INTERNATIONAL STANDARD

# ISO 13041-2

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# Test conditions for numerically controlled turning machines and turning centres —

## Part 2: Geometric tests for machines with a vertical workholding spindle

*Conditions d'essai des tours à commande numérique et des centres de tournage —*

*Partie 2: Essais géométriques pour les machines à broche verticale*

Reference number
ISO 13041-2:2008(E)

# Contents

Page

# 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 13041-2 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

ISO 13041 consists of the following parts, under the general title *Test conditions for numerically controlled turning machines and turning centres*:

— *Part 1: Geometric tests for machines with horizontal workholding spindle*

— *Part 2: Geometric tests for machines with vertical workholding spindle*

— *Part 3: Geometric tests for machines with inverted vertical workholding spindles*

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

— *Part 5: Accuracy of feeds, speeds and interpolations*

— *Part 6: Accuracy of a finished test piece*

— *Part 7: Evaluation of contouring performance in the coordinate planes*

— *Part 8: Evaluation of thermal distortions*

# Introduction

The object of ISO 13041 (all parts) is to supply information as wide and comprehensive as possible on geometric, positional, contouring, thermal and machining tests which can be carried out for comparison, acceptance, maintenance or any other purpose.

ISO 13041 (all parts) specifies, with reference to ISO 230-1 and ISO 230-7, tests for turning centres and numerically controlled turning machines with/without tailstocks standing alone or integrated in flexible manufacturing systems. ISO 13041 (all parts) also establishes the tolerances or maximum acceptable values for the test results corresponding to general-purpose and normal-accuracy turning centres and numerically controlled turning machines.

# Test conditions for numerically controlled turning machines and turning centres —

# Part 2: Geometric tests for machines with a vertical workholding spindle

## 1 Scope

This part of ISO 13041 specifies, with reference to ISO 230-1 and ISO 230-7, the geometric tests on general purpose numerically controlled (NC) turning machines and tuning centres with vertical workholding spindles, as well as the corresponding applicable tolerances.

This part of ISO 13041 explains different concepts or configurations and common features of NC turning machines and turning centres with vertical workholding spindles. It also provides a terminology and designation of controlled axes (see Figures 1, 2, 3, and 4).

This part of ISO 13041 deals only with the verification of the accuracy of the machine. It does not apply to the operational testing of the machine (e.g. vibration, abnormal noise, stick slip motion of components) nor to machine characteristics (e.g. speeds, feeds) as such checks are generally carried out before testing the accuracy.

## 2 Normative references

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

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

ISO 230-7:2006, *Test code for machine tools — Part 7: Geometric accuracy of axes of rotation*

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

## 3 Terms and definitions

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

**3.1**
**turning machine**
machine tool in which the principal movement is the rotation of the workpiece against the stationary cutting tool(s)

**3.2**
**manual control**
mode of operation where each movement of the machine is individually initiated and controlled by the operator

**3.3**
**numerical control (NC)**
**computerized numerical control (CNC)**
automatic control of a process performed by a device that makes use of numerical data introduced while the operation is in progress

[ISO 2806:1994]

**3.4**
**manually controlled turning machine**
turning machine whose process steps for the machining are controlled or started by an operator without support from a numerically controlled machining program

**3.5**
**numerically controlled turning machine**
**NC turning machine**
turning machine that operates under **numerical control** (**NC**, 3.3) or **computerized numerical control** (**CNC**, 3.3)

**3.6**
**numerically controlled vertical spindle-turning machine**
numerically controlled turning machine where the workpiece is mounted on a vertical workholding spindle against the stationary cutting tool(s) and where cutting energy is brought by the workpiece and not by the tool

NOTE 1 This machine is controlled by a numerical control (NC) providing automatic function.

NOTE 2 For vertical spindle-turning machines with inverted workholding spindle, i.e. with workholding device at the lower end of the spindle, see ISO 13041-3.

**3.7**
**vertical spindle-turning centre**
numerically controlled vertical spindle-turning machine equipped with toolholding spindles and the capacity to orientate the workholding spindle around its axis

NOTE 1 This machine may include additional features such as automatic toolchanging from a magazine or Y-axis motion.

NOTE 2 For vertical spindle-turning machines with inverted workholding spindle, i.e. with workholding device at the lower end of the spindle, see ISO 13041-3.

# 4 Preliminary remarks

## 4.1 Units of measurement

In this part of ISO 13041, all linear dimensions, deviation, and corresponding tolerances are expressed in millimetres; angular dimensions are expressed in degrees, and angular deviations and the corresponding tolerance are expressed in ratios, but in some cases microradians or arc seconds may be used for clarification purposes. The equivalence of the following expressions should always be kept in mind.

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

## 4.2 Reference to ISO 230-1 and ISO 230-7

To apply this part of ISO 13041, reference shall be made to ISO 230-1, especially for installation of the machine before testing, warming up of the spindle and over-moving components, description of measuring methods and recommended measurement uncertainty of testing equipment.

In the “Observation” block of the tests described in Clause 5, the instructions are preceded by a reference to the corresponding clause in ISO 230-1 or in ISO 230-7 in cases where the test concerned is in compliance with their specifications. Tolerances are given for each test (see G1 to G21).

## 4.3 Machine levelling

Prior to conducting tests on a machine, the machine should be levelled according to the recommendations of the supplier/manufacturer (see ISO 230-1:1996, 3.11).

## 4.4 Test sequence

The sequence in which tests are presented in this part of ISO 13041 in no way defines the practical order of testing. In order to make the mounting of instruments or gauging easier, tests may be performed in any order.

## 4.5 Test to be performed

When testing a machine, it is not always necessary or possible to carry out all the tests described in this part of ISO 13041. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the supplier/manufacturer, those tests relating to the components and/or the properties of the machine which are of interest. These tests are to be clearly stated when ordering a machine. Mere reference to this part of ISO 13041 for the acceptance tests, without specifying the tests to be carried out, and without agreement on the relevant expenses, cannot be considered as binding for any contracting party.

## 4.6 Measuring instruments

The measuring instruments indicated in the tests described in the following are examples only. Other instruments measuring the same quantities and having at least the same measurement uncertainty may be used. Linear displacement sensors shall have a resolution of 0,001 mm or better.

## 4.7 Diagrams

In this part of ISO 13041, for reasons of simplicity, the diagrams associated with geometric tests generally illustrate only one type of machine.

## 4.8 Software compensation

When built-in software facilities are available for compensating geometric, positioning, contouring, and thermal deviations, their use during these tests should be based on an agreement between the user and the supplier/manufacturer. When software compensation is used, this shall be stated in the test report.

### 4.9 Minimum tolerance

When the tolerance for a geometric test is established for a measuring length different from that given in this part of ISO 13041 (see ISO 230-1:1996, 2.311), it shall be taken into consideration that the minimum value of tolerance is 0,005 mm.

### 4.10 Machine classifications

The machines considered in this part of ISO 13041 are divided into the following basic configurations:

— type A: single column machines (Figure 1);

— type B: dual column machines (Figure 2).

Type B machine configurations are further classified into the following types:

— fixed columns — portal type;

— moving columns — gantry type.

### 4.11 Linear motions

For simplicity, all the machine examples shown in Figures 1 and 2 use the axis designation of a letter and a number (e.g. X, X1, X2…) as defined in ISO 841:2001, 6.1. In all examples the use of the letters U, V, or W could be substituted.

### 4.12 Turrets — toolholding components (element)

Depending on the machine configuration, cutting tools (stationary or power driven) can be located on the railhead ram and/or the side head ram and/or the turret. An automatic tool change device can also be used. However, ISO 13041 (all parts) does not provide any test methods for automatic tool change operations.

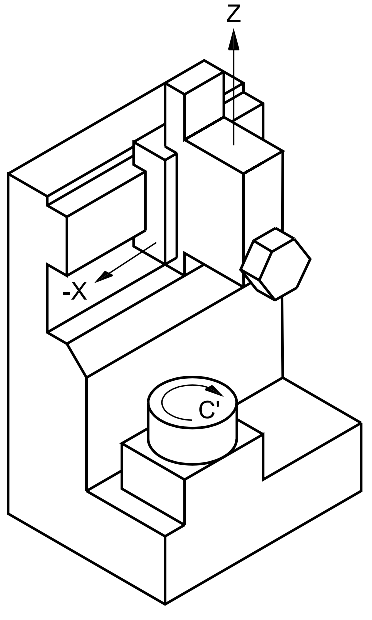
### 4.13 Machine size category

The machines are classified into four size categories, on the basis of the criteria specified in Table 1.

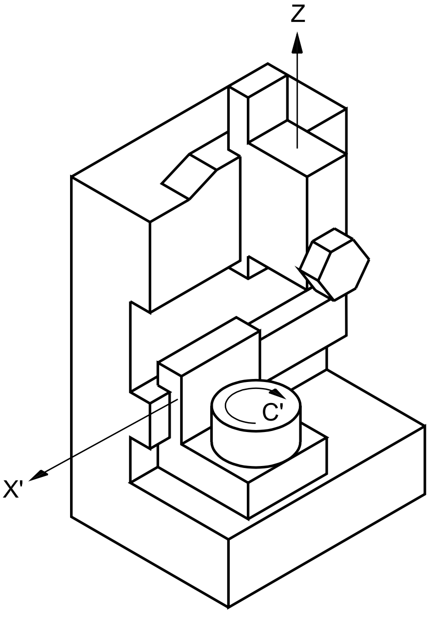
**Table 1 — Machine size range**

| Criteria | Category 1 | Category 2 | Category 3 | Category 4 |
|---|---|---|---|---|
| **Nominal diameter of chuck** $d$ | $d \leqslant 500$ | $500 < d \leqslant 1\,000$ | $1\,000 < d \leqslant 5\,000$ | $d > 5\,000$ |
| **Diameter of workholding spindle/table** $D$ | $D \leqslant 500$ | $500 < D \leqslant 1\,000$ | $1\,000 < D \leqslant 5\,000$ | $D > 5\,000$ |
| NOTE 1 The choice of criteria is at the manufacturer's discretion. | | | | |
| NOTE 2 Nominal diameter of chuck (up to 800 mm) is defined in ISO 3442-1, ISO 3442-2, and ISO 3442-3. | | | | |

