INTERNATIONAL STANDARD

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Fourth edition
2014-05-01

Test code for machine tools —

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

Code d'essai des machines-outils —

Partie 2: Détermination de l'exactitude et de la répétabilité de positionnement des axes à commande numérique

Reference number
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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This fourth edition cancels and replaces the third edition (ISO 230-2:2006), which has been technically revised. In particular, the following have been added:

a) for axes lengths larger than 4 000 mm, more than one 2 000 mm segment(s) can be defined for testing (see 5.3.3);

b) nomenclature for parameters of positioning tests, e.g. $E_{\mathrm{XX,A}\uparrow}$ (see 8.2.4);

c) evaluation of periodic positioning errors (see Annex C);

d) positioning tests with calibrated ball array or step gauge (see Annex D).

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

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

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

— *Part 3: Determination of thermal effects*

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

— *Part 5: Determination of the noise emission*

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

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

— *Part 8: Vibrations* [Technical Report]

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

- *Part 10: Determination of the measuring performance of probing systems of numerically controlled machine tools*
- *Part 11: Measuring instruments suitable for machine tool geometry tests* [Technical Report]

Introduction

The purpose of ISO 230 (all parts) is to standardize methods for testing the accuracy of machine tools, excluding portable power tools.

This part of ISO 230 specifies test procedures used to determine the accuracy and repeatability of positioning of numerically controlled axes. The tests are designed to measure the relative motion between the component of the machine that carries the cutting tool and the component that carries the workpiece.

The manufacturer/supplier is responsible for providing thermal specifications for the environment in which the machine can be expected to perform with the specified accuracy. The machine user is responsible for providing a suitable test environment by meeting the manufacturer/supplier's thermal guidelines or otherwise accepting reduced performance. An example of environmental thermal guidelines is given in ISO 230-3:2007, Annex C.

A relaxation of accuracy expectations is required if the thermal environment causes excessive uncertainty or variation in the machine tool performance and does not meet the manufacturer/supplier's thermal guidelines. If the machine does not meet performance specifications, the analysis of the uncertainty due to the compensation of the machine tool temperature, given in A.2.4 of this part of ISO 230, and the uncertainty due to the environmental variation error, given in A.2.5, can help in identifying sources of problems.

ISO/TC 39/SC 2 decided to add the following to this edition of this part of ISO 230:

a) for axes lengths larger than 4 000 mm, more than one 2 000 mm segment(s) can be defined for testing (see 5.3.3);

b) nomenclature for parameters of positioning tests, e.g. $E_{\mathrm{XX,A}\uparrow}$ (see 8.2.4);

c) evaluation of periodic positioning errors (see Annex C);

d) positioning tests with calibrated ball array or step gauge (see Annex D).

Test code for machine tools —

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

1 Scope

This part of ISO 230 specifies methods for testing and evaluating the accuracy and repeatability of positioning of numerically controlled machine tool axes by direct measurement of individual axes on the machine. These methods apply equally to linear and rotary axes.

When several axes are simultaneously under test, the methods do not apply.

This part of ISO 230 can be used for type testing, acceptance tests, comparison testing, periodic verification, machine compensation, etc.

The methods involve repeated measurements at each position. The related parameters of the test are defined and calculated. Their uncertainties are estimated as described in ISO/TR 230-9:2005, Annex C.

Annex A presents the estimation of the measurement uncertainty.

Annex B describes the application of an optional test cycle: the step cycle. The results from this cycle are not to be used either in the technical literature with reference to this part of ISO 230, nor for acceptance purposes, except under special written agreements between manufacturer/supplier and user. Correct reference to this part of ISO 230 for machine acceptance always refers to the standard test cycle.

Annex C contains considerations related to periodic positioning error.

Annex D describes tests using ball array and step gauge.

2 Normative references

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

ISO 230-1:2012, *Test code for machine tools — Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions*

ISO 230-3:2007, *Test code for machine tools — Part 3: Determination of thermal effects*

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

3 Terms and definitions

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

3.1
axis travel

maximum travel, linear or rotary, over which the moving component can move under numerical control

Note 1 to entry: For rotary axes exceeding 360°, there might not be a clearly defined maximum travel.

3.2
measurement travel

part of the axis travel, used for data capture, selected so that the first and the last target positions can be approached bi-directionally

Note 1 to entry: See Figure 1.

3.3
functional point

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

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

Note 1 to entry: In this part of ISO 230, 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
target position

P_i ($i = 1$ to m)

position to which the moving component is programmed to move

Note 1 to entry: The subscript i identifies the particular position among other selected target positions along or around the axis.

3.5
actual position

P_{ij} ($i = 1$ to m; $j = 1$ to n)

measured position reached by the functional point on the j^{th} approach to the i^{th} target position

3.6
positioning deviation
deviation of position

x_{ij}

actual position reached by the functional point minus the target position

$$x_{ij} = P_{ij} - P_i$$

[SOURCE: ISO 230-1:2012, 3.4.6, modified]

Note 1 to entry: Positioning deviations are determined as the relative motion between the component of the machine that carries the cutting tool and the component that carries the workpiece in the direction of motion of the axis under test.

Note 2 to entry: Positioning deviations constitute a limited representation of positioning error motion, sampled at discrete intervals.

3.7
unidirectional

refers to a series of measurements in which the approach to a target position is always made in the same direction along or around the axis

Note 1 to entry: The symbol ↑ signifies a parameter derived from a measurement made after an approach in the positive direction, and ↓ one in the negative direction, e.g. $x_{ij}\uparrow$ or $x_{ij}\downarrow$.

3.8
bi-directional

refers to a parameter derived from a series of measurements in which the approach to a target position is made in either direction along or around the axis

3.9
standard uncertainty

uncertainty of the result of a measurement expressed as a standard deviation

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.1]

3.10
combined standard uncertainty

standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.4]

3.11
expanded uncertainty

quantity defining an interval about the result of a measurement that can be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.5]

3.12
coverage factor

numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty

[SOURCE: ISO/IEC Guide 98-3:2008, 2.3.6]

