferred.

**Key**

- 1 axis average line 1
- 2 axis average line 2
- 3 offset of coaxiality deviation (measured in one plane)
- 4 angle of coaxiality deviation (measured in one plane)
- $L$  specified distance for offset measurement

**Figure 20 — Example of coaxiality error of axis average lines  
(depicted in one of the two orthogonal planes)**

**3.7.3****equidistance error of axis average lines**

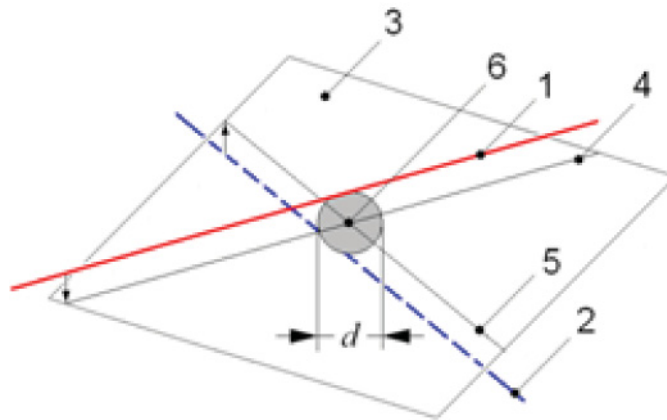
difference between the distance of an axis average line and a reference plane, and the distance of another axis average line and the same reference plane

**3.7.4****error of intersection between axis average lines**

shortest actual distance between two nominally intersecting axis average lines

See Figure 21.

NOTE The projections of the two non-intersecting axis average lines intersect at a point on their symmetry plane. The shortest actual distance between the two axis average lines is the diameter of the sphere, centred in their projections intersection point, tangent to the two axis average lines.



**Key**

- 1 axis average line 1
- 2 axis average line 2
- 3 symmetry plane
- 4 projection of axis average line 1 on the symmetry plane
- 5 projection of axis average line 2 on the symmetry plane
- 6 intersecting point of projections 4 and 5
- $d$  diameter of the sphere centred on 6 and tangent to the two axis average lines 1 and 2; error of intersection

**Figure 21 — Error of intersection between axis average lines**

### 3.8 Terms for multi-axes motion or kinematic tests

#### 3.8.1

**synchronous motion**

motion of the workpiece and/or the tool along a predetermined path in space, involving the motions of two or more axes, simultaneously coordinated by the machine controller

#### 3.8.2

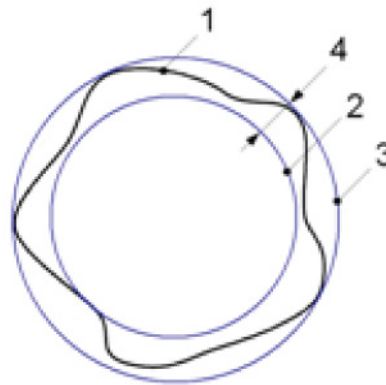
**circular error**

minimum radial separation between two concentric reference circles enveloping the actual circular path resulting from synchronous motion

See Figure 22.

NOTE 1 Reference circle may be **mean minimum zone circle** (3.8.3) or **least squares circle** (3.8.4).

NOTE 2 Circular error is different from the term “roundness”, which is related to parts and machine tool functional surfaces; the use of the term “roundness” in association to synchronous motion is not appropriate.

**Key**

- 1 circular path
- 2,3 minimum zone circles
- 4 minimum radial separation; circular deviation

**Figure 22 — Example of circular path showing circular deviation**

**3.8.3****mean minimum zone circle**

arithmetic mean of two concentric circles enclosing the actual circular path and having the least radial separation

NOTE Adapted from ISO 12181-1:2011, definition 3.3.1.1.

**3.8.4****least squares circle**

associated circle fitting the actual circular path such that the squares of the local circular deviations is a minimum

NOTE Adapted from ISO 12181-1:2011, definition 3.3.1.2.

**3.8.5****flatness**

property of a plane

[ISO 12781-1:2011, definition 3.1.1]

**3.8.6****surface generated by two linear motions**

set of functional points obtained by the combined motion of two linear components commanded to move on a (nominal) plane, creating a virtual surface

See Figure 23.

NOTE The expression “virtual surface” is conceptually similar to the “flatness surface” defined in ISO 12781-1:2011, 3.2.2, referring to the extracted surface representing a real surface.

**3.8.7****flatness deviation**

deviation of a point (on a surface generated by two linear motions) from a reference plane, the deviation being normal to the reference plane

NOTE 1 Adapted from ISO 12781-1:2011, definition 3.2.3.

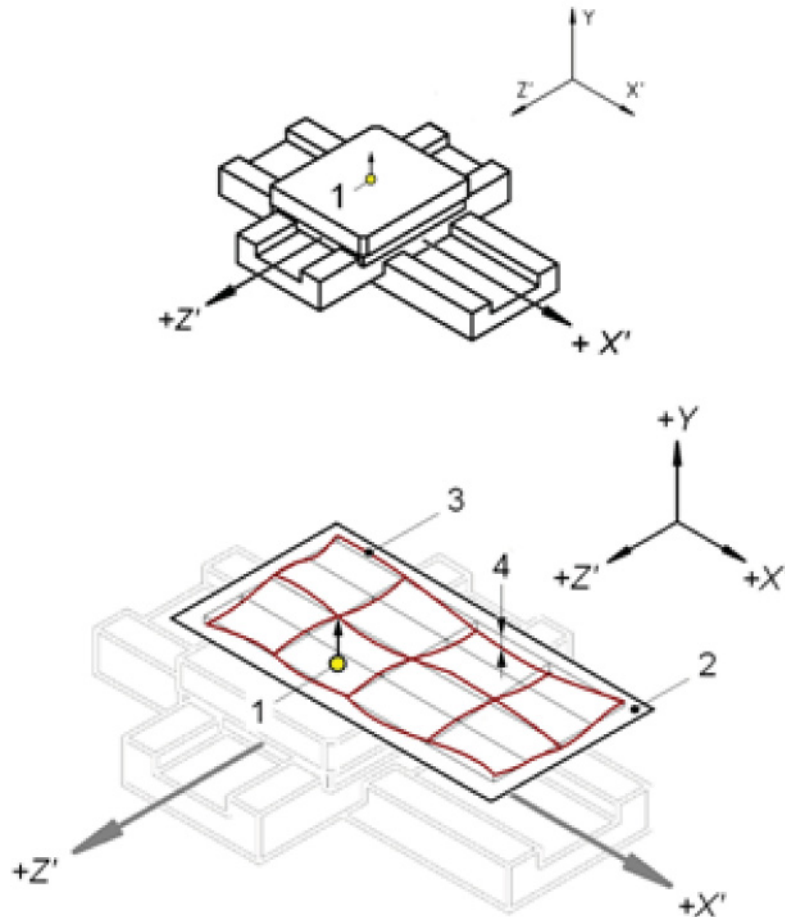
NOTE 2 The positive sign of the flatness deviation being in the positive direction according to ISO 841.