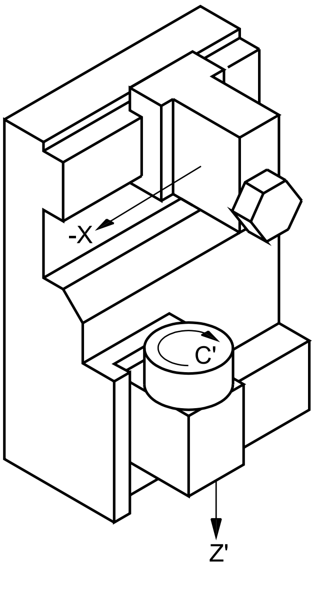
### 4.14 Machine configurations



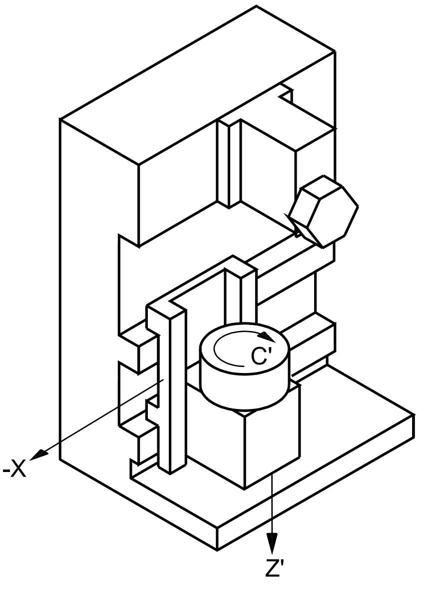

**a) Compound head type**




**b) Shared motion (moving workholding spindle) type**

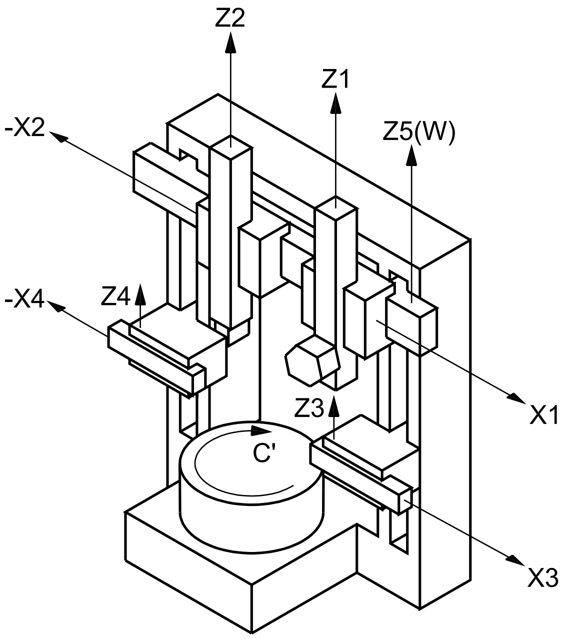



**c) Shared motion (moving head/saddle) type**

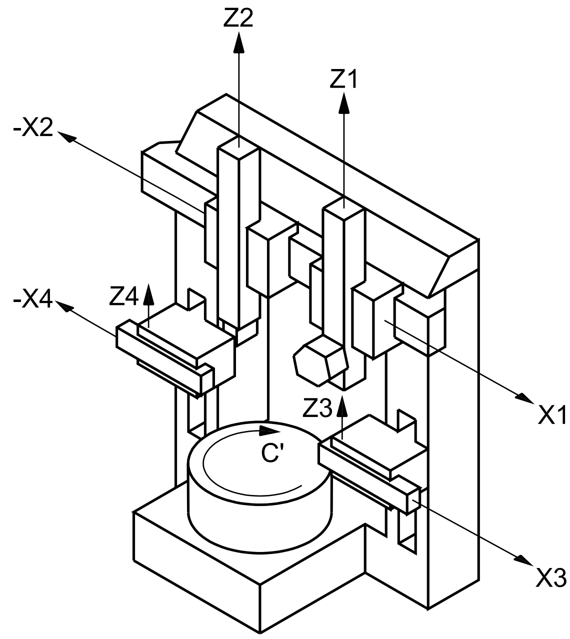



**d) Compound workholding spindle type**

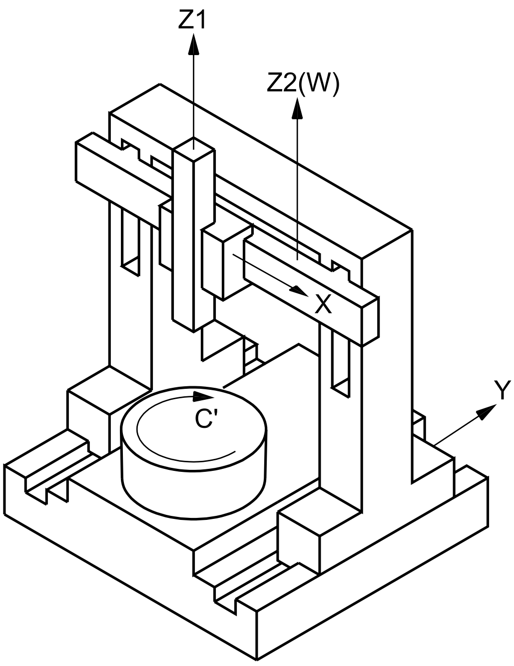
**Figure 1 — Examples of machine configurations: single column machines (type A)**



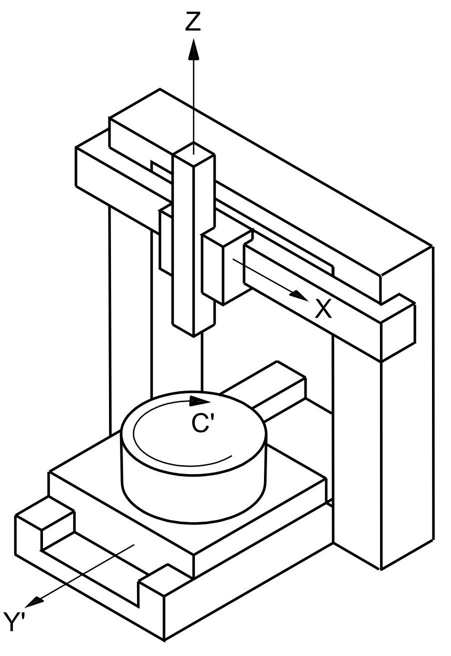

a) Fixed column, moving cross-rail




b) Fixed column, fixed cross-rail




c) Moving column (gantry type),
moving cross-rail




d) Fixed column (portal type),
moving workholding spindle (Y axis)

**Figure 2 — Examples of machine configurations: dual column machines (type B)**

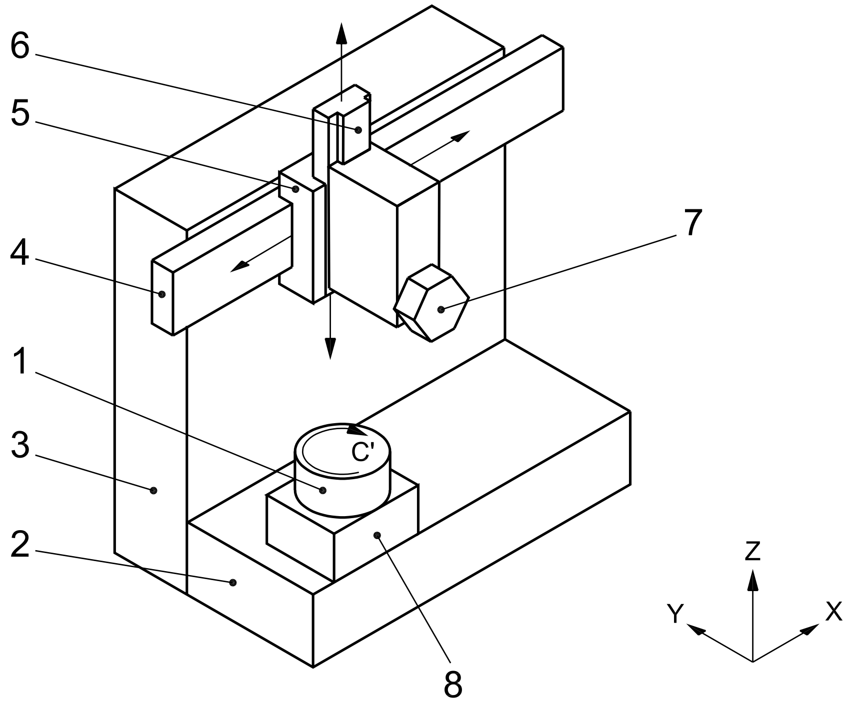



**Figure 3 — Machine with single column**

**Table 2 — Terminology corresponding to Figure 3**

| Item number | Designation | | |
|---|---|---|---|
| | English | German | French |
| 1 | workholding spindle (turntable) | Spannfutter | broche porte-outils |
| 2 | base | Maschinenbett | base |
| 3 | column | Maschinenständer | montant |
| 4 | cross-rail | Querführung | traverse porte-chariot |
| 5 | railhead (saddle) | Querschlitten | chariot de traverse (traînard) |
| 6 | turret slide | Revolverschlitten | chariot de tourelle |
| 7 | turret | Revolver | tourelle |
| 8 | workholding spindle head | Spindelkasten | tête de broche porte-outils |

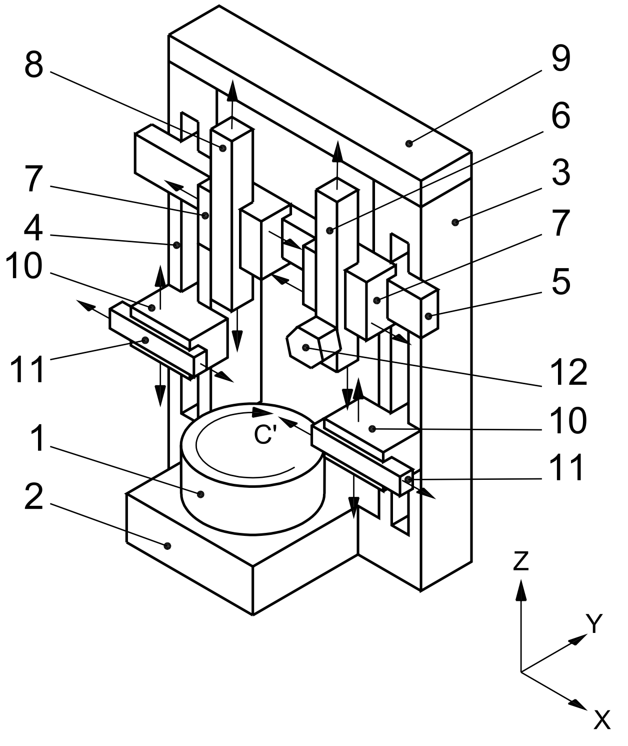



**Figure 4 — Machine with dual columns**

**Table 3 — Terminology corresponding to Figure 4**

| Item number | Designation | | |
|---|---|---|---|
| | English | German | French |
| 1 | workholding spindle (turntable) | Spannfutter | broche porte-outils |
| 2 | base | Maschinenbett | base |
| 3 | right-hand column | rechter Maschinenständer | montant droit |
| 4 | left-hand column | linker Maschinenständer | montant gauche |
| 5 | cross-rail | Querführung | traverse porte-chariot |
| 6 | turret slide | Revolverschlitten | chariot de tourelle |
| 7 | railhead (saddle) | Querschlitten | chariot de traverse (traînard) |
| 8 | railhead ram | Traghülse | coulisseau du chariot de traverse |
| 9 | bridge | Brücke/Traverse | traverse |
| 10 | side head | seitlicher Werkzeugträger | chariot porte-outils latéral |
| 11 | side head ram | seitliche Traghülse | broche porte-outils |
| 12 | turret | Revolver | tourelle |

# 5 Geometric tests

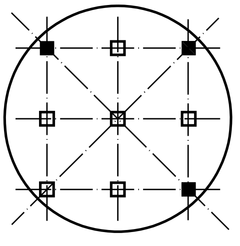
## 5.1 Workholding spindle

**Object** — **G1**

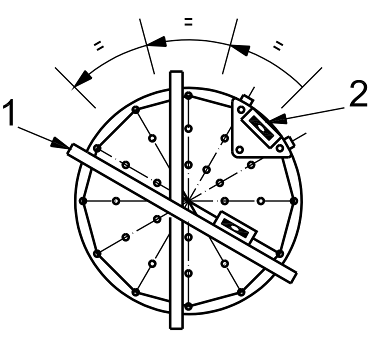
To check the flatness of the workholding spindle face (workholding table).

NOTE Table type only.

**Diagram**



Alternative




**Key**

1 guide bar

2 isostatic 3-bearing support

**Tolerance**

Local tolerance 0,01 over any measuring length of 300.

| Category 1 | Category 2 | Category 3 | Category 4 |
|---|---|---|---|
| 0,02 | 0,03 | 0,07 | 0,07 |

NOTE Category 4 machines only — for each further 1 000 increase in diameter, increase the tolerance by 0,01.

Spindle face shall not be convex.

**Measured deviation**

**Measuring instruments**

Straightedge, gauge blocks and linear displacement sensor or optical instruments

For alternative method: Guide bar and support blocks, precision level and an isostatic 3-bearing support.

**Observations and references to ISO 230-1:1996**, 5.322, 5.324

Alternative method (checking with the aid of a precision level): 5.323

1) Circular checking

   The precision level shall be placed on a support having three bearing points on the workholding table.

   The isostatic 3-bearing support shall be moved to positions equally spaced along the workholding table.

2) Diametrical checking

   The precision level shall be placed on the workholding table and along a diametrical direction with the aid of a guide bar.

   The precision level shall be moved at positions equally spaced along the guide bar.

   The procedure shall be repeated, moving the guide bar according to the successive positions occupied by the isostatic 3-bearing support or at maximum of 12 intervals (minimum of 30°).

Subject to agreement between manufacturer and user, it is permissible to carry out diametrical checking only.