3.13
mean unidirectional positioning deviation at a position

$\bar{x}_i \uparrow$ or $\bar{x}_i \downarrow$

arithmetic mean of the positioning deviations obtained by a series of n unidirectional approaches to a position P_i

$$\bar{x}_i \uparrow = \frac{1}{n} \sum_{j=1}^{n} x_{ij} \uparrow$$

and

$$\bar{x}_i \downarrow = \frac{1}{n} \sum_{j=1}^{n} x_{ij} \downarrow$$

3.14
mean bi-directional positioning deviation at a position

$\bar{x}_i$

arithmetic mean of the mean unidirectional positioning deviations $\bar{x}_i \uparrow$ and $\bar{x}_i \downarrow$ obtained from the two directions of approach at a position P_i

$$\bar{x}_i = \frac{\bar{x}_i \uparrow + \bar{x}_i \downarrow}{2}$$

3.15
reversal error at a position
reversal value at a position
B_i
difference between the mean unidirectional positioning deviations obtained from the two directions of approach at a position P_i

$$B_i = \bar{x}_i\uparrow - \bar{x}_i\downarrow$$

3.16
reversal error of an axis
reversal value of an axis
B
maximum of the absolute reversal errors $|B_i|$ at all target positions along or around the axis

$$B = \text{max.}\left[\left|B_i\right|\right]$$

3.17
mean reversal error of an axis
mean reversal value of an axis
$\bar{B}$
arithmetic mean of the reversal errors B_i at all target positions along or around the axis

$$\bar{B} = \frac{1}{m}\sum_{i=1}^{m} B_i$$

3.18
estimator for the unidirectional axis positioning repeatability at a position
$s_i\uparrow$ or $s_i\downarrow$
estimator of the standard uncertainty of the positioning deviations obtained by a series of n unidirectional approaches at a position P_i

$$s_i\uparrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\uparrow - \bar{x}_i\uparrow\right)^2}$$

and

$$s_i\downarrow = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}\downarrow - \bar{x}_i\downarrow\right)^2}$$

3.19
unidirectional positioning repeatability at a position
$R_i\uparrow$ or $R_i\downarrow$
range derived from the estimator for the unidirectional axis positioning repeatability at a position P_i using a coverage factor $k = 2$

$$R_i\uparrow = 4s_i\uparrow$$

and

$$R_i\downarrow = 4s_i\downarrow$$

3.20

bi-directional positioning repeatability at a position

R_i

$R_i = \text{max.}\left[2s_i\uparrow + 2s_i\downarrow + |B_i|; R_i\uparrow; R_i\downarrow\right]$

3.21

unidirectional positioning repeatability of an axis

$R\uparrow$ or $R\downarrow$

maximum value of the positioning repeatability at any position P_i along or around the axis

$$R\uparrow = \text{max.}\left[R_i\uparrow\right]$$

$$R\downarrow = \text{max.}\left[R_i\downarrow\right]$$

3.22

bi-directional positioning repeatability of an axis

R

maximum value of the repeatability of positioning at any position P_i along or around the axis

$$R = \text{max.}\left[R_i\right]$$

3.23

unidirectional systematic positioning error of an axis

$E\uparrow$ or $E\downarrow$

difference between the algebraic maximum and minimum of the mean unidirectional positioning deviations for one approach direction $\bar{x}_i\uparrow$ or $\bar{x}_i\downarrow$ at any position P_i along or around the axis

$$E\uparrow = \text{max.}\left[\bar{x}_i\uparrow\right] - \text{min.}\left[\bar{x}_i\uparrow\right]$$

and

$$E\downarrow = \text{max.}\left[\bar{x}_i\downarrow\right] - \text{min.}\left[\bar{x}_i\downarrow\right]$$

3.24

bi-directional systematic positioning error of an axis

E

difference between the algebraic maximum and minimum of the mean unidirectional positioning deviations for both approach directions $\bar{x}_i\uparrow$ and $\bar{x}_i\downarrow$ at any position P_i along or around the axis

$$E = \text{max.}\left[\bar{x}_i\uparrow; \bar{x}_i\downarrow\right] - \text{min.}\left[\bar{x}_i\uparrow; \bar{x}_i\downarrow\right]$$

3.25

mean bi-directional positioning error of an axis

M

difference between the algebraic maximum and minimum of the mean bi-directional positioning deviations $\bar{x}_i$ at any position P_i along or around the axis

$$M = \text{max.}\left[\bar{x}_i\right] - \text{min.}\left[\bar{x}_i\right]$$

3.26

unidirectional positioning error of an axis

unidirectional positioning accuracy of an axis

$A\uparrow$ or $A\downarrow$

range derived from the combination of the mean unidirectional systematic positioning errors and the estimator for the unidirectional positioning repeatability of an axis using a coverage factor $k = 2$

$$A\uparrow = \max.\left[\bar{x}_i\uparrow + 2s_i\uparrow\right] - \min.\left[\bar{x}_i\uparrow - 2s_i\uparrow\right]$$

and

$$A\downarrow = \max.\left[\bar{x}_i\downarrow + 2s_i\downarrow\right] - \min.\left[\bar{x}_i\downarrow - 2s_i\downarrow\right]$$

Note 1 to entry: The concept “positioning accuracy” is here applied in a quantitative form and is different from the concept “measurement accuracy” as defined in ISO/IEC Guide 99, 2.13.

3.27

bi-directional positioning error of an axis

bi-directional positioning accuracy of an axis

A

range derived from the combination of the mean bi-directional systematic positioning errors and the estimator for axis repeatability of bi-directional positioning using a coverage factor $k = 2$

$$A = \max.\left[\bar{x}_i\uparrow + 2s_i\uparrow; \bar{x}_i\downarrow + 2s_i\downarrow\right] - \min.\left[\bar{x}_i\uparrow - 2s_i\uparrow; \bar{x}_i\downarrow - 2s_i\downarrow\right]$$

Note 1 to entry: The concept “positioning accuracy” is here applied in a quantitative form and is different from the concept “measurement accuracy” as defined in ISO/IEC Guide 99:2007, 2.13.

3.28

sampling point

<numerical compensation> discrete point for which numerical representation of associated geometric error(s) is provided in an error table, in a compensation table, or in a spatial error grid

[SOURCE: ISO/TR 16907:—, 3.16]

4 Test conditions

4.1 Environment

It is recommended that the manufacturer/supplier offer guidelines regarding the kind of thermal environment acceptable for the machine to perform with the specified accuracy.

Such guidelines could contain, for example, a specification on the mean room temperature, maximum amplitude and frequency range of deviations from this mean temperature, and environmental thermal gradients. It shall be the responsibility of the user to provide an acceptable thermal environment for the operation and the performance testing of the machine tool at the installation site. However, if the user follows the guidelines provided by the machine manufacturer/supplier, the responsibility for machine performance according to the specifications reverts to the machine manufacturer/supplier.

Ideally, all dimensional measurements are made when both the measuring instrument and the measured object are soaked in an environment at a temperature of 20 °C. If the measurements are taken at temperatures other than 20 °C, then correction for nominal differential expansion (NDE) between the axis positioning system or the workpiece/tool holding part of the machine tool and the test equipment shall be applied to yield results corrected to 20 °C. This condition might require temperature measurement of the representative part of the machine as well as the test equipment and a mathematical correction with the relevant thermal expansion coefficients. The NDE correction might also be achieved automatically, if the representative part of the machine tool and the test equipment have the same temperature and the same thermal expansion coefficient.