### 3.8.8

#### reference plane

associated plane fitting the surface generated by two linear motions in accordance with specified conventions, to which the deviations from flatness and the flatness parameters are referred

NOTE Adapted from ISO 12781-1:2011, definition 3.3.1.



#### Key

- 1 functional point
- 2 reference plane
- 3 trajectory of functional point
- 4 local flatness deviation

Figure 23 — Plane defined by two linear motions

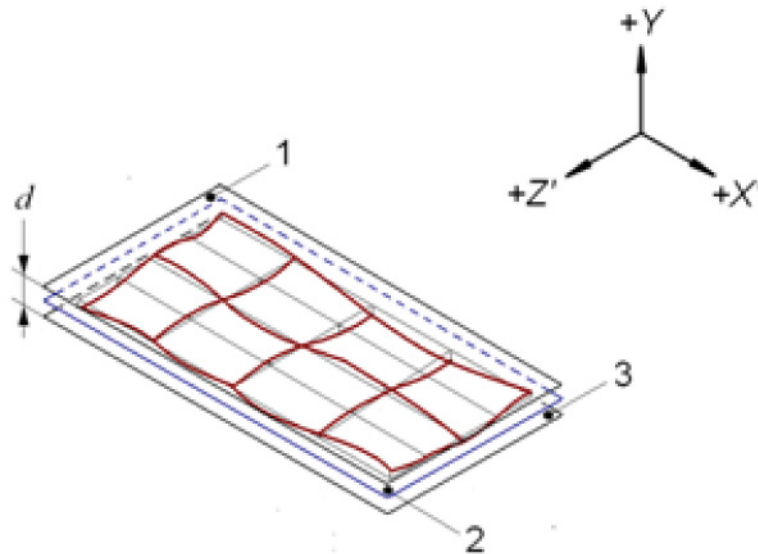
### 3.8.9

#### mean minimum zone reference plane

arithmetic mean plane of two parallel planes enclosing the surface generated by two linear motions and having the least separation

See Figure 24.

NOTE Adapted from ISO 12781-1:2011, definition 3.3.1.1.

**Key**

- 1 upper minimum zone reference plane
- 2 mean minimum zone reference plane
- 3 lower minimum zone reference plane
- $d$  least separation

**Figure 24 — Minimum zone reference planes****3.8.10****least squares zone reference plane**

plane such that the sum of the squares of the flatness deviations is a minimum

NOTE Adapted from ISO 12781-1:2011, definition 3.3.1.2.

**3.8.11****flatness error of a surface defined by two linear motions**

value of the largest positive flatness deviation added to the absolute value of the largest negative flatness deviation (with respect to any previously defined reference planes)

NOTE The minimum flatness error is evaluated by using minimum zone reference planes.

**3.8.12****volumetric accuracy for three linear axes**

$V_{XYZ}$

maximum range of relative deviations between actual and ideal position in X-, Y- and Z-axis directions and maximum range of orientation deviations for A-, B- and C-axis directions for X-, Y- and Z-axis motions in the volume concerned, where the deviations are relative deviations between the tool side and the workpiece side of the machine tool for specified primary and secondary axes of alignment

See Figure 25.

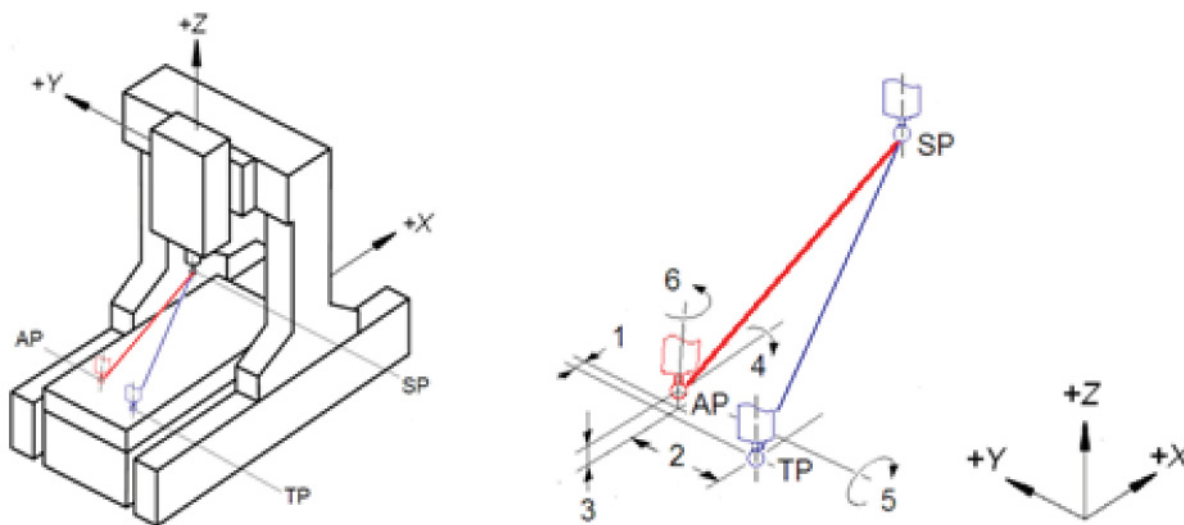
There are six statements for the volumetric accuracy,  $V_{XYZ}$ : one for each translational and one for each rotational range of deviations:

|             |                                          |             |                                              |
|-------------|------------------------------------------|-------------|----------------------------------------------|
| $V_{XYZ,X}$ | maximum X-axis relative deviations range | $V_{XYZ,A}$ | maximum deviations range in A-axis direction |
| $V_{XYZ,Y}$ | maximum Y-axis relative deviations range | $V_{XYZ,B}$ | maximum deviations range in B-axis direction |
| $V_{XYZ,Z}$ | maximum Z-axis relative deviations range | $V_{XYZ,C}$ | maximum deviations range in C-axis direction |

The measurement coordinate system used and the following parameters shall be stated:

- tool offset in X, Y, Z;
- volume concerned; X·Y·Z;
- volume centred at position X, Y, Z;
- adopted measurement coordinate system (see Annex A).

NOTE Although the rotary axes of motion also influence the volumetric accuracy of a machine, for simplicity, they are excluded from consideration here.