**G2**

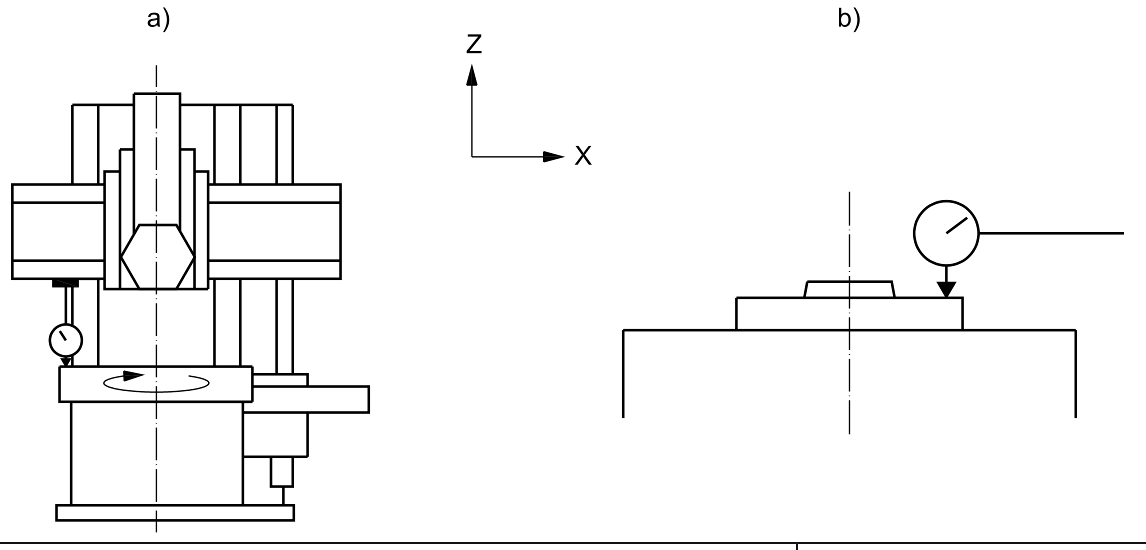
**Object**

To check the face run-out of workholding spindle:

a) face run-out of the workholding table surface;

b) face run-out of the spindle face.

**Diagram**




**Tolerance**

| | Category 1 | Category 2 | Category 3 | Category 4 |
|---|---|---|---|---|
| a) | 0,01 | | 0,035 | 0,05 |

NOTE Category 4 machines only — for each further 1 000 increase in diameter, increase the tolerance by 0,01.

| | Category 1 | Category 2 | Category 3 | Category 4 |
|---|---|---|---|---|
| b) | 0,01 | 0,015 | 0,02 | 0,02 |

**Measured deviation**

a)

b)

**Measuring instruments**

Linear displacement sensor

**Observations and references to ISO 230-1:1996**, 5.632

a) The linear displacement sensor shall be placed on a fixed part of the machine and shall be placed as near as possible to the workholding table periphery and approximately 180° from the position occupied by the tool when the workholding spindle was machined.

Cross-rail and railhead locked in position, where possible.

b) Measurements shall be taken on the maximum diameter.

NOTE If detaching the workholding table is difficult, this test need not be done.

| **Object** | **G3** |
|---|---|

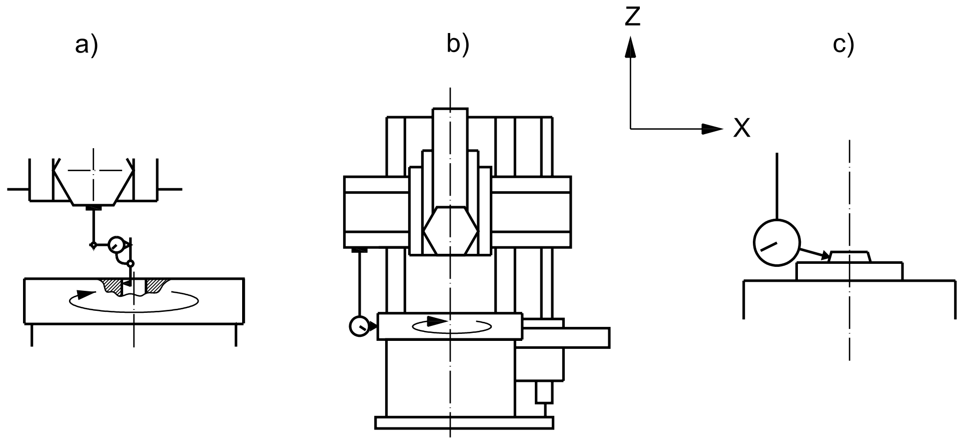
To check run-out of

a) the workholding spindle bore;

b) the external cylindrical surface of the workholding spindle (in the case of a workholding spindle not having a central bore);

c) centring diameter.

**Diagram**




| **Tolerance** | | | | | **Measured deviation** |
|---|---|---|---|---|---|
| | **Category 1** | **Category 2** | **Category 3** | **Category 4** | |
| a) and b) | 0,01 | 0,02 | 0,035 | 0,05 | a) |
| NOTE Category 4 machines only — for each further 1 000 increase in diameter, increase the tolerance by 0,01. | | | | | b) |
| c) | 0,01 | 0,015 | 0,02 | 0,02 | c) |

**Measuring instruments**

Linear displacement sensor

**Observations and references to ISO 230-1:1996**, 5.611.4 and 5.612.2

a) The linear displacement sensor shall be placed approximately 180° from the position occupied by the tool when the workholding spindle was machined.

Cross-rail, railhead and slide locked in position, where possible.

The linear displacement sensor shall also be placed on a fixed part of the machine.

b) Subclauses 5.611.4 and 5.612.2.

c) Subclause 5.612.2. When the surface is conical, the stylus of the linear displacement sensor shall be normal to the contacting surface.

## 5.2 Relationship between workholding spindle and linear axes of motion

**Object** — **G4**

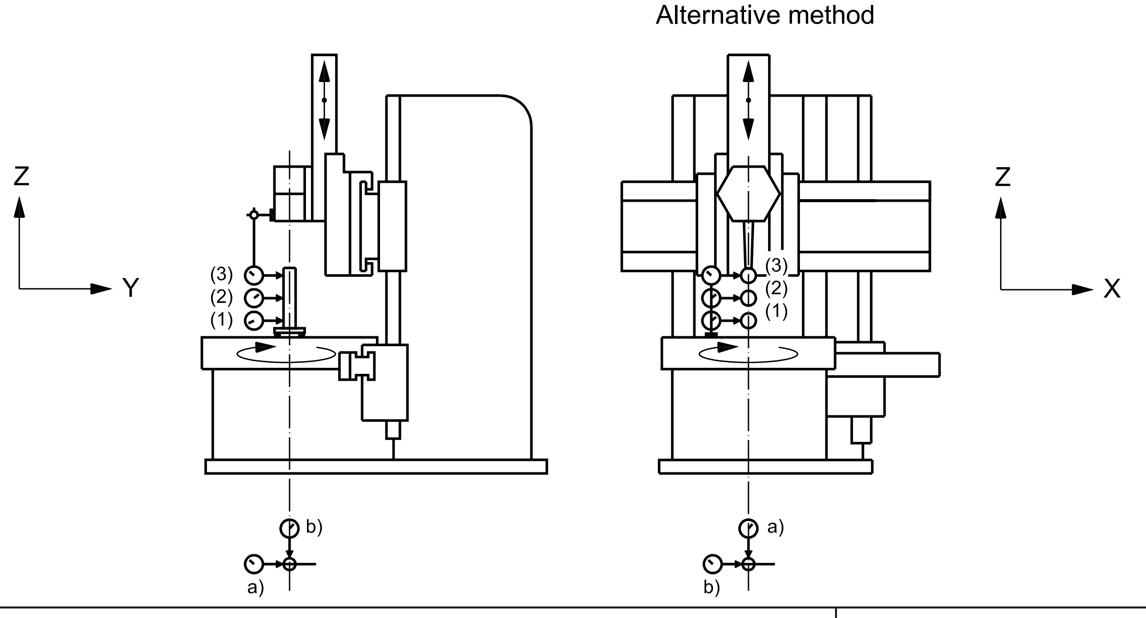
To check the parallelism between the Z-axis motion (railhead ram or turret slide) and the workholding spindle axis of rotation:

a) in the YZ plane;

b) in the XZ plane.

NOTE Also applicable for a second railhead ram and turret slides on the column.

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| a) 0,015 for the measuring length of 300 | a) |
| b) 0,01 for the measuring length of 300 | b) |

**Measuring instruments**

Test mandrel or cylindrical square and linear displacement sensors and adjustable blocks

Alternative method: Precision test ball and linear displacement sensors

**Observations and references to ISO 230-1:1996**, 5.412.1 and 5.422.3

Turn the workholding spindle to find the mean position of run-out and then move railhead ram successively in the Z direction to the upper position (3), mid-travel (2), and in the lower position (1) and take the maximum difference of the readings. The largest change of the difference gives the parallelism deviation in the XZ plane. The test is then repeated for the YZ plane.

**Alternative method**

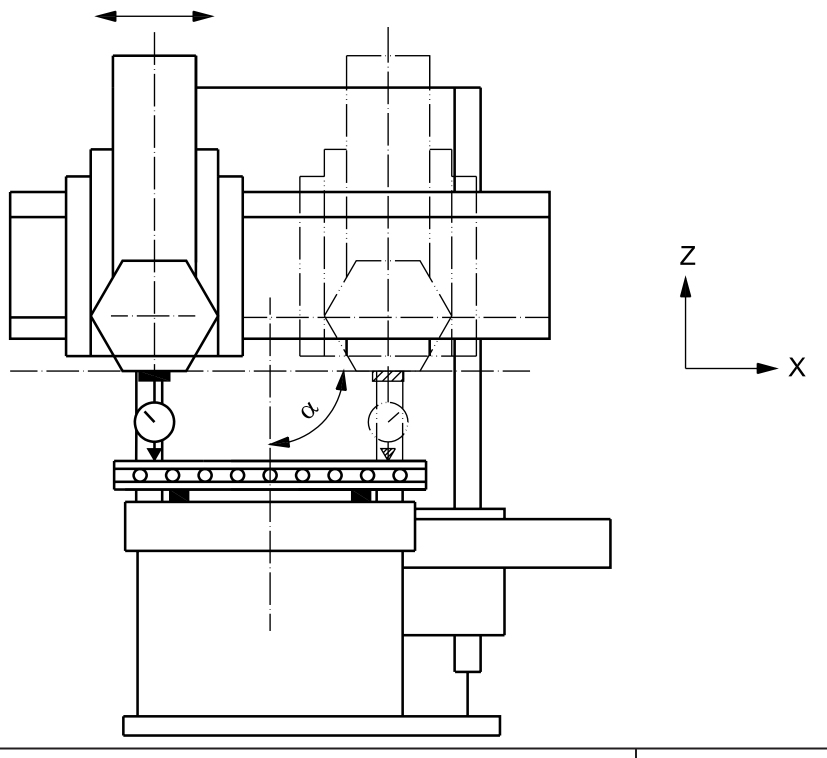
In this case, the test ball is positioned just using the Z-axis travel and the measurement repeated for each position (1, 2 and 3). The readings at 0° and 180° are taken and the difference between these two readings is noted for positions 1, 2 and 3. The largest change of the difference gives the parallelism deviation in the YZ plane. The test is then repeated for the XZ plane.

If the machine under test has an adjustable cross-rail, the test should be repeated with the cross-rail in its lower, mid, and upper positions. This test applies to all railheads.

| **Object** | **G5** |
|---|---|
| To check the squareness between the railhead motion (X axis) and the workholding spindle axis of rotation (C axis). | |

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| For a measuring length of 300 or full stroke up to 300:<br>categories 1 and 2: 0,020<br>categories 3 and 4: 0,030<br>Direction of deviation: $\alpha \geqslant 90°$ | |

**Measuring instruments**

Straightedge, adjustable blocks and linear displacement sensor

**Observations and references to ISO 230-1:1996,** 5.422.22, 5.522.2

A linear displacement sensor is fixed to the turret close to the tool position.

Block gauges are used to set the straightedge square to the workholding spindle rotation axis.

Checking shall be carried out by placing the stylus of the linear displacement sensor placed on the railhead onto a straightedge laid square to the axis of rotation of the workholding spindle.