It should be noted, however, that any temperature departure from 20 °C can cause an additional uncertainty related to the uncertainty in the effective expansion coefficient(s) used for compensation. A typical minimum range value for the resulting uncertainty is 2 µm/(m·°C) (see Annex A). Therefore, the actual temperatures shall be stated in the test report.

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

For 12 h before the measurements and during them, the environmental temperature gradient in degrees per hour shall be within limits agreed between manufacturer/supplier and user.

4.2 Machine to be tested

The machine shall be completely assembled and fully operational. If necessary, levelling operations and geometric alignment tests shall be completed satisfactorily before starting the positioning accuracy and repeatability tests.

If built-in compensation routines are used during the test cycle, this should be stated in the test report.

All tests shall be carried out with the machine in the unloaded condition, i.e. without a workpiece.

The positions of the axis slides or moving components on the axes which are not under test shall be stated in the test report.

4.3 Warm-up

When testing the machine under normal operating conditions, the tests shall be immediately preceded by an appropriate warm-up operation as specified by the manufacturer/supplier of the machine, or agreed between manufacturer/supplier and user.

If no conditions are specified, the warm-up operations can take the form of a “preliminary dummy run” of the positioning accuracy test without gathering data; or the preliminary movements can be restricted to those necessary for setting up the measuring instruments. The warm-up operation chosen shall be stated in the test report.

Non-stable thermal conditions are recognized as an ordered progression of deviations between successive approaches to any particular target position. These trends should be minimized through the warm-up operation.

5 Test programme

5.1 Mode of operation

The machine shall be programmed to move the moving component along or around the axis under test and to position it at a series of target positions where it will remain at rest long enough for the actual position to be reached, measured, and recorded. The machine shall be programmed to move between the target positions at a feed speed agreed between manufacturer/supplier and user.

5.2 Selection of target position

Where the value of each target position can be freely chosen, it shall take the general form of Formula (1):

$$P_i = (i - 1)p + r \tag{1}$$

where

i is the number of the current target position;

p is the nominal interval based on a uniform spacing of target points over the measurement travel;

r is a random number within ± one period of expected periodic positioning error (such as errors caused by the pitch variations of the ball screw and pitch variations of linear or rotary scales), used to ensure that these periodic errors are adequately sampled, and where, if no information on possible periodic errors is available, r shall be within ±30 % of p.

Target positions selected for the execution of acceptance or reverification tests shall be different from the sampling points used for numerical compensation of the relevant axis positioning errors.

NOTE Annex C provides information related to periodic positioning error.

5.3 Measurements

5.3.1 Set-up and instrumentation

The measurement setup is designed to measure the relative motion between the component of the machine that carries the cutting tool and the component that carries the workpiece in the direction of motion of the axis under test.

Typical measuring instruments for the determination of positioning error and repeatability of linear axes are calibrated laser interferometers (including tracking interferometers) and calibrated linear scales. Calibrated ball arrays can also be used (see Annex D).

Positioning error and repeatability of short axes up to 100 mm can also be measured with long-range linear displacement sensors.

If mathematical NDE correction is applied, the position of the temperature sensor(s) on the machine components, the expansion coefficients used for NDE correction, and the type of compensation routine shall be stated on the test report.

Typical measuring instruments for the determination of positioning error and repeatability of rotary axes are polygons with autocollimators, reference indexing tables with laser interferometer/autocollimator, and reference rotary (angle) encoders.

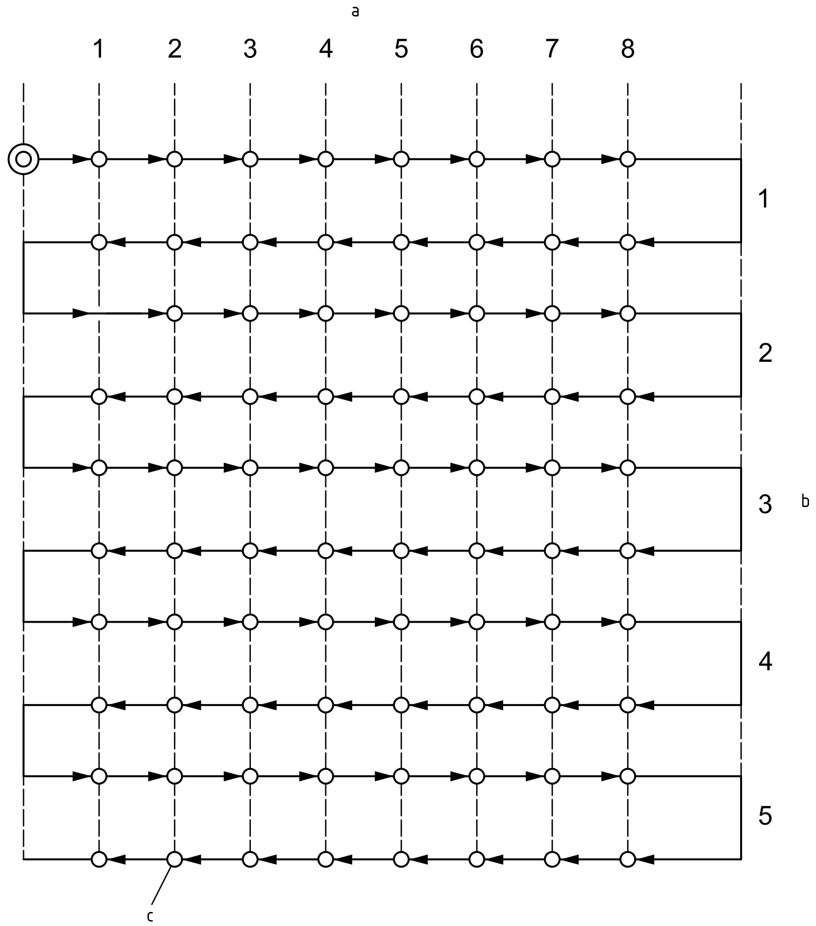
The position of the measuring instruments and reference artefacts, if any, shall be recorded on the test report.

5.3.2 Tests for linear axes up to 2 000 mm

On machine axes of travel up to 2 000 mm, a minimum of five target positions per metre and an overall minimum of five target positions shall be selected in accordance with 5.2.

Measurements shall be made at all the target positions according to the standard test cycle (see Figure 1). Each target position shall be attained five times in each direction.