#### Key

- 1 deviation in X-axis direction
- 2 deviation in Y-axis direction
- 3 deviation in Z-axis direction
- 4 deviation in A-axis direction
- 5 deviation in B-axis direction
- 6 deviation in C-axis direction
- AP actual position
- SP starting position
- TP target position

Figure 25 — Target position deviations

#### 3.8.13 volumetric performance

ability of a machine tool to perform the intended multi-axes functions anywhere within the entire machine working volume or a smaller volume as agreed between the manufacturer/supplier and user

### 3.9 Terms for geometric accuracy of machine functional surfaces, machine tool components and test pieces

#### 3.9.1 General

Machine tool functional surfaces are actual components. Terms and definitions related to their geometric accuracy are derived from the definitions of tolerances given in ISO 1101.

Terms and definitions for **straightness** (3.4.11), **reference straight line** (3.4.12), **flatness** (3.8.5) and **reference plane** (3.8.8) also apply for components.

Terms and definitions for parallelism error and perpendicularity error between machine functional surfaces are conceptually different from definitions for parallelism error and squareness error related to axis of motion. “Perpendicularity” is the preferred term for the relationship between features pertaining to functional surfaces, to maintain consistency with ISO 1101 and to distinguish it from the term “squareness”, which refers to the angular relationship between geometrical elements involving axes of motion.

### 3.9.2

#### **straightness error of a functional line in a plane**

minimum distance between two straight lines, parallel to the general direction of the line, that just contain all measured points of the referred line

NOTE 1 The general direction of the line or reference straight line is defined so as to minimize the straightness error [see **mean minimum zone reference straight line** (3.4.9)]. It may also be conventionally defined either by two points appropriately chosen near the ends of the line to be checked [see **end-point reference straight line** (3.4.11)] or by a straight line calculated from plotted points [see **least squares reference straight line** (3.4.10)].

NOTE 2 Straightness error of a line in space is specified by the straightness error of its projections in two orthogonal planes.

### 3.9.3

#### **parallelism error between a functional line and a plane**

minimum distance between two straight lines, parallel to a **reference plane** (3.8.8) associated with the (datum) functional plane, that just contain all measured points of the referred line

NOTE 1 Adapted from ISO 1101:2004, 18.9.3.

NOTE 2 Parallelism error according to this definition includes the (referred) line straightness deviations and is conceptually different from the **parallelism error between an axis of linear motion and a surface** (3.6.5).

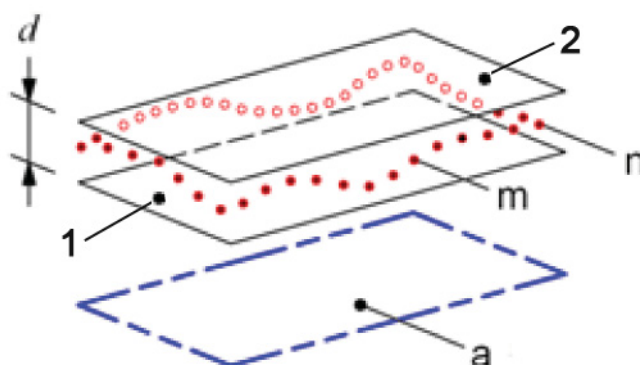
### 3.9.4

#### **parallelism error between two functional planes**

minimum distance between two planes, parallel to a **reference plane** (3.8.8) associated with the (datum) functional plane, that just contain all measured points of the (referred) functional plane

NOTE 1 Adapted from ISO 1101:2004, 18.9.6.

NOTE 2 Parallelism error according to this definition includes the (referred) functional plane flatness deviations (see Figure 26).



#### **Key**

- 1, 2 planes parallel to a
- a reference plane associated to the (datum) functional plane
- n, m measured points of the (referred) functional plane
- d minimum distance; parallelism error

**Figure 26 — Parallelism error between two functional planes**

### 3.9.5

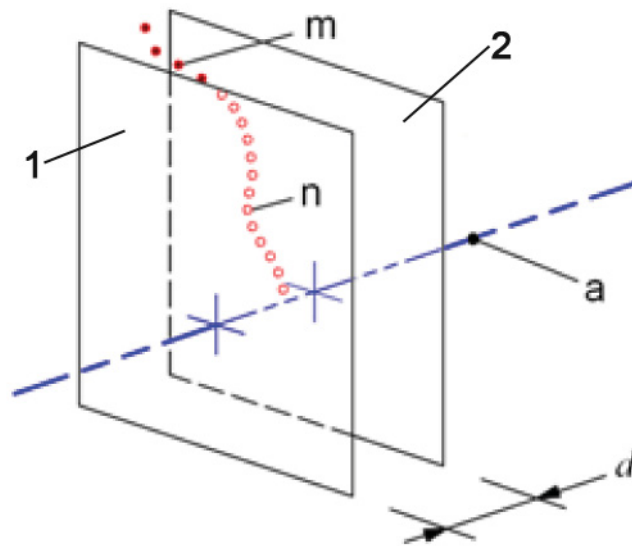
#### perpendicularity error between two functional lines

minimum distance between two parallel planes, perpendicular to a **reference straight line** (3.4.8) associated to the (datum) line, that just contain all measured points of the (referred) functional line

NOTE 1 Adapted from ISO 1101:2004, 18.10.1.

NOTE 2 The datum line may also be the axis average line of a rotating component or the straight line intersecting two reference planes (see Figure 27).

NOTE 3 Perpendicularity error, according to this definition, includes the (referred) line straightness deviations and is conceptually different from **squareness error between two axes of linear motion** (3.6.7).



#### Key

- 1, 2 planes, square to a
- a datum reference straight line
- n, m measured points of the (referred) functional line
- d minimum distance; perpendicularity error

**Figure 27 — Perpendicularity error between two functional lines**

### 3.9.6

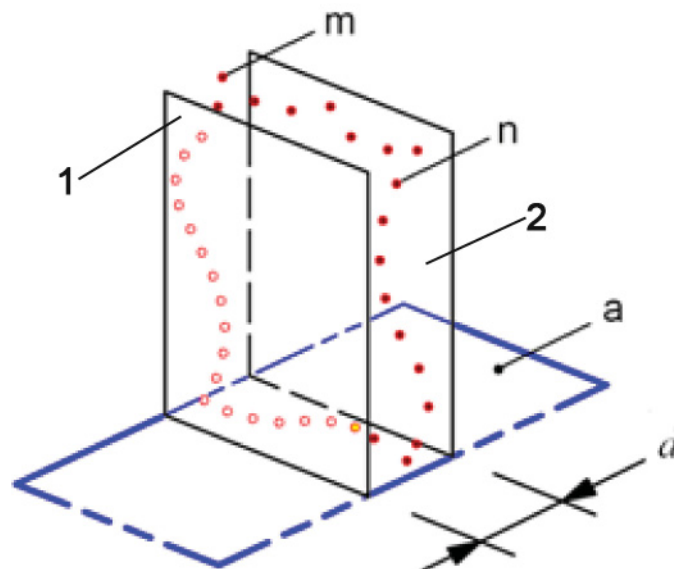
#### perpendicularity error between two functional planes

minimum distance between two parallel planes, perpendicular to a **reference plane** (3.8.8) associated to the (datum) plane, that just contain all measured points of the (referred) functional plane

See Figure 28.