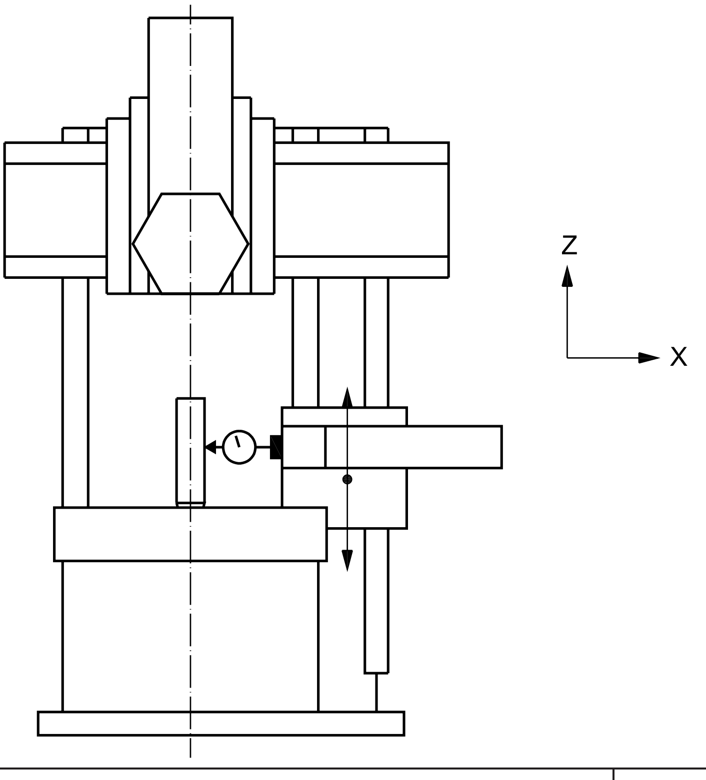
Or

Set straightedge approximately parallel to the work table surface. Measurements should be taken at several positions of the X-axis motion, then rotate the spindle through 180° and take a second set of measurements at the same X locations. The squareness deviation is the range of the mean of these two sets of measurements. The surface generated shall be concave unless by special arrangement between the user and supplier/manufacturer.

| **Object** | **G6** |
|---|---|
| To check the parallelism between the side head (Z axis) motion and the workholding spindle axis of rotation (C axis). | |

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| 0,02 over a measuring length of 300 | |

**Measuring instruments**

Test mandrel or cylindrical square and linear displacement sensor

**Observations and references to ISO 230-1:1996**, 5.422.3

Turn the workholding spindle to find the mean position of run-out and then move the side head in the Z direction and take maximum difference of the readings.

Or

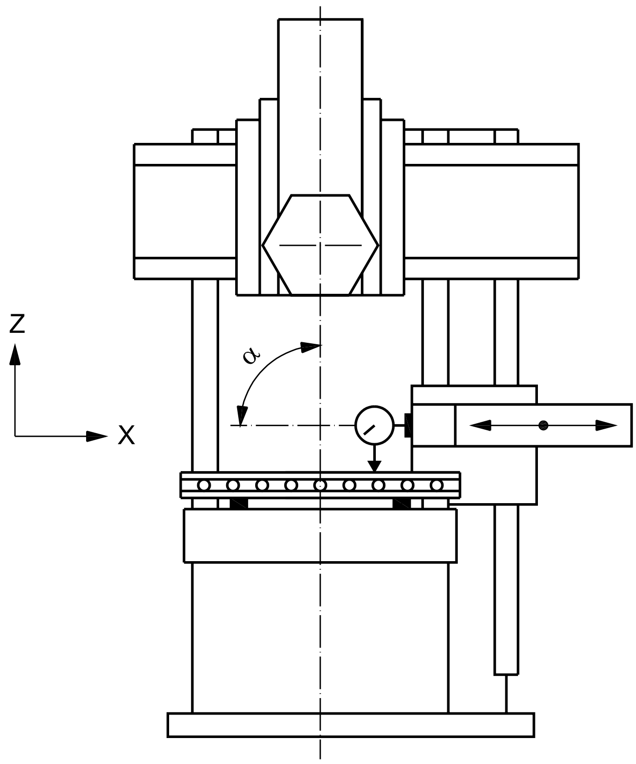
Take readings at several positions of the Z axis and then rotate the workholding spindle by 180° and take the second set of readings at the same Z positions. The parallelism deviation is the range of the mean of these two sets of measurements.

This test applies to all side heads.

**Object** — **G7**

To check the squareness between the side head ram (X axis) motion and the workholding spindle axis of rotation.

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| 0,02 over a measuring length of 300<br>Direction of deviation: $\alpha \geqslant 90°$ | |

**Measuring instruments**

Straightedge, gauge blocks, and linear displacement sensor

**Observations and references to ISO 230-1:1996**, 5.522.2

The side head shall be locked in position.

Gauge blocks are used to set the straightedge perpendicular to the workholding spindle rotation axis.

Checking shall be carried out by placing the stylus of the linear displacement sensor placed on the side head ram on to a straightedge laid square to the axis of rotation of the workholding spindle.

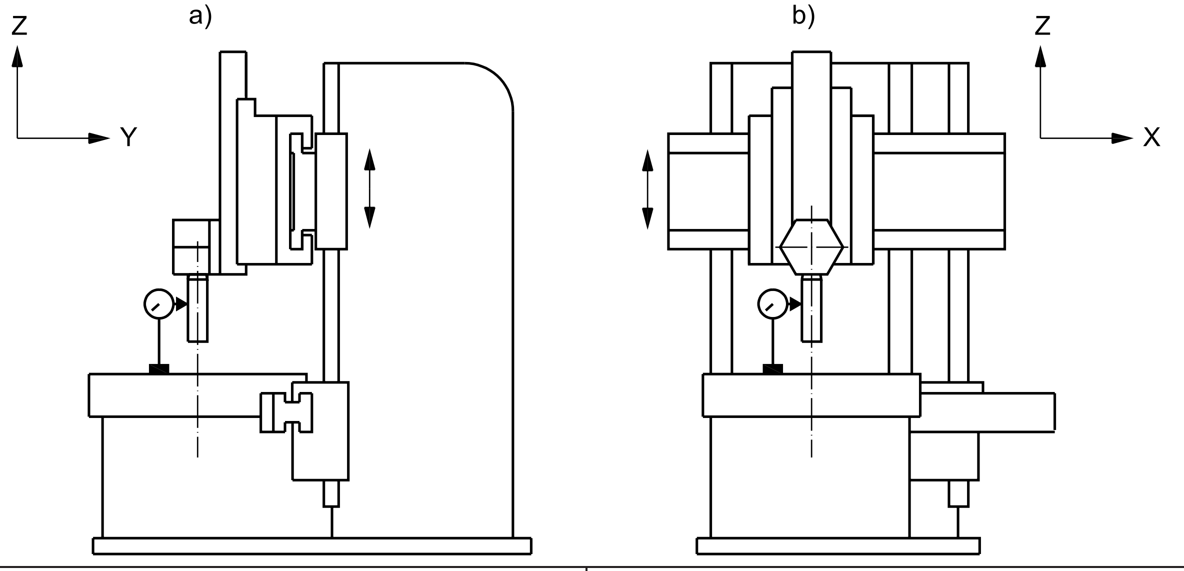
Or

Set straightedge approximately parallel to the work table surface. Take readings at several positions of the X axis and then rotate the C axis by 180° and take the second set of readings at the same X positions. The squareness deviation is the range of the mean of these two sets of measurements.

This test applies to all side heads.

| **Object** | **G8** |
|---|---|
| To check the parallelism between the toolholding spindle axis of rotation and the railhead ram motion:<br>a) in the YZ plane;<br>b) in the ZX plane. | |

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| For a) and b) | a) |
| 0,02 for any measuring length of 300 | b) |

**Measuring instruments**

Linear displacement sensor and test mandrel

**Observations and references to ISO 230-1:1996**, 5.412.1, 5.422.3

A test mandrel is mounted on the live tooling spindle.

NOTE If necessary, workholding spindle should be clamped.

a) Linear displacement sensor is attached to the workholding spindle indicating against the mandrel in the Y direction. Mean orientation of the mandrel is determined by rotating the live tooling spindle between the two extreme readings of the displacement sensor. Displacement sensor is set to zero at this mean orientation. Then the railhead ram is moved to the other end of the measuring stroke and the displacement sensor reading is recorded.

b) Linear displacement sensor is attached to the workholding spindle indicating against the mandrel in the X direction. Mean orientation of the mandrel is determined by rotating the live tooling spindle between the two extreme readings of the displacement sensor. Displacement sensor is set to zero at this mean orientation. Then the railhead ram is moved to the other end of the measuring stroke and the displacement sensor reading is recorded.

Or

Take readings at several positions of the Z axis and then rotate the toolholding spindle by 180° and take the second set of readings at the same Z positions. The parallelism deviation is the range of the mean of these two sets of measurements.

**Object**

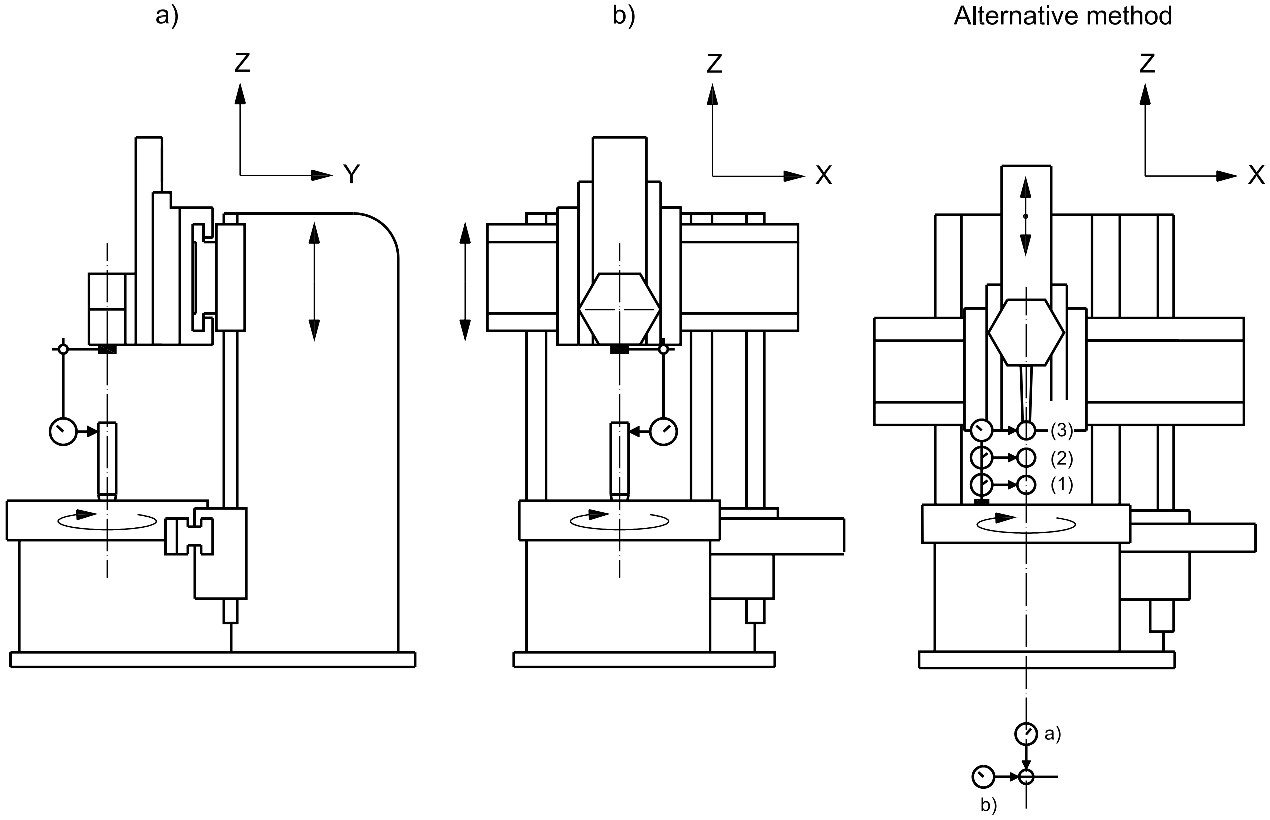
**G9**

To check the parallelism between the cross-rail Z-axis motion and the workholding spindle axis of rotation:

a) in the YZ plane;

b) in the ZX plane.

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| For a) and b) | a) |
| 0,02 for a measuring length of 300 | b) |

**Measuring instruments**

Linear displacement sensor and test mandrel or cylindrical square

**Observations and references to ISO 230-1:1996**, 5.422.3

Turn the workholding spindle to find the mean position of run-out and then move the cross-rail in the Z direction and take the maximum difference of the readings.

Or

Take readings at several positions of the cross-rail Z axis and then rotate the workholding spindle by 180° and take the second set of readings at the same Z positions. The parallelism deviation is the range of the mean of these two sets of measurements.

**Alternative method**

In this case, the test ball is positioned just using the Z-axis travel and the measurement repeated for each position (1, 2 and 3). The readings at 0° and 180° are taken and the difference between these two readings is noted for positions 1, 2 and 3. The largest change of the difference gives the parallelism deviation in the YZ plane. The test is then repeated for the XZ plane.