The position of changing direction should be chosen to allow for normal behaviour of the machine (to achieve the agreed feed speed).



a Position i ($m = 8$).

b Cycle j ($n = 5$).

c Target points.

Figure 1 — Standard test cycle

5.3.3 Tests for linear axes exceeding 2 000 mm

For axes longer than 2 000 mm, the whole measurement travel of the axis shall be tested by making one unidirectional approach in each direction to target positions selected according to 5.2 with an average interval length, p, of 250 mm. If the measuring transducer consists of several segments, additional target points have to be selected to ensure that each segment has at least one target position.

Additionally, the test specified in 5.3.2 shall be made over a length of 2 000 mm in the normal working area as agreed between manufacturer/supplier and user.

For axes longer than 4 000 mm, the number of tests specified in 5.3.2 to be performed as well as their position within the working area shall be subject to specific agreement between manufacturer/supplier and user.

5.3.4 Tests for rotary axes up to 360°

Tests shall be made at the target positions given in Table 1. The principal positions 0°, 90°, 180°, and 270° should be included when available along with other target positions in accordance with 5.2. Each target position shall be attained five times in each direction.

Table 1 — Target positions for rotary axes

Measurement travel	Minimum number of target positions
≤90°	3
>90° and ≤180°	5
>180°	8

5.3.5 Tests for rotary axes exceeding 360°

For axes exceeding 360°, the total measurement travel of the axis up to 1 800° (five revolutions) shall be tested by making one unidirectional approach in each direction with a minimum of eight target points per revolution.

Additionally, the test specified in 5.3.4 shall be made over an angle of 360° in the normal working area as agreed between manufacturer/supplier and user.

6 Evaluation of the results

6.1 Linear axes up to 2 000 mm and rotary axes up to 360°

For each target position P_i and for five approaches (n = 5) in each direction, the parameters defined in Clause 3 are evaluated. Furthermore, the deviation boundaries

$$\bar{x}_i\uparrow + 2s_i\uparrow \text{and } \bar{x}_i\uparrow - 2s_i\uparrow$$

and

$$\bar{x}_i\downarrow + 2s_i\downarrow \text{ and } \bar{x}_i\downarrow - 2s_i\downarrow$$

are calculated.

6.2 Linear axes exceeding 2 000 mm and rotary axes exceeding 360°

For each target position and for one approach (n = 1) in each direction, the applicable parameters defined in Clause 3 are evaluated. Estimators for the unidirectional axis repeatability (3.18), repeatabilities (3.19, 3.20, 3.21, and 3.22), and positioning errors (3.26 and 3.27) are not applicable. The evaluation of results in 6.1 over a length of 2 000 mm or 360° shall also be provided as agreed between manufacturer/supplier and user.

7 Points to be agreed between manufacturer/supplier and user

The points to be agreed between the manufacturer/supplier and the user are as follows:

a) the minimum and maximum ambient temperature values;

b) the maximum rate of environmental temperature gradient in degrees per hour for 12 h before and during the measurements (see 4.1);

c) the location of the measuring instrument and the positions of the temperature sensors, if relevant (see 5.3.1);

d) the warm-up operation to precede testing the machine (see 4.3);

e) the feed speed between target positions;

f) the position(s) of the 2 000 mm or 360° measurement travel(s) to be regarded as the normal working area (see 5.3.3 or 5.3.5), if relevant;

g) position of the slides or moving components which are not under test;

h) dwell time at each target position;

i) location of first and last target positions.

8 Presentation of results

8.1 Method of presentation

The preferred method of presentation of the results is a graphical one with the following list of items recorded on the test report in order to identify the measurement setup:

- name of inspector;
- position of axes not under test;
- offset to tool reference (X/Y/Z);
- offset to workpiece reference (X/Y/Z);
- if mathematical NDE correction is applied:
  - coefficient(s) of thermal expansion used for NDE correction,
  - position of the temperature sensor(s) used for NDE correction on the machine components and on the test equipment,
  - temperatures of sensors for NDE correction on the machine components representing machine scale or workpiece/tool-holding part of the machine and temperatures of sensors on the test equipment, at the start and end of the test,
  - type of compensation routine (e.g. frequency of updating compensation parameters);
- date of test;
- machine name, type (horizontal spindle or vertical spindle), and its coordinate axes travels;
- list of the test equipment used, including manufacturer's name, type, and serial number of the components (laser head, optics, temperature sensors, etc.);
- type of machine scale used for positioning of axis and its coefficient of thermal expansion, obtained from machine tool manufacturer/supplier (e.g. ball screw/rotary resolver system, linear scale system);
- name of axis under test:
  - for linear axis, the location of its measurement line relative to the axes not under test (this location is determined by the offset to tool reference, offset to workpiece reference, and the locations of axes not under test, with both of these offsets being determined by the specific machine configuration),
  - for rotary axis, a description of nominal position and orientation of the axis;
- feed speed and dwell time at each target position, list of nominal target positions;
- warm-up operation to precede testing the machine (number of cycles or idling time and feed speed);

- if relevant, air temperature, air pressure, and humidity near the laser beam at the start and end of the test;
- whether or not built-in compensation routines were used during the test cycle;
- use of air or oil shower, when applied;
- number of approaches ($n = 5$ or $n = 1$);
- contributors and parameters used for estimation of measurement uncertainty.

8.2 Parameters

8.2.1 General

The following parameters shall be specified numerically. A summary of results using the parameters denoted with an asterisk followed by a parenthesis can provide a basis for machine acceptance. A presentation of the results given in Table 2 is shown in Table 3, Figure 2, and Figure 3.

Each parameter should be given together with the measurement uncertainty U with a coverage factor of 2, U ($k = 2$). The minimum requirements for information regarding the measurement uncertainty U are

- the parameters for the uncertainty due to the measuring device,
- the parameters for the uncertainty due to the compensation of the machine tool temperature,
- the parameters for the uncertainty due to the environmental temperature variation error, and
- the parameters for the uncertainty due to the misalignment of the measuring device, if relevant.

For linear axes, Annex A shows a simplified method for the estimation of the measurement uncertainty, including examples. More detailed information and formulae are included in ISO/TR 230-9:2005, Annex C.

8.2.2 Tests for linear axes up to 2 000 mm and rotary axes up to 360°

— Bi-directional positioning error of an axis$^{*)}$	A
— Unidirectional positioning error of an axis$^{*)}$	$A\uparrow$ and $A\downarrow$
— Bi-directional systematic positioning error of an axis$^{*)}$	E
— Unidirectional systematic positioning error of an axis	$E\uparrow$ and $E\downarrow$
— Range of the mean bi-directional positioning error of an axis$^{*)}$	M
— Bi-directional positioning repeatability of an axis	R
— Unidirectional positioning repeatability of an axis$^{*)}$	$R\uparrow$ and $R\downarrow$
— Reversal error of an axis$^{*)}$	B
— Mean reversal error of an axis	$\bar{B}$

$^{*)}$ is the potential parameter for machine tool acceptance.