NOTE 1 Adapted from ISO 1101:2004, 18.10.5.

NOTE 2 Perpendicularity error, according to this definition, includes the (referred) plane flatness deviations.

**Key**

- 1, 2 planes, square to *a* and parallel to each other  
*a* datum reference plane  
*n*, *m* measured points of the (referred) functional plane  
*d* minimum distance; perpendicularity error

**Figure 28 — Perpendicularity error between two functional planes**

**3.9.7****run-out of a functional surface at a given section**

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

NOTE 1 Adapted from ISO 1101:2004, 18.15.

NOTE 2 Radial run-out is twice the radial throw of an axis in a given section (see Figure 14) when no account is taken of the out-of-roundness or of the radial error motion.

NOTE 3 In general, the measured run-out is the resultant of

- a) the radial throw of the axis at the measurement point (3.5.10),
- b) the out-of-roundness of the component (see ISO 1101:2004, 18.3), and
- c) the radial error motion of the axis of rotation (see ISO 230-7:2006, 3.2.10).

NOTE 4 In geometric testing of machine tools, the radial throw of an axis is measured by observing the run-out of a part mounted on the axis. In order to avoid any confusion in the minds of the personnel in charge of machine testing and to eliminate any risk of error, only the term run-out is used in this part of ISO 230, and the indicated tolerance to be given has been applied systematically to this run-out so that the readings of the measuring instruments are not to be divided by two. The proposed measuring methods take this note into consideration.

NOTE 5 With rolling bearings, the rollers and cage rotate once for more than two rotations of the shaft and it is common for the run-out of a shaft to repeat cyclically every several rotations. To account for these variations, run-out is measured over several (at least two) rotations (see ISO 230-7:2006, 5.4 and 5.5).

NOTE 6 From the metrological point of view, the bearing of a cylindrical or conical surface is said to have an axis exactly coincident with a rotating axis if, on measuring over a given length (after fixing a test mandrel in this bearing, if necessary), the run-out at each measuring point does not exceed the given value.

### 3.9.8

#### **flatness error of a functional surface**

minimum distance between two planes, parallel to the general direction of the plane, that just contains all its measured points and that have minimum separation

NOTE 1 Adapted from ISO 1101:2004, 18.2.

NOTE 2 The general direction of the plane or **reference plane** (3.8.8) is defined so as to minimize the flatness error, i.e. conventionally, either

- by three points conveniently chosen in the plane to be tested (usually the part very near to the edge, having minor local defects, can be disregarded), or
- by a plane calculated from the plotted points by the least squares method (see 3.8.11), or
- by the mean minimum zone reference plane.

### 3.9.9

#### **coaxiality error of a functional cylinder to a datum straight line**

twice the maximum radial distance (evaluated within a specified measuring length) between the median line of the functional cylinder and the datum straight line

NOTE 1 Adapted from ISO 1101:2004, 18.13.2.

NOTE 2 A typical functional cylinder is a quill; a typical datum straight line is its associated spindle axis average line.

## 4 Tolerances

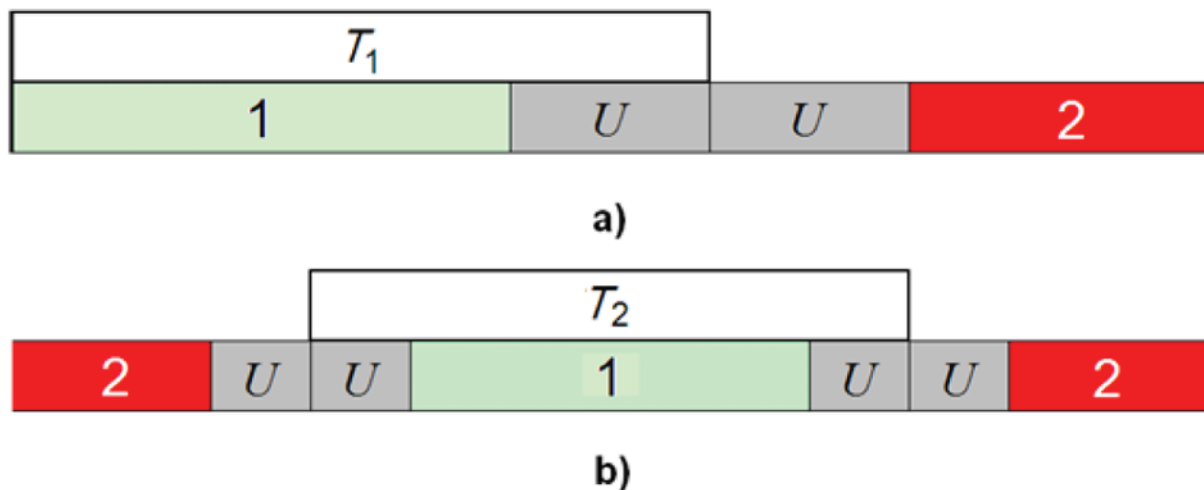
### 4.1 General

Tolerances identify the permissible errors of the machine tool characteristic and geometric accuracy parameters being evaluated and shall be specified in accordance with functional requirements. When establishing tolerances, manufacturing, assembling and inspection requirements should also be considered.

Tolerances shall be expressed with the unit of the corresponding measured characteristic under test.

#### 4.1.1 Rules concerning tolerances and conformance zone

Measurement uncertainties should be taken into account (see Clause 5 and 6.3) when specifying tolerances and when evaluating conformance with specified tolerances. The zones of conformance and non-conformance shall be determined in accordance with the rules provided in ISO 14253-1 [see Figure 29 a) and b)].

**Key**

- 1 conformance zone
- 2 non-conformance zone
- $T_1$  one-sided tolerance zone, e.g.  $E_{ZX}$  straightness 0,012 mm
- $T_2$  two-sided tolerance zone, e.g. 100 mm  $\pm$  0,006 mm
- U measurement uncertainty

**Figure 29 — Determination of zones of conformance and non-conformance for one-sided tolerance zone and two-sided tolerance zone**

**EXAMPLE** Tolerance of run-out:  $x$  mm  
 Measurement uncertainty:  $y$  mm  
 Maximum permissible difference in the readings during the test:  $(x-y)$  mm (zone of conformance)

Other definitions of conformance zone are subject to agreement between the parties involved (supplier/manufacture and user).