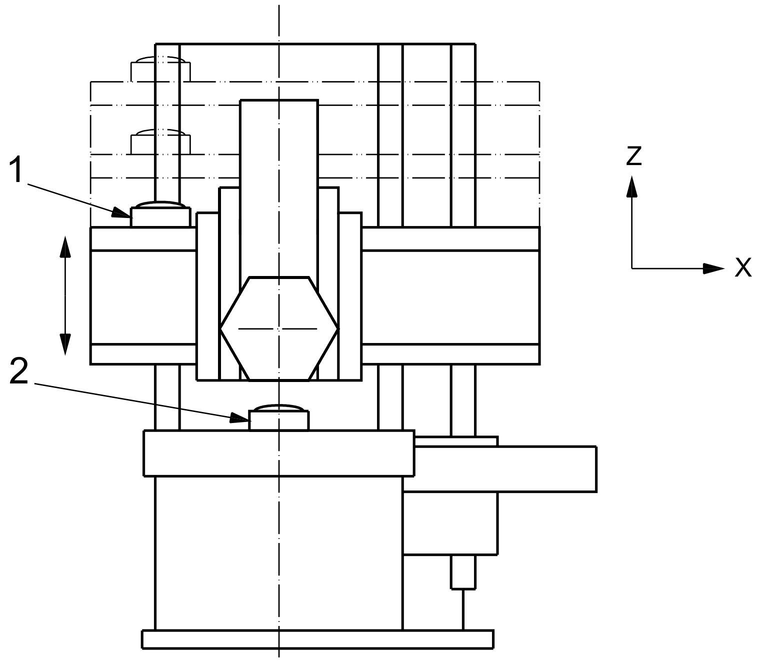
If the machine under test has an adjustable cross-rail, the test should be repeated with the cross-rail in its lower, mid, and upper positions. This test applies to all railheads.

## 5.3 Angular deviations of linear axes of motion

**Object** — **G10**

To check the angular deviation of the cross-rail in its Z-axis motion in the vertical ZX plane (EBZ).

**Diagram**




**Key**

1 measuring level

2 reference level

| Tolerance | Measured deviation |
|---|---|
| For any measuring length up to 1 000:<br>categories 1 and 2: 0,02/1 000 (20 µrad or 4″)<br>categories 3 and 4: 0,04/1 000 (40 µrad or 8″) | |

**Measuring instruments**

Precision level

**Observations and references to ISO 230-1:1996**, 5.232.21

Place the measuring level at possibly mid-position of the cross-rail on an appropriate surface and read the indication in the quoted positions.

The railhead shall be placed in a central position of the cross-rail.

When Z-axis motion causes angular deviation of both the cross-rail and the workholding spindle, differential measurements of the two angular movements shall be taken.

When differential measurement is applied, the reference level shall be placed on the workholding spindle.

Lock the cross-rail at each position, where possible.

| **Object** | **G11** |
|---|---|

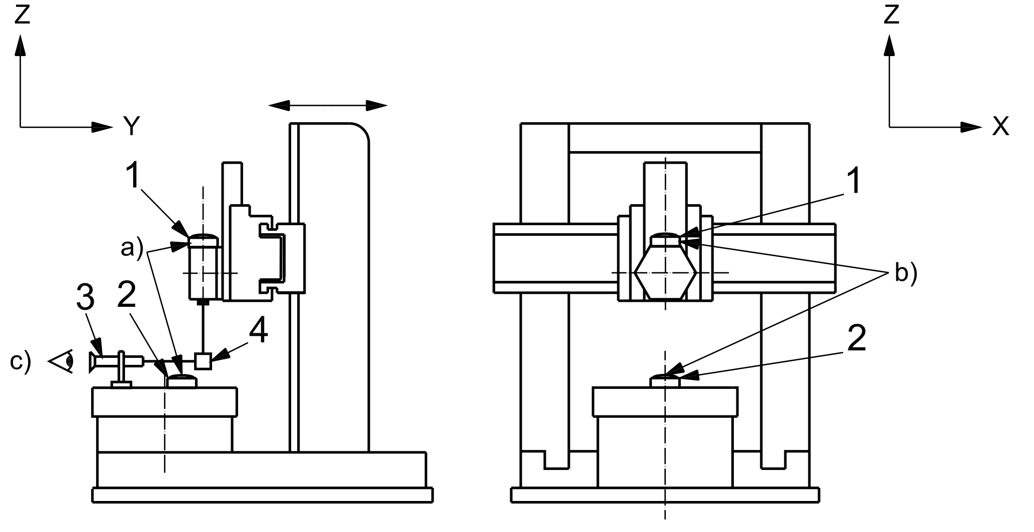
To check the angular deviations of the moving column (gantry type) or moving workholding spindle (portal type) in the Y direction:

a) in the YZ plane EAY (pitch);

b) in the ZX plane EBY (roll);

c) in the XY plane ECY (yaw).

**Diagram**




**Key**

1 measuring level

2 reference level

3 autocollimator

4 mirror

| **Tolerance** | **Measured deviation** |
|---|---|
| For a), b), and c). | a) |
| For any measuring length up to 1 000: | b) |
| categories 1 and 2: 0,02/1 000 (20 µrad or 4″) | c) |
| categories 3 and 4: 0,04/1 000 (40 µrad or 8″) | |

**Measuring instruments**

a) Precision level, or optical angular deviation measuring instrument

b) Precision level

c) Optical angular deviation measuring instrument

**Observations and references to ISO 230-1:1996**, 5.231.3, 5.232.2

The measuring level or instrument shall be placed on the railhead which is fixed in position:

a) (EAY: pitch) in the Y-axis direction;

b) (EBY: roll) in the X-axis direction;

c) (ECY: yaw) in the Z-axis direction.

When workholding spindle slide motion causes angular deviations of both workholding spindle and column, differential measurements of the two angular deviations shall be made and this shall be stated.

The reference level shall be placed on the workholding spindle (turntable), which is fixed in position.

Measurements shall be carried out at a minimum of five positions equally spaced along the path of travel in both directions of the movement.

**Object** | **G12**

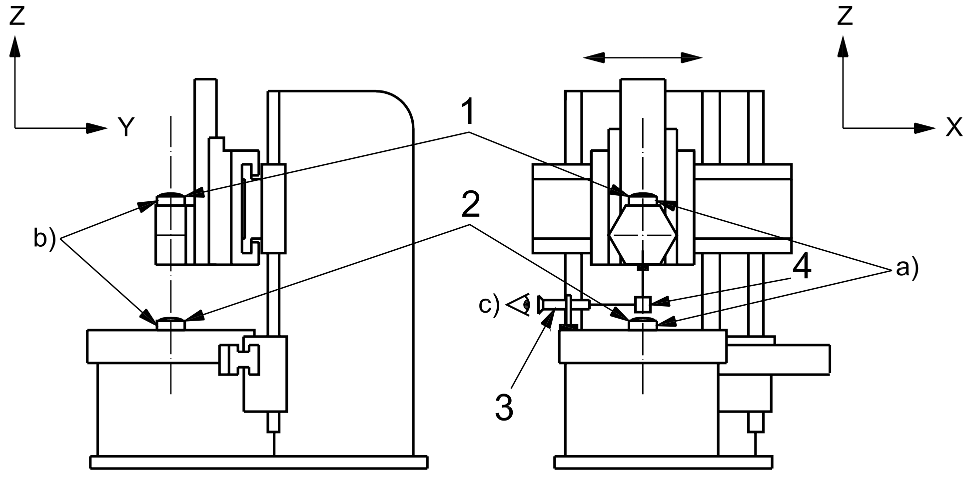
To check the angular deviations of the railhead motion on the cross-rail (X axis);

a) in the ZX plane EBX (pitch);

b) in the YZ plane EAX (roll);

c) in the XY plane ECX (yaw).

**Diagram**




**Key**

1 measuring level

2 reference level

3 autocollimator

4 mirror

| **Tolerance** | **Measured deviation** |
|---|---|
| For a), b), and c). | a) |
| For any measuring length up to 1 000: | b) |
| categories 1 and 2: 0,02/1 000 (20 µrad or 4″) | c) |
| categories 3 and 4: 0,04/1 000 (40 µrad or 8″) | |

**Measuring instruments**

a) Precision level, or optical angular deviation measuring instrument

b) Precision level

c) Optical angular deviation measuring instrument

**Observations and references to ISO 230-1:1996**, 5.231.3, 5.232.2

The measuring level or instrument shall be placed on the turret or railhead.

a) (EBX: pitch) in the X-axis direction (set vertically);

b) (EAX: roll) in the Y-axis direction (set vertically);

c) (ECX: yaw) in the Z-axis direction (set horizontally).

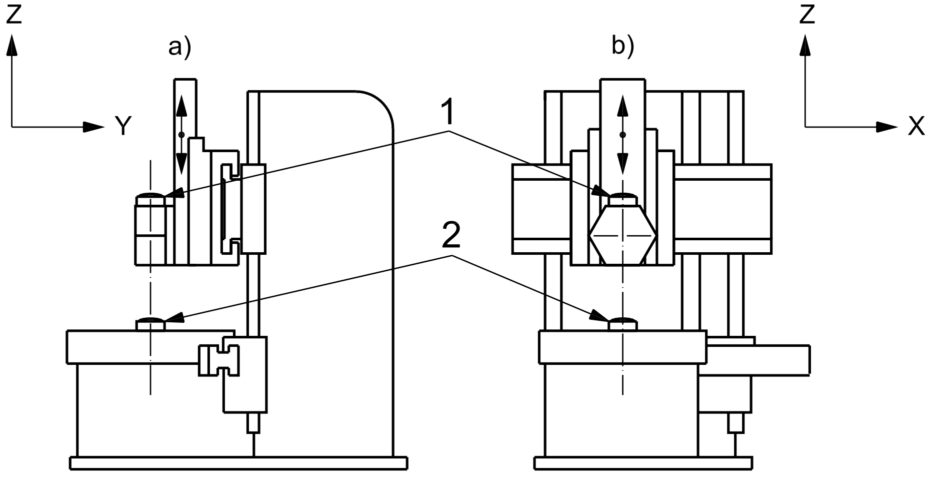
When railhead motion causes an angular deviation of both railhead and workholding spindle, differential measurements of the two angular deviations shall be made and this shall be stated.

The reference level shall be placed on the workholding spindle.

Measurements shall be carried out at a minimum of five positions equally spaced along the path of travel in both directions of the movement.

| **Object** | **G13** |
|---|---|
| To check the angular deviations of the turret slide (ram) motion (Z axis);<br>a) in the YZ plane EAZ (tilt around X);<br>b) in the XZ plane EBZ (tilt around Y). | |

**Diagram**




**Key**

1 measuring level

2 reference level

| **Tolerance** | **Measured deviation** |
|---|---|
| For any measuring length up to 1 000: | a) |
| 0,02/1 000 (20 µrad or 4″) | b) |

**Measuring instruments**

Precision level or optical angular deviation measuring instrument.

**Observations and references to ISO 230-1:1996**, 5.231.3, 5.232.2

The measuring level shall be placed on the workholding spindle and the measuring level placed on a special fixture located at the tool location.

Measurements shall be carried out at a minimum of five positions equally spaced along the travel in both directions of the movement.

## 5.4 Straightness deviation of linear axes of motion

**Object** — **G14**

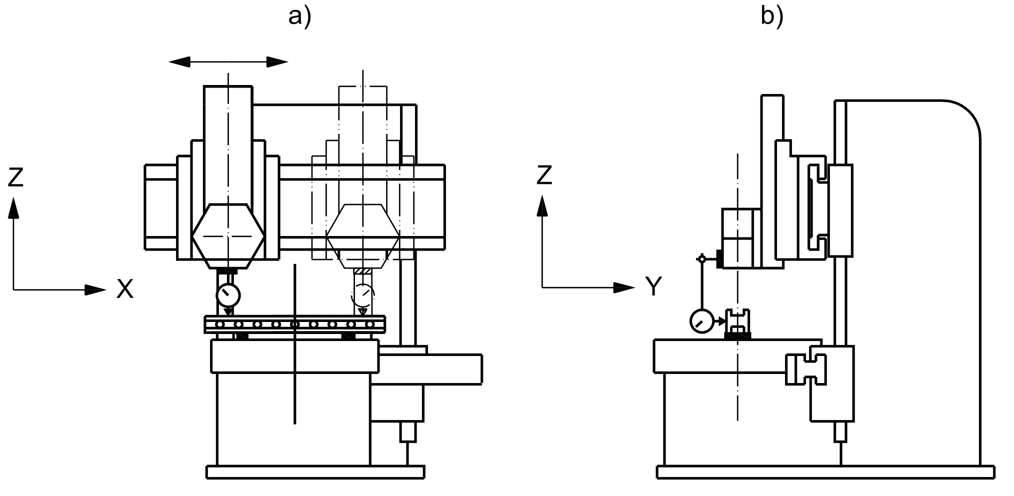
To check the straightness of the railhead (X axis) motion on the cross-rail:

a) in the vertical ZX plane (EZX);

b) in the horizontal XY plane (EYX).