8.2.3 Tests for linear axes exceeding 2 000 mm and rotary axes exceeding 360°

— Bi-directional systematic positioning error of an axis*)	E
— Unidirectional systematic positioning error of an axis	$E\uparrow$ and $E\downarrow$
— Range of the mean bi-directional positioning error of an axis*)	M
— Reversal error of an axis*)	B
— Mean reversal error of an axis	$\bar{B}$

*) is the potential parameter for machine tool acceptance.

8.2.4 Clarification on terms related to the components of positioning error of an axis

Error motions of machine tool axes are defined in ISO 230-1:2012. In general, such error motions are evaluated by collecting deviations at certain measurement intervals and processing them following the prescribed methods, mostly resulting in single error parameters associated with the nominal motion addressed. ISO 230-1:2012 provides nomenclature to represent such error parameters, for example, E_{YX} being straightness error of x-axis motion in the y-axis direction, E_{CX} being angular error of x-axis motion in the c-direction (rotation around z-axis), and E_{XX} being the positioning error of the x-axis motion.

In case of the positioning error motion of numerically controlled machine tool axes, this part of ISO 230 provides multiple parameters as components of such error motion (e.g. repeatability of unidirectional positioning error motion, mean bi-directional positioning error motion, etc.). Such multiple parameters are components that provide additional qualification of the specific positioning error being evaluated. So, in application of the new symbolism used in ISO 230-1:2012, the nomenclature for parameters introduced in this part of ISO 230 can be expressed as subscripts of the symbol for the positioning error of the relevant axis. For example, the unidirectional positioning error, $A\uparrow$ or $A\downarrow$, of the x-axis can be expressed as $E_{\mathrm{XX,A}\uparrow}$ or $E_{\mathrm{XX,A}\downarrow,}$ and the reversal error of a c-axis can be expressed as $E_{\mathrm{CC,B.}}$

It is recognized that the symbols for components of positioning error of an axis that are applied throughout this part of ISO 230 are consolidated terms, well known in industrial applications, and used for automatic reporting of results by dedicated measuring instruments. So, the application of the new symbolism used in ISO 230-1:2012 might need some time to be implemented.

Table 2 — Typical test results (tests for linear axis up to 2 000 mm)

i		1		2		3		4		5		6		7		8		9		10		11	
Target position P_i (mm)		6,711		175,077		353,834		525,668		704,175		881,868		1 055,890		1 234,304		1 408,462		1 580,269		1 750,920	
Approach direction		↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑
Positioning deviations (µm)	$j = 1$	2,3	−1,2	3,6	−0,5	3,5	0,2	3,0	−0,6	1,7	−1,9	0,4	−3,0	−0,4	−3,7	−0,2	−3,7	0,2	−3,5	0,3	−3,2	−0,1	−3,6
	2	2,1	−1,7	3,5	−0,9	3,3	−0,6	2,7	−1,2	1,5	−2,3	0,2	−3,5	−0,7	−4,3	−0,6	−4,4	-0,2	−4,3	−0,1	−3,8	−0,6	−4,0
	3	1,9	−1,9	3,1	−1,1	3,0	−0,7	2,4	−1,3	1,0	−2,9	−0,2	−3,7	−1,0	−4,6	−1,0	−5,1	-1,0	−5,0	−0,9	−4,7	−1,2	−4,5
	4	2,8	−1,3	3,7	−0,2	3,8	0,1	3,2	−0,3	1,9	−1,4	0,9	−2,8	0,0	−3,6	−0,2	−3,6	0,5	−3,2	0,5	−2,8	0,4	−3,2
	5	2,2	−1,9	3,2	−0,8	3,5	−0,7	2,6	−1,3	1,1	−2,3	−0,1	−3,7	−0,9	−4,5	−1,1	−4,6	-0,5	−4,5	-0,4	−4,1	−0,9	−4,5
Mean unidirectional positioning deviation $\overline{x}_i$ (µm)		2,3	−1,6	3,4	−0,7	3,4	−0,3	2,8	−0,9	1,4	−2,2	0,2	−3,3	−0,6	−4,1	−0,6	−4,3	-0,2	-4,1	-0,1	−3,7	−0,5	−4,0
Estimator of standard uncertainty s_i (µm)		0,3	0,3	0,3	0,4	0,3	0,5	0,3	0,5	0,4	0,6	0,4	0,4	0,4	0,5	0,4	0,6	0,6	0,7	0,6	0,7	0,6	0,6
$2s_i$ (µm)		0,7	0,7	0,5	0,7	0,6	0,9	0,6	0,9	0,8	1,1	0,9	0,8	0,8	0,9	0,9	1,3	1,2	1,5	1,1	1,5	1,3	1,1
$\overline{x}_i - 2s_i$ (µm)		1,6	−2,3	2,9	−1,4	2,8	−1,2	2,1	−1,9	0,7	−3,3	−0,6	−4,2	−1,4	−5,1	−1,5	−5,5	-1,4	−5,6	-1,2	−5,2	−1,8	−5,1
$\overline{x}_i + 2s_i$ (µm)		2,9	−0,9	3,9	0,0	4,0	0,6	3,4	0,0	2,2	−1,1	1,1	−2,5	0,2	−3,2	0,2	−3,0	1,0	−2,6	1,0	−2,2	0,8	−2,8
Unidirectional repeatability $R_i = 4s_i$ (µm)		1,3	1,3	1,0	1,4	1,2	1,8	1,3	1,8	1,5	2,2	1,8	1,8	1,6	1,8	1,7	2,5	2,3	3,0	2,2	3,0	2,6	2,3
Reversal error B_i (µm)		−3,9		−4,1		−3,8		−3,7		−3,6		−3,6		−3,6		−3,7		−3,9		−3,6		−3,5	
Bidirectional repeatability R_i (µm)		5,2		5,3		5,3		5,2		5,5		5,3		5,3		5,8		6,6		6,2		5,9	
Mean bidirectional positioning deviation $\overline{x}_i$ (µm)		0,3		1,4		1,5		0,9		−0,4		−1,6		−2,4		−2,5		−2,2		−1,9		−2,2	
Parameter (mm)		Unidirectional ↓						Unidirectional ↑						Bi-directional									
Reversal error B		Not applicable						Not applicable						0,004 ± 0,001 (at $i = 2$) ($k = 2$)									
Mean reversal error $\overline{B}$		Not applicable						Not applicable						−0,004									
Range of mean bidirectional positioning error M		Not applicable						Not applicable						0,004 ± 0,004 ($k = 2$) (0,001 5 − (−0,002 5))									
Systematic positioning error E		0,004 (0,003 4 − (−0,000 6))						0,004 (−0,000 3 − (−0,004 3))						0,008 ± 0,004 ($k = 2$) (0,003 4 − (−0,004 3))									