If the determinations of geometric accuracy parameters are repeated, the arithmetical mean of these parameters should be taken. The dispersion of the resulting parameters is one of the contributors to the measurement uncertainty.

#### 4.1.2 Specified measuring boundaries

Unless otherwise specified, for any tests described in this part of ISO 230, tolerances shall indicate the maximum allowable value for the parameter of interest within the specified measurement boundary (measurement length for straightness test, measurement volume for volumetric accuracy test, applied force range for compliance and hysteresis test, etc.).

When the tolerance is specified for a given boundary, the tolerance for another boundary comparable to the first one may be determined by means of the law of proportionality. For example, when a tolerance,  $T_1$ , is given for a specific measurement length of up to  $L_1$ , and a larger tolerance,  $T_2$ , is given for a measurement length,  $L_2$ , a tolerance,  $T_L$ , for a measurement length between  $L_1$  and  $L_2$  can be determined by the law of proportionality:

$$L \leq L_1 : T_L = T_1 \quad (6)$$

$$L_1 < L < L_2 : T_L = T_1 + \frac{T_2 - T_1}{L_2 - L_1} (L - L_1) \quad (7)$$

$$L \geq L_2 : T_L = T_2 \quad (8)$$

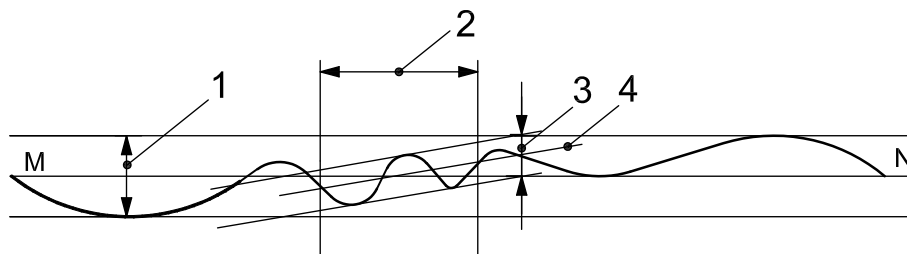
For measurement lengths greatly different from the specified measurement length (e.g. the available measurement length is 30 mm instead of 300 mm), the law of proportionality cannot be applied.

#### 4.1.3 Local tolerances

Unless otherwise specified, tolerances apply to measurement results obtained over the entire measurement boundary. It may be desirable to specify a local tolerance with reference to a partial measurement boundary.

Local tolerances shall not be established by the simple application of the law of proportionality. Specification of local tolerances shall take into account functional requirements and inspection requirements associated to the characteristic under test or to the component under test.

Local straightness error specification for axis of linear motion directly applies to definition 3.4.10, but the reference straight line is evaluated over the local measurement length (see Figure 30).



#### Key

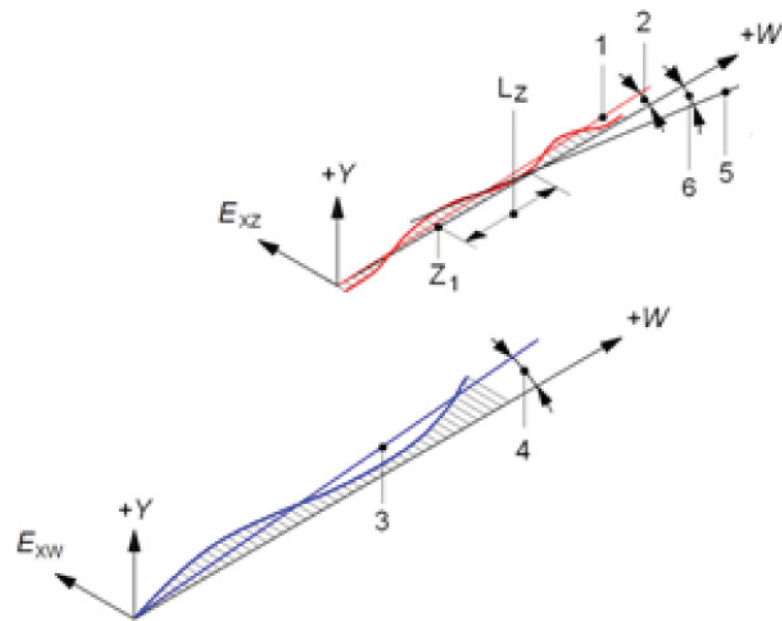
- 1 total straightness error
- 2 local measurement length
- 3 local straightness error
- 4 end-points reference straight line associated to local straightness measurement results
- MN end-points reference straight line associated to straightness measurements conducted over the full measurement length

**Figure 30 — Local straightness error**

Additional attention shall be devoted to clearly specify local tolerances for parallelism error and squareness error between axes of linear motion.

Parallelism error and squareness error between axes of linear motion refer to the angular relationship between the reference straight lines associated to the referred axis trajectory and to the datum axis trajectory.

When specifying and testing local parallelism error and local squareness error, it shall be clearly stated whether the reference straight line associated to the datum axis trajectory shall be evaluated from the results obtained from measurements over the full travel of the datum axis or if it shall be evaluated from the results obtained from measurements over the local travel of the datum axis (see Figures 31, 32 and 33).

**Key**

$E_{XZ}$  Z-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis

$E_{XW}$  W-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis

$L_Z$  local Z-axis measurement length

1 reference straight line associated to  $E_{XZ}$  measurements over the full Z-axis travel

2 inclination of reference straight line 1;  $\theta_{Z1,ZX}$  (positive value, as shown)