NOTE Applicable for turning centres only.

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| For a) and b)<br>0,015 for a measuring length of 1 000<br>Add 0,01 for each additional length of 500<br>Local tolerance: 0,01 for any measuring length of 500 | a)<br>b) |

**Measuring instruments**

a) Straightedge, adjustable block and linear displacement sensor or optical equipment

b) Straightedge, adjustable block and linear displacement sensor or optical equipment or taut wire and microscope

**Observations and references to ISO 230-1:1996**, 5.232.1

If the column or workholding spindle (table) is movable in the Y-axis direction, it shall be positioned such that the railhead ram or turret tool pockets are in line with the workholding spindle axis average line.

Position and lock the cross-rail in the middle position of its travel, with the column locked in position near to the workholding spindle (if movable in the Y-axis direction and if locking is possible). The straightness reference (straightedge, the straightness reflector, the alignment telescope, the taut wire) shall be placed on the workholding spindle parallel (parallel means that the readings at both ends of the movement are the same value and, in this case, the maximum difference of the readings gives the straightness deviation) to the railhead slide movement.

The linear displacement sensor, the interferometer, the target or the microscope shall be mounted on the railhead near to the position of a tool. The cross-rail is in the middle of its path of travel.

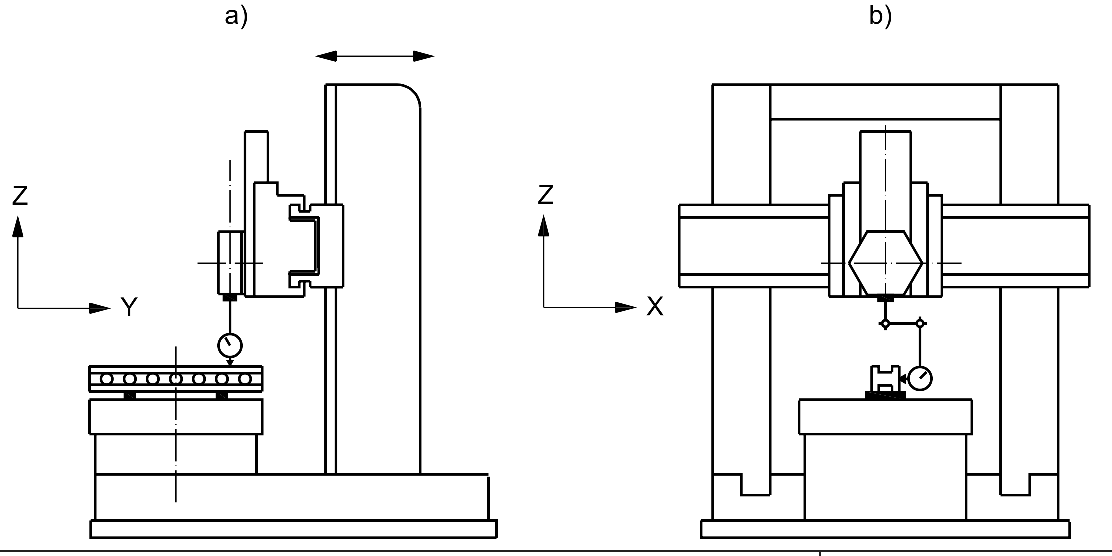
| **Object** | **G15** |
|---|---|

To check the straightness of motion of moving column(s) (gantry type) or moving workholding spindle (portal type) in the Y-axis direction:

a) in the vertical YZ plane (EZY);

b) in the horizontal XY plane (EXY).

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| a) 0,02 for a measuring length of 500 | a) |
| b) 0,04 for a measuring length of 500 | b) |

**Measuring instruments**

a) Straightedge, adjustable block and linear displacement sensor or optical equipment

b) Straightedge, adjustable block and linear displacement sensor optical equipment or microscope and taut wire

**Observations and references to ISO 230-1:1996**, 5.212.11

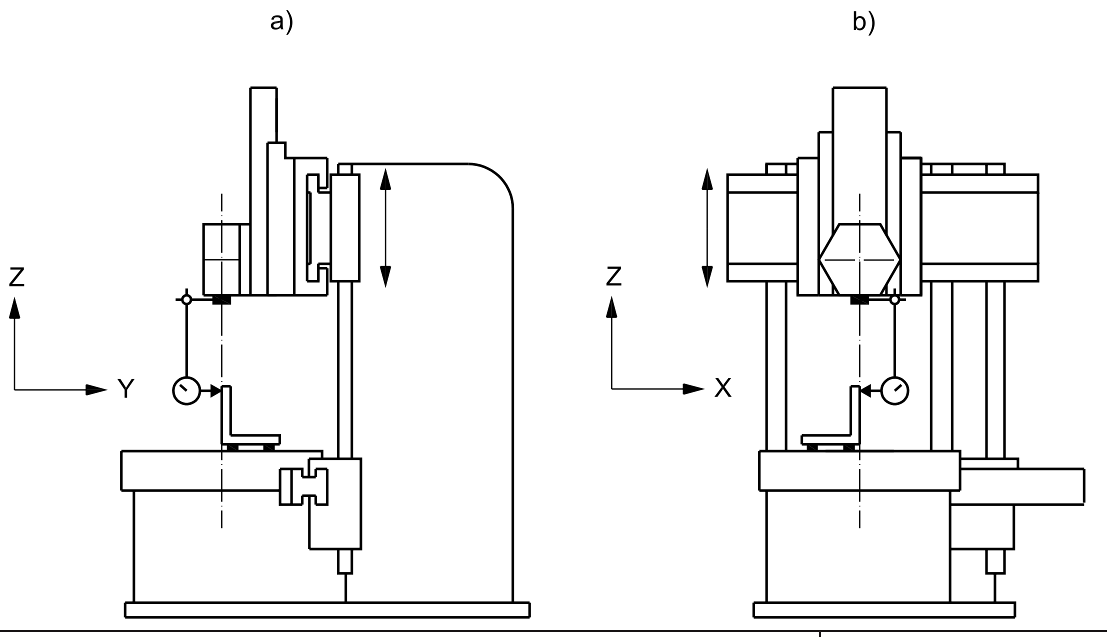
Cross-rail locked in the middle position, railhead locked in the measuring position, where possible.

The straightness reference (straightedge, the straightness reflector, the alignment telescope, the taut wire) shall be placed on the workholding spindle parallel (parallel means that the readings at both ends of the movement are the same value and, in this case, the maximum difference of the readings gives the straightness deviation) to the column movement.

The linear displacement sensor, the interferometer, the target or the microscope shall be mounted on the railhead near to the position of a tool. The measuring line should be close to the workholding spindle axis of rotation.

| **Object** | **G16** |
|---|---|
| To check the straightness of motion of the cross-rail in the Z-axis direction:<br>a) in the YZ plane;<br>b) in the ZX plane. | |

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| For a) and b) | a) |
| 0,02 for a measuring length of 300 | b) |

**Measuring instruments**

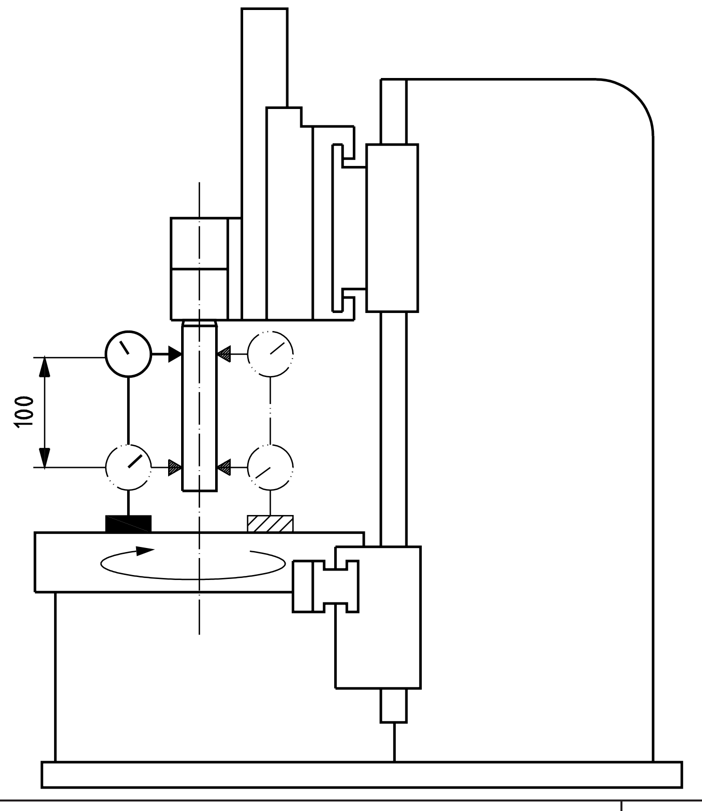
Straightedge, square, adjustable blocks or test mandrel and linear displacement sensor

**Observations and references to ISO 230-1:1996**, 5.212.11

The square is set on the workholding spindle surface to obtain the same readings at both ends of the measuring length.

## 5.5 Turret and workholding and toolholding spindle(s)

### 5.5.1 Turret and workholding spindle

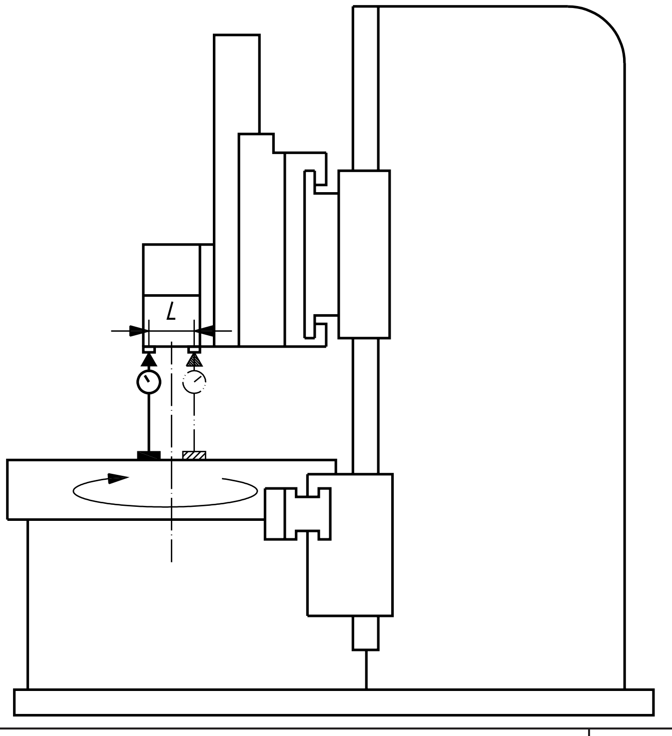
<table>
<tr><td colspan="2">Object<br>To check the co-axiality deviation between the axes of the turret bore(s) and the workholding spindle axis of rotation.</td><td>G17</td></tr>
<tr><td colspan="3">Diagram<br></td></tr>
<tr><td>Tolerance<br>0,025</td><td colspan="2">Measured deviation</td></tr>
<tr><td colspan="3">Measuring instruments<br>Test mandrel and linear displacement sensor</td></tr>
<tr><td colspan="3">Observations and references to ISO 230-1:1996, 5.442<br>A mandrel of sufficient length shall be inserted in one of the turret bores.<br>A linear displacement sensor shall be fixed on the workholding spindle and shall touch the test mandrel near the turret bore and a distance of 100 mm without moving the railhead ram or cross-rail in the vertical direction.<br>Repeat the same operations for each of the turret bores.<br>NOTE The value of permissible deviation is equal to half of the readings of the linear displacement sensor.</td></tr>
</table>

| **Object** | **G18** |
|---|---|

To check the squareness between the tool-fixing faces of the turret and the workholding spindle axis of rotation.

NOTE The test applies to tool-fixing faces of turrets that are square to the workholding spindle axis.

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| 0,02/100 | |
| *L* is the diameter of measurement | |

**Measuring instruments**

Linear displacement sensor and reference block

**Observations and references to ISO 230-1:1996**, 5.512.11

A linear displacement sensor shall be fixed on the workholding spindle and shall touch the reference block located on the face of turret located opposite.