Table 2 *(continued)*

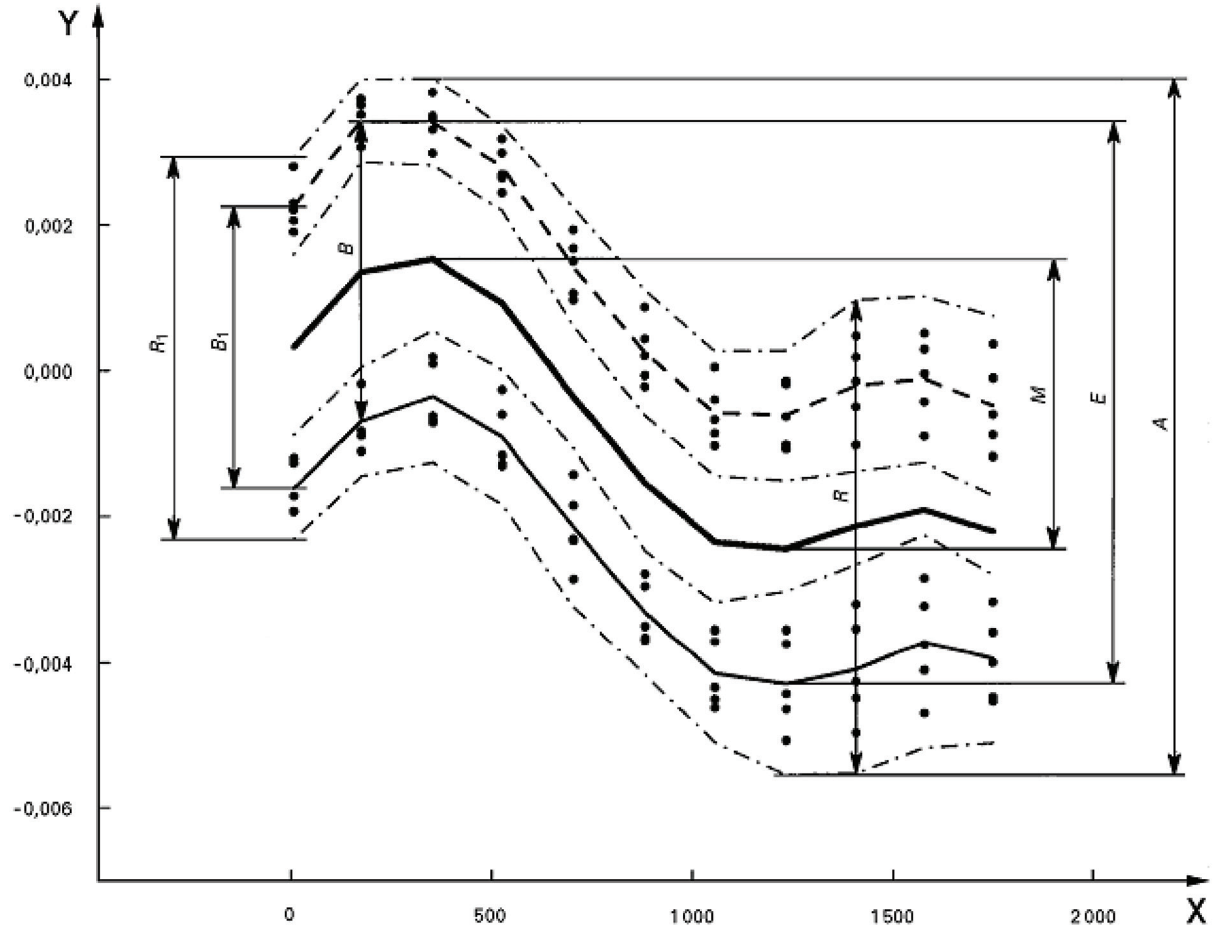
i	1	2	3	4	5	6	7	8	9	10	11
Positioning repeatability R	0,003	(at i = 11)		0,003	(at i = 10)		0,007 ± 0,002	(k = 2)			
Positioning error A	0,006	(0,004 0 – (−0,001 8))		0,006	(0,0006 – (−0,005 5))		0,010 ± 0,004	(k = 2)	(0,004 0 – (−0,005 6))		

NOTE 1 Uncertainty values are according to Table A.5; coverage factor, k, is according to 3.9.

NOTE 2 The values given in this table are rounded.

Table 3 — Example of test report information complementing graphical representation of results shown in Figure 2 and Figure 3