3 reference straight line associated to  $E_{XW}$

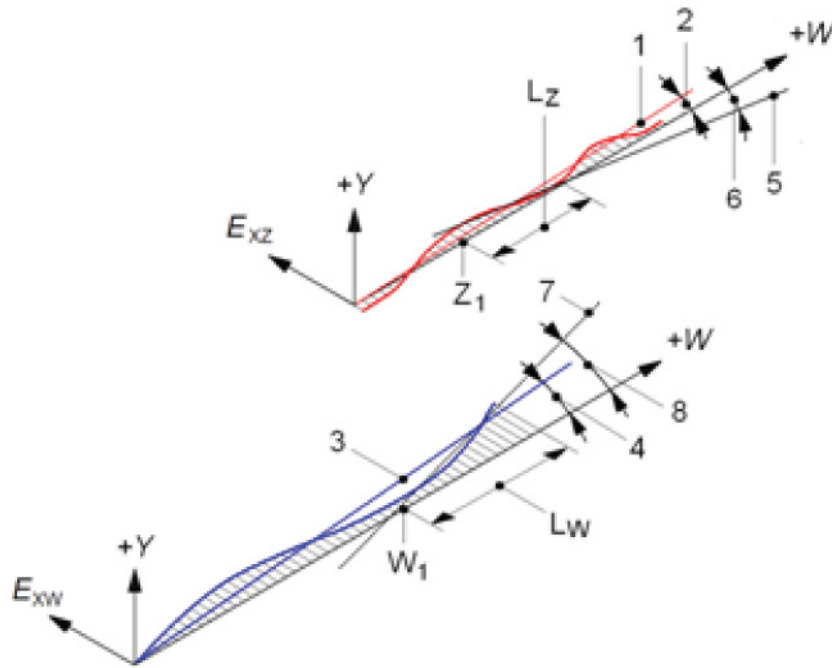
4  $E_{XW}$  reference straight line inclination;  $\theta_{W,ZX}$  (positive value, as shown)

5 reference straight line associated to  $E_{XZ}$  measurements over measurement length  $L_Z$  starting at  $Z_1$

6 inclination of reference straight line 5;  $\theta_{ZL,ZX}$  (negative value, as shown)

NOTE Local parallelism error:  $\theta_{Z1,ZX} - \theta_{W,ZX}$ .

**Figure 31 — Evaluation of local Z-axis parallelism error with respect to the full travel of the datum W-axis**

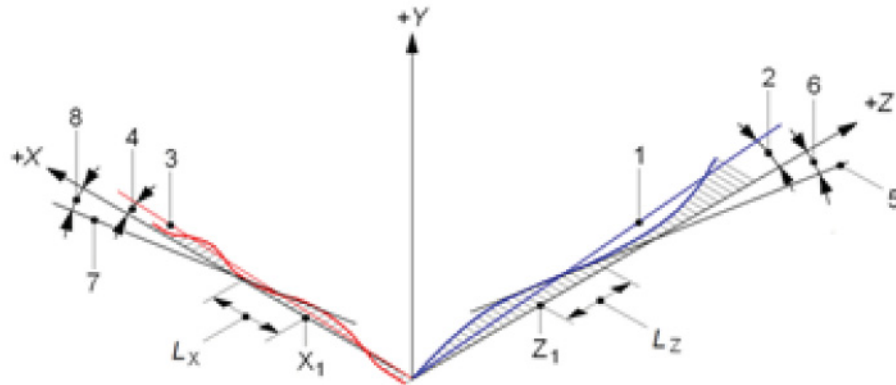


**Key**

- $E_{XZ}$  Z-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis
- $E_{XW}$  W-axis straightness deviations, measured in the ZX plane, with respect to a physical straightness reference aligned with the W-axis
- $L_W$  local W-axis measurement length
- $L_Z$  local Z-axis measurement length
- 1 reference straight line associated to  $E_{XZ}$  measurements over the full Z-axis travel
- 2 inclination of reference straight line 1;  $\theta_{Z1,ZX}$  (positive value, as shown)
- 3 reference straight line associated to  $E_{XW}$
- 4  $E_{XW}$  reference straight line inclination;  $\theta_{W,ZX}$  (positive value, as shown)
- 5 reference straight line associated to  $E_{XZ}$  measurements over measurement length  $L_Z$  starting at  $Z_1$
- 6 inclination of reference straight line 5;  $\theta_{ZL,ZX}$  (negative value, as shown)
- 7 reference straight line associated to  $E_{XW}$  measurements over measurement length  $L_W$  starting at  $W_1$
- 8 inclination of reference straight line 7;  $\theta_{ZW,ZX}$  (positive value, as shown)

NOTE Local parallelism error:  $\theta_{ZL,ZX} - \theta_{ZW,ZX}$ .

**Figure 32 — Evaluation of local Z-axis parallelism error with respect to the local travel of the datum W-axis**



### Key

- $L_X$  local X-axis measurement length
- $L_Z$  local Z-axis measurement length
- 1 reference straight line associated to  $E_{XZ}$ , evaluated over the full Z-axis travel
- 2  $E_{XZ}$  reference straight line inclination;  $\theta_{Z,ZX}$  (positive value, as shown)
- 3 reference straight line associated to  $E_{ZX}$ , evaluated over the full X-axis travel
- 4  $E_{ZX}$  reference straight line inclination;  $\theta_{X,ZX}$  (negative value, as shown)
- 5 reference straight line associated to  $E_{XZ}$  measurements over measurement length  $L_Z$  starting at  $Z_1$
- 6 inclination of reference straight line 5;  $\theta_{ZL,ZX}$  (negative value, as shown)
- 7 reference straight line associated to  $E_{ZX}$  measurements over measurement length  $L_X$  starting at  $X_1$
- 8 inclination of reference straight line 7;  $\theta_{XL,ZX}$  (positive value, as shown)

NOTE Local squareness error:  $E_{B0X} = \theta_{X,ZX} - \theta_{ZL,ZX}$ .

**Figure 33 — Evaluation of local squareness error between axes of linear motion**

Specification of local tolerances for parallelism error and squareness error between two axes of motion, defined over short measurement lengths, can tend to lose significance. Measurement results might be significantly bigger than the corresponding results evaluated over the entire available measurement lengths.

**EXAMPLE** Specification of tolerances for straightness error, parallelism error and squareness error shall consider the following three alternatives [related, for simplicity, to specification of parallelism error of Z-axis (referred axis) to W-axis (datum axis)].

- a) No specification for local tolerances.

Parallelism error of Z relative to W: full stroke of Z-axis over the full stroke of W-axis (corresponds to lines 1 and 3 in Figure 31).

- b) Specification of local tolerances for Z-axis only.

Parallelism error of Z relative to W for each 300 mm of Z: full stroke for W-axis, local measurement length of 300 mm for Z, evaluation of maximum difference over all contiguous 300 mm segments of Z (corresponds to lines 5 and 3 in Figure 31, whereas, for the evaluation,  $Z_1$  varies from 0 to full stroke minus 300 mm);

- c) Specification of local tolerances for Z-axis and local tolerances for W-axis.