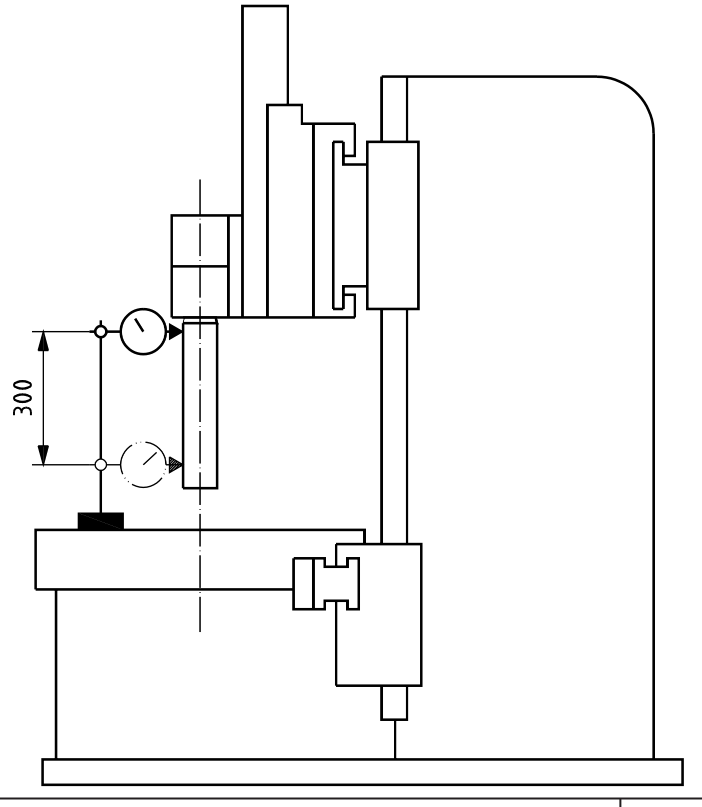
The workholding spindle shall be rotated and the linear displacement sensor shall be moved to touch the face of the turret on the largest possible diameter.

The test shall be repeated for each of the tool-fixing faces of the turret.

### 5.5.2 Turret and toolholding spindle(s)

| | |
|---|---|
| **Object** | **G19** |
| To check the run-out of the internal taper of the toolholding spindle(s):<br>a) at the spindle nose;<br>b) at a distance of 300 mm from the spindle nose.<br>NOTE Carry out these tests for each toolholding spindle of the machine. | |

**Diagram**




| **Tolerance** | **Measured deviation** |
|---|---|
| $D_f \leqslant 200$ a) 0,010 b) 0,020 | a) |
| $D_f > 200$ a) 0,015 b) 0,030 | b) |
| where $D_f$ is the external diameter of the spindle-nose face. | |

**Measuring instruments**

Linear displacement sensor and test mandrel

**Observations and references to ISO 230-1:1996**, 5.612.3

Attach a linear displacement sensor to the table (workholding spindle) and insert the test mandrel in the live tooling spindle.

Place the displacement sensor as close as possible to position a), rotate the toolholding spindle and record the reading.

Repeat the same operation at position b).

### 5.5.3 Accuracy of turret indexing

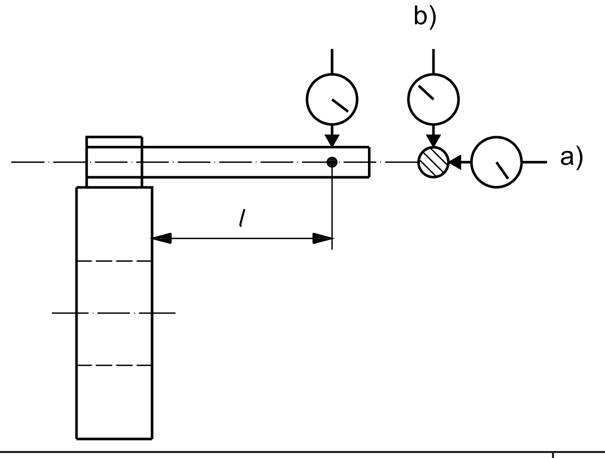
**Object** — **G20**

To check the repeatability of the turret indexing:

a) in the X direction;

b) in the Z direction.

**Diagram**




| **Tolerance** | | | | **Measured deviation** |
|---|---|---|---|---|
| | **Category 1** | **Category 2** | **Categories 3 and 4** | a) |
| | *l* = 50 | *l* = 100 | *l* = 100 | b) |
| a) and b) | 0,005 | 0,010 | 0,015 | |

**Measuring instruments**

Test mandrel and linear displacement sensor

**Observations and references to ISO 230-1:1996**, 6.42

Measure at distance *l* from the turret face or tool-fixing face. With the turret in mid-stroke, position the linear displacement sensors so they contact the test mandrel at the 0° and 90° measurement positions. Record the turret's axis position and the linear displacement sensor readings.

Move the turret to a position clear of the linear displacement sensors, then index the turret 360°. Move the turret axis to the recorded position under an automatic cycle. Record the linear displacement sensor readings.

Repeat the cycle three times; the linear displacement sensor should be reset to zero at the start of the test. Deviation is the maximum difference between the three sets of readings.

Also, the linear displacement sensor can be mounted on the spindle housing to avoid locking the spindle (preferred method).

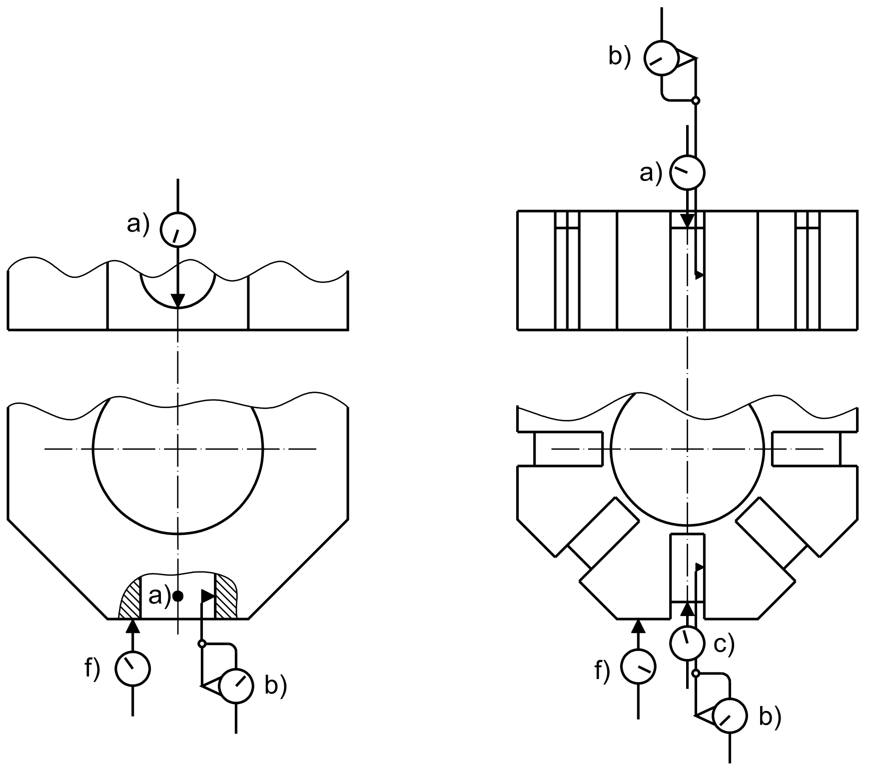
The test should be repeated at a minimum of three different turret orientations and, for each orientation, the linear displacement sensor should be set to zero.

The repeatability of positioning of the linear axes (used for clearing the linear displacement sensors) may influence the measuring result.

**Object** — **G21**

To check the accuracy of the turret indexing.

**Diagram**




| **Tolerance** | | **Measured deviation** |
|---|---|---|
| **Category 1** | **Categories 2, 3, and 4** | |
| 0,030 | 0,040 | |

**Measuring instruments**

Linear displacement sensor

**Observations and references to ISO 230-1**

Position the linear displacement sensor styli a), b) and c) so that they contact the turret reference holes or grooves. Record the turret axis position. Record the linear displacement sensor readings. Withdraw the turret position to clear off the linear displacement sensor, index the turret to the next orientation, and reposition the turret axis. Record the linear displacement sensor readings.

If the turret reference face is used, the linear displacement sensor should be used at position f).

Repeat the test three times for each turret orientation; the readings at each orientation are then averaged to minimize the effect of turret repeatability. The maximum difference of all averaged linear displacement sensor readings is the accuracy of turret indexing.

The repeatability of the turret indexing might influence the readings.

# 6 Tests for checking the accuracy of axes of rotation

## 6.1 Rotational accuracy of workholding spindle

**R1**

**Object**

Axis of rotation error motion for workholding spindle (C axis):

a) radial error motion in direction of X (EXC);

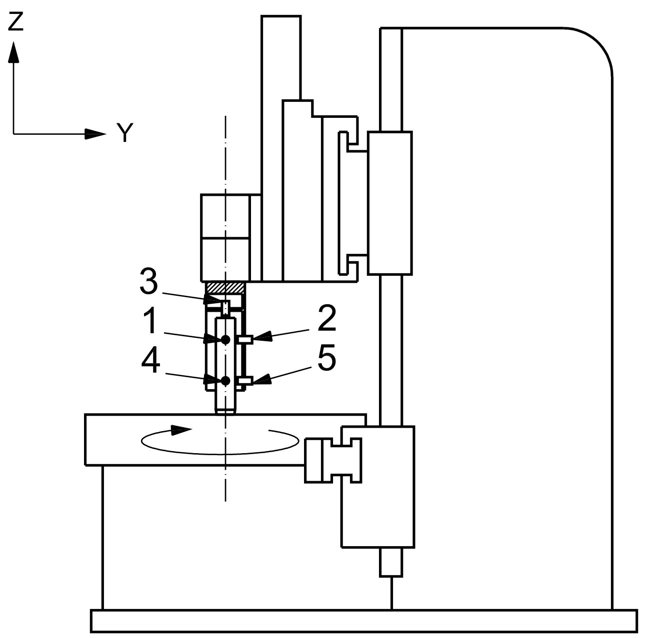
b) radial error motion in direction of Y (EYC), for turning centres only;

c) axial error motion (EZC);

d) tilt error motion around the X axis (EAC), for turning centres only;

e) tilt error motion around the Y axis (EBC).

**Diagram**




**Key**

1 to 5 probes

NOTE Probes 2 and 5 are for turning centres only.

| **Tolerance** | | | | **Measured deviation** | | |
|---|---|---|---|---|---|---|
| | **At percentage of maximum speed** | | | **At percentage of maximum speed** | | |
| | 10 % | 50 % | 100 % | 10 % | 50 % | 100 % |
| a) total radial error motion value EXC | | | | a) | | |
| b) total radial error motion value EYC | | | | b) | | |
| c) total axial error motion value EZC | | | | c) | | |
| d) total tilt error motion value EAC | | | | d) | | |
| e) total tilt error motion value EBC | | | | e) | | |

If the minimum speed is larger than 10 % of the maximum speed, then the spindle should be operated at minimum speed instead.

If the supplier/manufacturer decides, by mutual agreement, to include this test in the contractual machine acceptance procedures, then they should also define, by mutual agreement, the corresponding tolerances to be applied.

NOTE The second edition of this part of ISO 13041 may provide tolerances for this test when confirmed data from such measurements for spindle performance in the industrial environment are available.

**Measuring instruments**

Test mandrel, non-contacting probes and angular measuring device or two precision spheres located slightly eccentric to the spindle average line and non-contacting probes.

**Observations and references to ISO 230-7**

This test is a spindle test with fixed sensitive direction (ISO 230-7:2006, 5.5).

After setup of the measuring instrument, the spindle shall be warmed up at 50 % of the maximum spindle speed for a time period of 10 min, if not otherwise agreed between manufacturer/supplier and user.

Total error motion and total error motion value are defined in ISO 230-7:2006, 3.2.4 and 3.5.1, respectively.

a), b) Total radial error motion values EXC and EYC (using probes 4 and 5).

Radial error motion measurement is described in ISO 230-7:2006, 5.5.3. The radial error motion shall be measured as close as possible to the spindle nose (probes 4 and 5 in the R1 diagram).

For each radial error motion EXC and EYC, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a least squares circle (LSC) centre (ISO 230-7:2006, 3.4.3) shall be provided.

c) Total axial error motion value EZC (using probe 3).

Axial error motion measurement is described in ISO 230-7:2006, 5.5.4.

For the axial error motion EZC, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a polar chart (PC) centre (ISO 230-7:2006, 3.4.1) shall be provided.

d), e) Total tilt error motion values EAC and EBC (using probes 2 and 5, 1 and 4).

Tilt error motion measurement is described in ISO 230-7:2006, 5.5.5. Any tilt error motion can also be checked with just one non-contacting probe (see ISO 230-7:2006, 5.5.5.3).

For each tilt error motion EAC and EBC, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a polar chart (PC) centre (ISO 230-7:2006, 3.4.1) shall be provided.