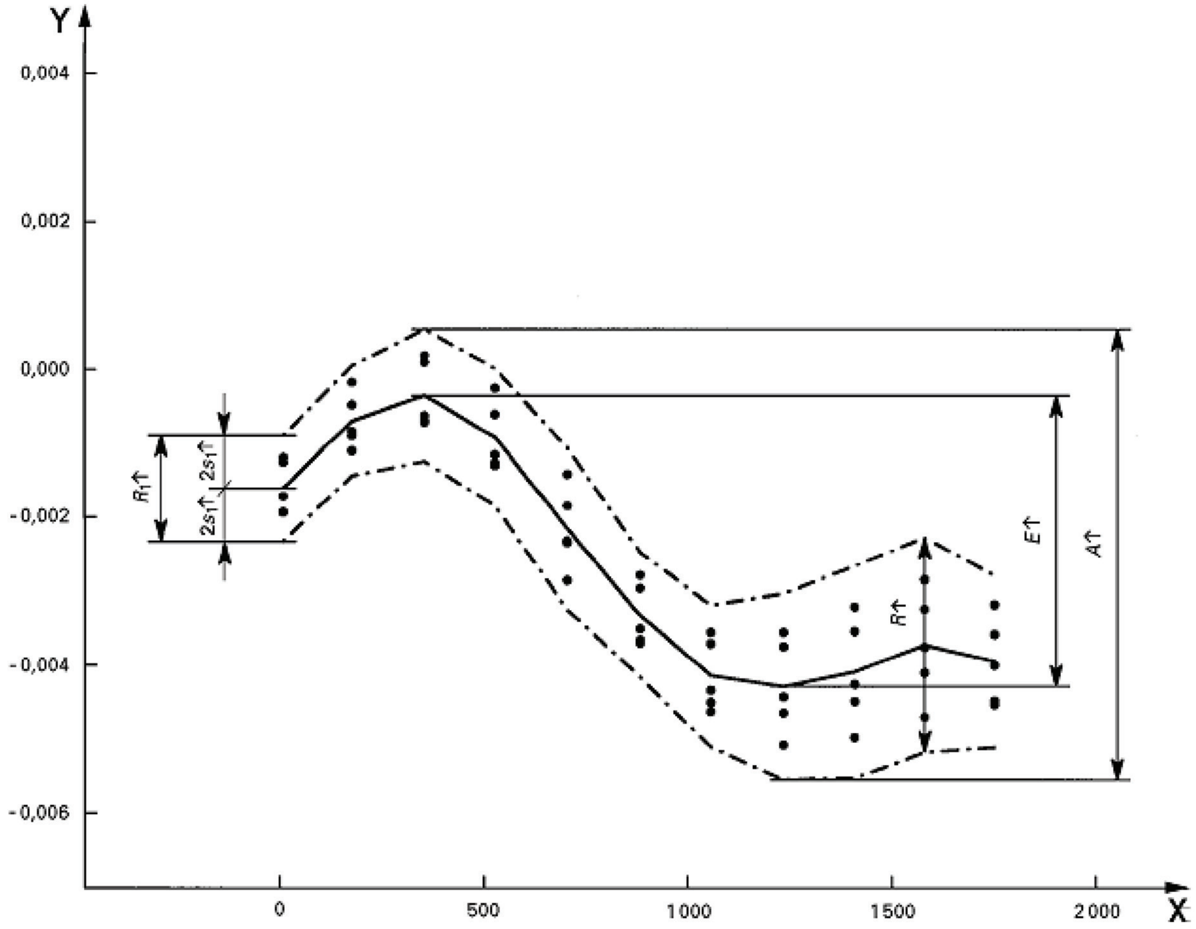
Date of test:	YY/MM/DD			
Name of inspector:	Joe Smith			
Machine name, type and serial no.:	AAA, vertical spindle machining centre, serial no.: 1111111			
Measuring instrument and serial no.:	laser interferometer BBB, serial no.: 1234567			
Test parameters				
tested axis:	X			
type of scale:	ball screw and rotary encoder			
NDE correction		location	*T* start (°C)	*T* end (°C)
material sensor used for NDE correction:		table, centre	21,8	22,9
coefficient of thermal expansion (used for NDE correction):	11	µm/(m·°C)		
compensation routine		update each 20 s		
feed speed:	1 000	mm/min		
dwell time at each target position:	5	s		
compensation used:	reversal and leadscrew			
Test location				
position of axes not under test:	Y = 300 mm; Z = 350 mm; C = 0°			
offset to tool reference (X/Y/Z):	0/0/120 mm			
offset to workpiece reference (X/Y/Z):	0/0/30 mm			
Air conditions used for compensation of laser interferometer, updated each 20 s				
	location		*T* start (°C)	*T* end (°C)
air temperature:	centre of work zone		20,6	20,9
air pressure:	102,4 kPa			
air humidity:	60 %			



Key

X	positions (mm)	B_1	reversal error at position 1
Y	deviations (mm)	B	reversal error of the axis
——	$\overline{x}_i \uparrow$	R	bi-directional positioning repeatability of the axis
— — —	$\overline{x}_i \downarrow$	M	mean bi-directional positioning error of the axis
—·—	$\overline{x}_i \uparrow \pm 2s \uparrow$ or $\overline{x}_i \downarrow \pm 2s \downarrow$	E	bi-directional systematic positioning error of the axis
━━	$\overline{x}_i$	A	bi-directional positioning error of the axis
R_1	bi-directional positioning repeatability at position 1		

Figure 2 — Bi-directional error(s) and positioning repeatability



Key

X	positions (mm)
Y	deviations (mm)
———	$\bar{x}_i \uparrow$
— · —	$\bar{x}_i \uparrow \pm 2s_i \uparrow$
R_1↑	unidirectional positioning repeatability at position 1
$2s_1$↑	twice the estimator of unidirectional positioning repeatability at position 1
R↑	unidirectional positioning repeatability of the axis
E↑	unidirectional systematic positioning error of the axis
A↑	unidirectional positioning error of the axis

Figure 3 — Unidirectional accuracy and positioning repeatability (for positive approaches)

Annex A

(informative)

Measurement uncertainty estimation for linear positioning measurement — Simplified method

A.1 Estimation of the expanded measurement uncertainty

The estimation of the measurement uncertainty follows the procedures and formulae of ISO/TR 230-9:2005, Annex C. In ISO/TR 230-9:2005, the estimation follows the ISO/IEC Guide 98-3:2008, i.e. contributors to the measurement uncertainty are expressed by their standard uncertainties, u, which are combined to the combined standard uncertainty, u_{c}, and used for the calculation of the expanded measurement uncertainty, U.

In this annex, the influence of relevant contributors to the measurement uncertainty, e.g. alignment of the measuring device, is expressed by the expanded measurement uncertainty, $U_{\mathrm{ALIGNMENT}}$, in order to demonstrate directly its influence to the expanded measurement uncertainty, U, especially with the help of tables. The influence of relevant contributors to parameters of the test, e.g. to bi-directional systematic positioning error of an axis, E, is expressed by the expanded measurement uncertainty, U_E, which is evaluated as a combination of relevant expanded measurement uncertainties, U_{X}. The measurement uncertainties, U, are calculated for a coverage factor of $k = 2$.

A.2 Contributors to the measurement uncertainty

A.2.1 General

The main contributors to the measurement uncertainty are the measuring device, the misalignment of the measuring device to the machine axis under test, the uncertainty due to the compensation of the machine tool temperature due to measurements at temperatures other than 20 °C, and environmental variation errors (E_{VE}).

The contributors and assumptions are according to ISO/TR 230-9:2005, Annex C, except the set-up error, because it is assumed that the set-up is within 10 mm of the position recorded on the test report.

A.2.2 Expanded uncertainty due to measuring device, U_{DEVICE}

The formulae used in this subclause are based on ISO/TR 230-9:2005, C.2.2, and Formulae (C.1) and (C.2).

The use of a calibrated measuring device is recommended. If the calibration certificate states the maximum uncertainty in micrometres (µm), Formula (A.1) applies. If the calibration certificate states the uncertainty in micrometres per metre (µm/m), Formula (A.2) applies.