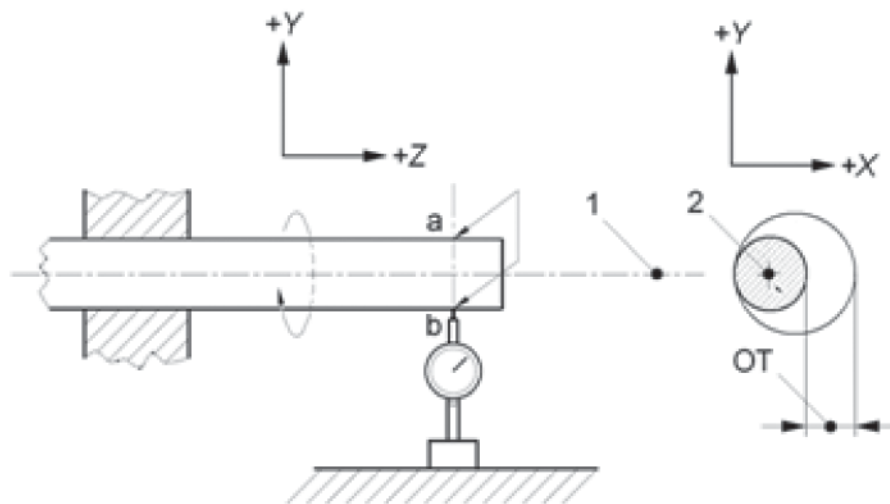
Parallelism error of Z relative to W for each 300 mm of Z and each 300 mm of W: local measurement length of 300 mm for Z-axis and for W-axis, evaluation of maximum difference over all possible 300 mm segments of Z and W (corresponds to lines 1 and 7 in Figure 32, whereas, for the evaluation,  $Z_1$  varies from 0 to overall Z-axis stroke minus 300 mm, and  $W_1$  varies from 0 to overall W-axis stroke minus 300 mm).

Specification of local tolerances shall primarily reflect functional requirements but due consideration shall be given to practical testing of the machine tool performances.

#### 4.1.4 Overall or inclusive tolerances

In many cases, overall tolerances are used to limit a geometric parameter which is the resultant effect of several geometric errors. Such a parameter is determined by a single measurement, without each error being individually known or measured.

**EXAMPLE** The run-out of a shaft shall be taken as the sum of the out-of-roundness of the circumference in the plane “ab”, with which the stylus is in contact, the coaxiality error between the geometric axis and the axis of rotation of the shaft and the radial error motion of the spindle axis of rotation in the plane “ab” (see Figure 34).



#### Key

- 1 axis average line
- 2 geometric axis of shaft
- ab measurement plane
- OT overall tolerance (run-out)

**Figure 34 — Overall tolerance for run-out of a rotating shaft**

#### 4.2 Tolerances applicable to machine tool functional surfaces, machine tool components and test pieces

ISO 1101 is the reference standard for tolerances applicable to machine tool components and workpiece characteristics. Such a standard shall also be applied for specification and testing of machine tool functional surfaces.

#### 4.3 Additional limiting conditions associated with tolerances

Specific functional requirements, as well as assembling and inspection requirements, might need to be stated by adding limiting conditions to the specification of tolerance for a given geometric characteristic or accuracy parameter. Such additional limiting conditions shall be specified with plain text. Table 1 contains a non-exhaustive list of such conditions.

Table 1 — Examples of additional limiting conditions associated with tolerances

| Geometric characteristic or accuracy parameter                                   | Reference for definition | Additional limiting conditions for the corresponding tolerance                                                                                                                                                                                                          |
|----------------------------------------------------------------------------------|--------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Parallelism of motions                                                           | 3.6                      | As a rule, the direction of the error is not important; however, if the error of parallelism is to be allowed only in one direction, the direction shall be indicated, e.g. angle between motions only greater than zero.                                               |
| Squareness involving axes of linear motion and/or axis of rotation average lines | 3.6.7<br>3.6.8<br>3.6.9  | When the squareness error is permissible in only one direction, that direction shall be indicated, e.g. angle greater than 90°.                                                                                                                                         |
| Intersection between axis average lines                                          | 3.7.4                    | If one of the two axis average lines can be considered as the reference axis, then the tolerance may have additional specification e.g. axis average line 1 to be higher than (or in front of) axis average line 2.                                                     |
| Equidistance of axis average lines                                               | 3.7.3                    | If the difference is permissible in one direction only, that direction shall be specified, e.g. axis average line 1 higher than axis average line 2.                                                                                                                    |
| Coaxiality of axis average lines                                                 | 3.7.2                    | In special cases, an additional indication may be given depending on operating conditions, for instance:<br>— axis average line 1 only higher than axis average line 2,<br>— free end of axis average line 1 directed only outwards in relation to axis average line 2. |
| Straightness and/or flatness of functional surfaces                              | ISO 1101                 | Additional requirement could be specified, were applicable, e.g. concave or convex (with respect to the material side).                                                                                                                                                 |

## 5 Uncertainty of measurements, test methods and measuring instruments

Uncertainty of measurement should be taken into account when specifying tolerances and when evaluating conformance with specified tolerances.

When reporting the result of a measurement, a quantitative indication of the quality of the result shall be given in order to allow the comparison of measurement results, either among themselves or with specified values. Such quantitative indication is evaluated and expressed as the measurement uncertainty.

ISO/IEC Guide 98-3 contains internationally recognized procedures for the expression and the evaluation of measurement uncertainty.

ISO/TR 230-9 provides practical information for the estimation of measurement uncertainty for machine tool tests according to the ISO 230 series.

ISO 14253-2 introduces the Procedure for Uncertainty Management (PUMA). Other practical information can be found in Knapp<sup>[7]</sup>, W. Knapp *et al.*<sup>[8]</sup> and Bell<sup>[9]</sup>.

It shall be considered that simplified testing for verification purposes does not require the preparation of a formal statement for measurement uncertainty, nevertheless good practice suggests that an uncertainty budget is made available for all most common measurements (straightness, squareness, accuracy and repeatability of positioning numerically controlled axes, etc.) with the application of the available testing procedures and measurement systems.

Proper definition of the object of the measurement (the measurand) is indispensable. No measurement shall be performed without clear understanding of what shall be measured and under what conditions.

The main contributors to the measurement uncertainty shall be taken as:

- a) the measurement uncertainty of the measuring device;
- b) the calibration uncertainty and deviations of artefacts;
- c) the application of the measuring device and the artefacts, such as misalignment and centring of the measuring device and artefacts to the machine tool axis;
- d) environmental variation errors, such as temperature influences and vibration;
- e) the repeatability of the measurement including the set up.

The following assumptions shall be made.