For these tests, the following parameters shall be stated:

1) the radial, axial or face locations at which the measurements are made;
2) identification of all artifacts, targets and fixtures used;
3) the location of the measurement setup;
4) the position of any linear or rotary positioning stages that are connected to the device under test;
5) the direction angle of the sensitive direction, e.g. axial, radial or intermediate angles as appropriate;
6) presentation of the measurement result, e.g. error motion value, polar plot, time-based plot, frequency-content plot;
7) the rotational frequency of the spindle (zero for static error motion);
8) the time duration in seconds or number of spindle rotations;
9) appropriate warm up or break-in procedure;
10) the frequency response of the instrumentation, given in hertz or cycles per revolution, including roll-off characteristics of any electronic filters. In the case of digital instrumentation, the displacement resolution and sampling rate;
11) the structural loop, including the position and orientation of sensors relative to the spindle housing from which the error motion is reported, specified objects with respect to which the spindle axes and the reference coordinate axes are located and the elements connecting these objects;
12) time and date of measurement;
13) type and calibration status of all measurement instrumentation;
14) any other operating conditions which may influence the measurement, such as ambient temperature.

If the tilt measurements are not needed (by agreement between the supplier and the user), then only three displacement probes are used (1, 2, and 3) and the test mandrel may be replaced by precision test sphere.

## 6.2 Rotational accuracy of toolholding spindle(s)

**Object** — **R2**

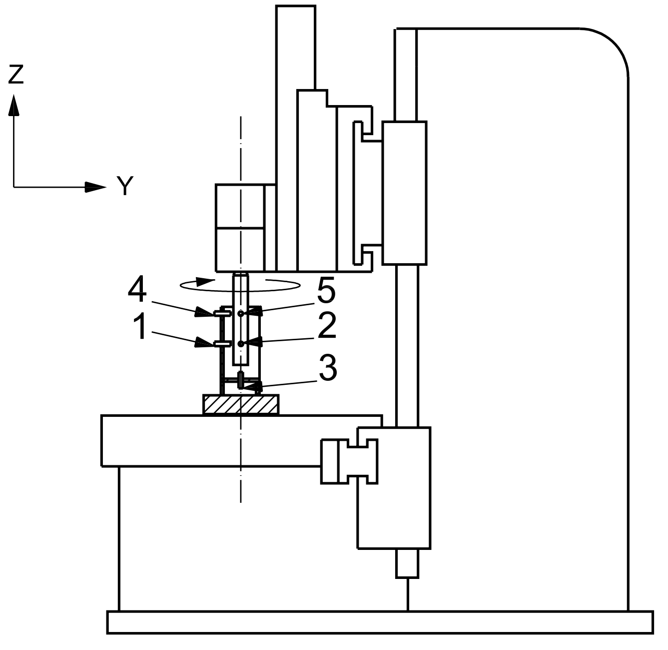
Axis of rotation error motion for toolholding spindle(s) (live tool) C:

a) radial error motion (ERC);

b) axial error motion (EZC);

c) tilt error motion (ETC).

**Diagram**




**Key**

1 to 5 probes

**Tolerance**

| | At percentage of maximum speed 10 % | 50 % | 100 % | Measured deviation At percentage of maximum speed 10 % | 50°% | 100°% |
|---|---|---|---|---|---|---|
| a) total radial error motion value ERC1 | | | | a) | | |
| b) total axial error motion value EZC1 | | | | b) | | |
| c) total tilt error motion value ETC1 | | | | c) | | |

If the minimum speed is larger than 10 % of the maximum speed, then the spindle should be operated at minimum speed instead.

If the supplier/manufacturer decides, by mutual agreement, to include this test in the contractual machine acceptance procedures, then they should also define, by mutual agreement, the corresponding tolerances to be applied.

NOTE The second edition of this part of ISO 13041 may provide tolerances for this test when confirmed data from such measurements for spindle performance in the industrial environment are available.

**Measuring instruments**

Test mandrel, non-contacting probes and angular measuring device or two precision spheres located slightly eccentric to the spindle average line and non-contacting probes.

**Observations and references to ISO 230-7**

This test is a spindle test with rotating sensitive direction (ISO 230-7:2006, 5.4).

After setup of the measuring instrument, the spindle shall be warmed up at 50 % of the maximum spindle speed for a time period of 10 minutes, if not otherwise agreed between manufacturer/supplier and user.

Total error motion is defined in ISO 230-7:2006, 3.2.4; total error motion value is defined in ISO 230-7:2006, 3.5.1.

a) Total radial error motion value ERC1, (using probes 1 and 2).

Radial error motion measurement is described in ISO 230-7:2006, 5.4.2. The radial error motion shall be measured as close as possible to the spindle nose (probes 1 and 2 in the diagram of this test).

For the radial error motion ERC1, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a least squares circle (LSC) centre (ISO 230-7:2006, 3.4.3) shall be provided.

b) Total axial error motion value EZC1 (using probe 3).

Axial error motion measurement is described in ISO 230-7:2006, 5.4.4.

For the axial error motion EZC1, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a polar chart (PC) centre (ISO 230-7:2006, 3.4.1) shall be provided.

c) Total tilt error motion values ETC1 (using probes 1, 2, 4, 5).

Tilt error motion measurement is described in ISO 230-7:2006, 5.4.3. The tilt error motion can be also be checked with just two non-contacting probes (see ISO 230-7:2006, 5.4.3.2).

For the tilt error motion ETC1, a total error motion polar plot (ISO 230-7:2006, 3.3.1) with a polar chart (PC) centre (ISO 230-7:2006, 3.4.1) shall be provided.

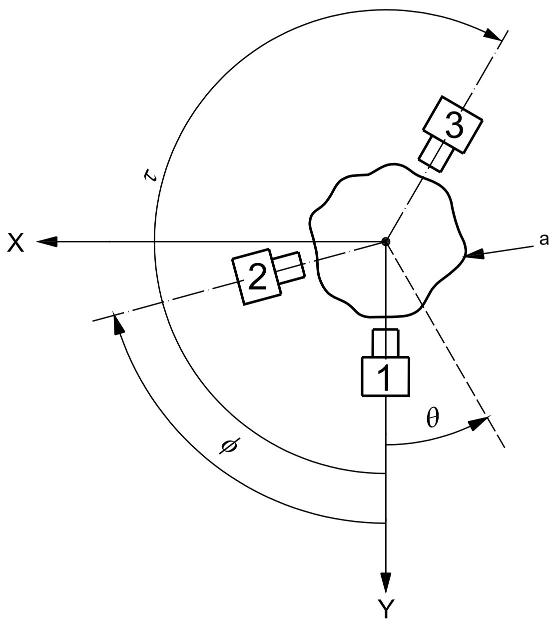
For these tests the following parameters shall be stated:

1) the radial, axial or face locations at which the measurements are made;
2) identification of all artifacts, targets and fixtures used;
3) the location of the measurement setup;
4) the position of any linear or rotary positioning stages that are connected to the device under test;
5) the direction angle of the sensitive direction, e.g. axial, radial or intermediate angles, as appropriate;
6) presentation of the measurement result, e.g. error motion value, polar plot, time-based plot, frequency-content plot;
7) the rotational frequency of the spindle (zero for static error motion);
8) the time duration in seconds or number of spindle rotations;
9) appropriate warm-up or break-in procedure;
10) the frequency response of the instrumentation, given in hertz or cycles per revolution, including roll-off characteristics of any electronic filters — in the case of digital instrumentation, the displacement resolution and sampling rate;
11) the structural loop, including the position and orientation of sensors relative to the spindle housing from which the error motion is reported, specified objects with respect to which the spindle axes and the reference coordinate axes are located and the elements connecting these objects;
12) time and date of measurement;
13) type and calibration status of all measurement instrumentation;
14) any other operating conditions which may influence the measurement such as ambient temperature.

If the tilt measurements are not needed (by agreement between the supplier and the user) then only three displacement probes are used (1, 2, and 3) and the test mandrel may be replaced by precision test sphere.

# Annex A
(informative)

# Three point method




**Key**

1 to 3 sensors

$\theta$ angle measured from the Y axis

$\tau$ angle between sensor 1 and sensor 3

$\phi$ angle between sensor 1 and sensor 2

a Roundness profile.

**Figure A.1 — Three point measuring method**

Roundness deviation of the artefact used in measurement of axis of rotation error influences the measurement results. The following method of measurement utilizing three radially arranged linear displacement sensors against an "imperfect" artefact is one way to eliminate the influence of artefact roundness deviations on the axis of rotation measurements.

As shown in Figure A.1, the angle between sensor 1 and sensor 2 is $\phi$, and the angle between sensor 1 and sensor 3 is $\tau$. The angle measured from the Y axis is $\theta$. The roundness profile of the reference artefact (test bar) is expressed as $r(\theta)$. Furthermore, $x$ and $y(\theta)$ represent the radial error motion in the X and Y directions. The output signals of these three sensors are given by Equations (A.1).

$$\begin{cases} S_1(\theta) = r(\theta) + y(\theta) \\ S_2(\theta) = r(\theta + \phi) + y(\theta)\cos\phi + x(\theta)\sin\phi \\ S_3(\theta) = r(\theta + \tau) + y(\theta)\cos\tau + x(\theta)\sin\tau \end{cases} \tag{A.1}$$

After multiplying the output signals of sensor 1, sensor 2 and sensor 3 by the coefficients “1, $p$, $q$”, total summation is given as $S(\theta)$.

$$\begin{aligned} S(\theta) &= S_1(\theta) + pS_2(\theta) + qS_3(\theta) \\ &= r(\theta) + pr(\theta+\phi) + qr(\theta+\tau) + (1 + p\cos\phi + q\cos\tau)x(\theta) + (p\sin\phi + q\sin\tau)y(\theta) \end{aligned} \tag{A.2}$$

$$\begin{cases} 1 + p\cos\phi + q\cos\tau = 0 \\ p\sin\phi + q\sin\tau = 0 \end{cases} \Leftrightarrow \begin{cases} p = -\dfrac{\sin\tau}{\sin(\tau-\phi)} \\ q = \dfrac{\sin\phi}{\sin(\tau-\phi)} \end{cases} \tag{A.3}$$

If $p$, $q$, $\phi$, $\tau$ are chosen so as to satisfy Expression (A.3), then Equation (A.2) becomes independent of error motion $x(\theta)$ and $y(\theta)$. The roundness profile of the reference artefact $r(\theta)$ is expressed as

$$r(\theta) = \sum_{k=2}^{N} \left( A_k \cos k\theta + B_k \sin k\theta \right) \tag{A.4}$$

Thus, $S(\theta)$ is given by

$$\begin{aligned} S(\theta) = \sum_{k=2}^{N} \Big\{ & \left[ (1 + p\cos k\phi + q\cos k\tau) A_k + (p\sin k\phi + q\sin k\tau) B_k \right] \cos k\theta + \\ & \left[ -(p\sin k\phi + q\sin k\tau) A_k + (1 + p\cos k\phi + q\cos k\tau) B_k \right] \sin k\theta \Big\} \end{aligned} \tag{A.5}$$

$$\begin{cases} \alpha_k = 1 + p\cos k\phi + q\cos k\tau \\ \beta_k = p\sin k\phi + q\sin k\tau \end{cases} \tag{A.6}$$

Substituting $\alpha_k$, $\beta_k$ from Equations (A.6), the Fourier coefficients of $S(\theta)$, i.e. $F_k$, $G_k$, are given by Equations (A.7):

$$\begin{cases} F_k = \alpha_k A_k + \beta_k B_k \\ G_k = -\beta_k A_k + \alpha_k B_k \end{cases} \tag{A.7}$$

Then, Fourier coefficients of the roundness profile of the reference artefact, $A_k$, $B_k$, are obtained as follows.

$$\begin{cases} A_k = \dfrac{\alpha_k F_k - \beta_k G_k}{{\alpha_k}^2 + {\beta_k}^2} \\ B_k = \dfrac{\alpha_k G_k + \beta_k F_k}{{\alpha_k}^2 + {\beta_k}^2} \end{cases} \tag{A.8}$$

Then, the radial error motion in X and Y direction are estimated as follows. Here, $\hat{r}$ represents the estimated roundness profile of the reference artefact.

$$\begin{cases} x(\theta) = \dfrac{\left\{ S_2(\theta) - \hat{r}(\theta+\phi) - \left[ S_1(\theta) - \hat{r}(\theta) \right] \cos\phi \right\}}{\sin\phi} \\ y(\theta) = S_1(\theta) - \hat{r}(\theta) \end{cases} \tag{A.9}$$

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