- The measurement device and artefacts are used according to the guidelines of the equipment supplier/manufacturer.
- The measurement device and artefacts are mounted statically and dynamically stiff and without any hysteresis (see 6.3.2).
- The machine components holding the equipment behave as rigid bodies, if not stated otherwise.
- If these assumptions are not fulfilled, additional contributors to the measurement uncertainty shall be taken into account and reported.
- For any measurement, the combined standard uncertainty [in accordance with Equation (1) of ISO/TR 230-9:2005] should be calculated and the measurement uncertainty,  $U$ , should be stated for a coverage factor  $k$  of 2 [in accordance with Equation (3) of ISO/TR 230-9:2005].
- Geometrical tests are generally performed using measuring instruments, reference artefact(s) and/or natural references (e.g. light beam, gravity). Reference artefacts are objects, such as straightedges and test mandrels.
- Inaccuracies of measurement due to the instruments, as well as to the methods used, shall be taken into account during the tests.
- The measuring instrument should not cause any error of measurement exceeding a given fraction of the tolerance to be verified. A calibration sheet should be available for each instrument. Machines under test and instrumentation should be protected from effects of external temperature variation, such as draughts and from disturbing light or heat radiation (sunlight, excessively close electric lamps, etc.), and the temperature of the measuring instruments should be stabilized before measuring.
- A given measurement should preferably be repeated, the result of the test being obtained by taking the average of the measurements. If the measurement results vary significantly, the cause should be sought either in the method or the measuring instrument, or in the machine tool itself. For more precise indications, see ISO/TR 230-11.

## 6 Preliminary operations

### 6.1 Installation of the machine before tests

#### 6.1.1 General

The machine shall be completely assembled and fully operational in accordance with the supplier/manufacturer's instructions that shall be provided in written form. All necessary operations, geometric alignment and functional checks shall be completed satisfactorily and results be documented before starting the tests.

The machine tool should be installed on a suitable foundation subject to agreement between the supplier/manufacture and the user. Geometric tests shall be carried out in an environment with acceptable vibration conditions. If vibration problems occur, environmental vibration values (amplitude and frequency) should be checked to satisfy the requirement of the manufacturer. The vibration test methods are specified in ISO/TR 230-8.

### 6.1.2 Levelling

The aim of the levelling is to obtain the condition of static stability of the machine, which facilitates subsequent measurements, especially those relative to the straightness of certain components.

Although often a convenient method for achieving straightness of motion, absolute levelling is not a requirement for machine tools (e.g. machine tools used in ships cannot be levelled, but function just like the stationary machine tools).

## 6.2 Conditions before machine tests

### 6.2.1 Disassembling of certain components

As the tests are carried out, in principle, on a completely finished machine, disassembling of certain components should only be carried out in exceptional circumstances, in accordance with the instructions of the supplier/manufacture (e.g. disassembling of a machine table in order to check the slideways).

### 6.2.2 Temperature conditions of certain components before tests

The aim of the tests described in this part of ISO 230 is to evaluate the accuracy of the machine under conditions as near as possible to those of normal operation as regards lubrication and warm up. During the geometric and machining tests, components such as spindles, which are susceptible to warm up and consequently to changing position or shape, shall be brought to the proper temperature by idling the machine in accordance with the conditions of use and the instructions of the supplier/manufacture.

In accordance with ISO 1, the reference temperature for industrial dimensional measurements is 20 °C, therefore the measuring instruments and the measured objects should be in equilibrium with the environment where the temperature is kept at 20 °C. If the environment is at a temperature other than 20 °C, Nominal Differential thermal Expansion (NDE) correction between the measurement system and the measured object (machine tool) shall be made to correct the results to correspond to 20 °C.

**NOTE** Special conditions can be applied to high-precision machines and some numerically controlled machines for which temperature fluctuations have a marked effect on the accuracy.

It shall be taken into consideration how much the machine alters in dimensions during a normal working cycle from ambient to working temperature. The preliminary warm-up sequence and the ambient temperature at which the machine is to be tested should be the subject of agreement between the supplier/manufacture and the user.

Useful information on the machine tool thermal environment can be gathered from ISO 230-3:2007, Annex C.

### 6.2.3 Preliminary checks

Spindle speeds and feedrates may influence geometric and machining tests. Therefore, conformance of actual spindle speeds and feedrates with those commanded should be verified before conducting these tests.

### 6.2.4 Operating conditions

Geometric tests shall be made either when the machine is at a standstill (e.g. flatness) or when it is running under quasi-static no-load conditions. However, under special circumstances, the machine supplier/manufacture and the user may agree that the tests be run with a specified workpiece weight.

## 6.3 Test setup and instrumentation

### 6.3.1 General

Most measurements described in this part of ISO 230 are carried out to measure error motion between the component of the machine that holds the workpiece and the component of the machine that holds the cutting tool.

The setups and instrumentation described are provided as suggestions only. Other instruments and setups capable of measuring the same quantities and having the same or smaller measurement uncertainty may be used. All software compensation used shall be stated on the test report.

Attention shall be devoted to the thermal stabilization of the instruments in accordance with the manufacturer/supplier's instructions (see ISO/TR 230-11).

All test setups normally involve two fixtures, one which establishes the reference point or surface, and the second which holds some type of sensor to read against this reference point or surface. The reference point can be the test ball or the retroreflector. The sensor can be a linearly variable differential transformer (LVDT), a capacitance gauge, an eddy current sensor, laser interferometer or a dial indicator. Before starting any of the measurements, ensure that the particular setup and instrumentation function properly within the machine tool environment. Two main tests are recommended for such checks: setup hysteresis and stability.

### 6.3.2 Setup hysteresis and play test

The goal of this test is to discover any effects of setup hysteresis or play, which may be caused by loose bolts in test setups, insufficient structural strength in the brackets, etc. Any hysteresis associated with the setup used for geometric accuracy measurements is normally observed as lack of repeatability in measurement results, which may erroneously be attributed to the machine's behaviour.

Hysteresis of a measurement setup is determined by applying a suitable bi-directional force, in the measurement direction, between the two fixtures and observing the resulting deflection. The sensitivity of the test result to the magnitude of such force is, in general, insignificant. The range of forces can be between 20 N and 200 N, depending upon the test setup and the resolution of the linear displacement sensor. The forces applied should not threaten damage to the machine or the metrology setups. Forces less than 40 N are recommended to avoid causing machine hysteresis. There is no need to measure forces.

The test procedure is the following.

- a) Set up and zero a displacement sensor between the two fixtures in the direction and location of the intended axis performance test.
- b) Apply a force, by hand, to the fixture holding the reference point/surface.
- c) After the force is applied, gradually decrease this force to zero and read the displacement sensor.
- d) Apply a force by hand in the opposite direction, gradually decrease the force to zero and read the displacement sensor.
- e) The difference in readings is the reference point/surface fixture hysteresis.
- f) Apply the force to the fixture holding the displacement sensor.
- g) Gradually decrease this force to zero and read the displacement sensor.
- h) Apply a force by hand in the opposite direction, gradually decrease the force to zero and read the displacement sensor.
- i) The difference in readings is the displacement sensor fixture hysteresis.