If no calibration certificate is available and the manufacturer states an error range in micrometres per metre, then Formula (A.3) should be used. The influence of the resolution of the measuring device is in general negligible and can be checked according to ISO/TR 230-9:2005, C.2.2 and Formulae (C.3) and (C.4).

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

where

U_{DEVICE}	is the expanded uncertainty due to the measuring device, in micrometres (µm);
$U_{\mathrm{CALIBRATION}}$	is the uncertainty of calibration according to the calibration certificate, in micrometres (µm), with coverage factor $k = 2$.

$$U_{\mathrm{DEVICE}} = U_{\mathrm{CALIBRATION}} \cdot L \tag{A.2}$$

where

U_{DEVICE}	is the expanded uncertainty due to the measuring device, in micrometres (µm);
$U_{\mathrm{CALIBRATION}}$	is the uncertainty of the calibration according to the calibration certificate, in micrometres per metre (µm/m), with coverage factor $k = 2$;
L	is the measurement length, in metres (m).

$$U_{\mathrm{DEVICE}} = 0{,}6 \cdot R_{\mathrm{DEVICE}} \cdot L \tag{A.3}$$

where

U_{DEVICE}	is the expanded uncertainty due to the measuring device, in micrometres (µm);
R_{DEVICE}	is the error range given by the manufacturer of the device, in micrometres per metre (µm/m);
L	is the measurement length, in metres (m).

A.2.3 Expanded uncertainty due to misalignment of measuring device to machine axis under test, $U_{\mathrm{MISALIGNMENT}}$

The formulae used in this subclause are based on ISO/TR 230-9:2005, C.2.3 and Formula (C.5).

The measuring device has to be aligned parallel to the machine axis under test, otherwise a measurement error is observed. The influence is of second order, however, if the misalignment is larger than 1 mm and if the machine axis under test is shorter than 300 mm, this influence can become significant. Formula (A.4) and Table A.1 show the influences of a misalignment.

With optical measurement equipment such as a laser interferometer, the misalignment will be within 1 mm, if the movement of the reflected beam is as recommended by the equipment manufacturers. If the alignment is simply made in order to have sufficient return beam intensity, which is not recommended, the misalignment might be up to 4 mm.

With mechanical measurement equipment such as a linear scale, the alignment with the help of a side face will result in a misalignment smaller than 0,5 mm.

$$U_{\mathrm{MISALIGNMENT}} = 0{,}3 \cdot \frac{R^2_{\mathrm{MISALIGNMENT}}}{L} \tag{A.4}$$

where

$U_{\mathrm{MISALIGNMENT}}$	is the expanded measurement uncertainty due to misalignment, in micrometres (µm);
$R_{\mathrm{MISALIGNMENT}}$	is the misalignment, in millimetres (mm);
L	is the measurement length, in metres (m).

Table A.1 — Expanded measurement uncertainty due to misalignment of measurement equipment, $U_{\mathrm{MISALIGNMENT}}$

Measurement length mm	$U_{\mathrm{MISALIGNMENT}}$ µm					
	Misalignment mm					
	0,5	1,0	1,5	2,0	3,0	4,0
200	0	1	3	6	13	23
300	0	1	2	4	9	15
500	0	1	1	2	5	9
800	0	0	1	1	3	6
1 000	0	0	1	1	3	5
1 500	0	0	0	1	2	3
2 000	0	0	0	1	1	2
4 000	0	0	0	0	1	1

A.2.4 Expanded uncertainty due to compensation of machine tool temperature

A.2.4.1 General

The formulae used in this subclause are based on ISO/TR 230-9:2005, C.2.4.

If measurements are carried out at temperatures other than 20 °C, the relative expansion between machine tool (or workpiece) and the measuring device has to be compensated for. This task is often a hidden one, because the measurement equipment compensates automatically.

The temperature measurements needed for that compensation have a measurement uncertainty that adds to the overall measurement uncertainty of the length measurement for this part of ISO 230.

For the compensation, the thermal expansion coefficients of the machine tool (or workpiece) and of the measuring device are also needed. Their uncertainties are further contributors to the length measurement uncertainty.

A.2.4.2 and A.2.4.3 are concerned with the estimation of these uncertainties.

A.2.4.2 Expanded uncertainty due to measurement of temperature

The formulae used in this subclause are based on ISO/TR 230-9:2005, Formula (C.6).

The most important influence for the temperature measurement is the selection of the point of measurement that has to be representative for the temperature of the machine tool (or the workpiece). It is recommended that the workpiece holding device be taken as representative. However, the points of temperature measurements are required to be stated in the test report according to 8.1.

The other influences are the mounting of the temperature sensors, which should be firmly fixed on the machine tool component, and the measurement uncertainty of the temperature sensors.

For practical applications, these influences are expressed as a possible error range of the temperature measurement.

NOTE A range of 1 °C corresponds to the expression ±0,5 °C.

For temperature sensors that are fixed according to the instructions of the sensor manufacturer and mounted at the representative point, the range of the possible sensor error can be used for the estimation of the measurement uncertainty. Commonly used temperature sensors have a range of deviation of about 0,7 °C (± 0,35 °C). If the temperature sensors are mounted incorrectly or placed at non-representative points, the measurement error might be larger than 4 °C. The influence of the measurement error of the temperature sensor and the influence of the measurement length is given in Table A.2.

Table A.2 — Influence of the error of temperature measurement, U_{M}

Measurement length mm	$U_{\text{M, DEVICE}}$ and $U_{\text{M, MACHINE TOOL}}$ µm							
	Measurement error °C							
	0,1 (±0,05)	0,2 (±0,1)	0,5 (±0,25)	0,7 (±0,35)	1,0 (±0,5)	2,0 (±1,0)	3,0 (±1,5)	4,0 (±2,0)
200	0	0	1	1	1	3	4	6
300	0	0	1	1	2	4	6	8
500	0	1	2	2	3	7	10	14
800	1	1	3	4	6	11	17	22
1 000	1	1	3	5	7	14	21	28
1 500	1	2	5	7	10	21	31	42
2 000	1	3	7	10	14	28	42	55
4 000	3	6	14	19	28	55	83	111
Expansion coefficient	12,0 µm/(m·°C)							

The expanded measurement uncertainty due to the temperature measurement has to be estimated for the machine tool, $U_{\text{M, MACHINE TOOL}}$, and for the measuring device, $U_{\text{M, DEVICE}}$.

Most laser interferometer systems automatically compensate for the expansion of the device (i.e. the influence of the air temperature) and include the uncertainty of this compensation in the stated measurement uncertainty of the device. In these cases, no expanded measurement uncertainty due to the temperature measurement of the device, $U_{\text{M, DEVICE}}$, has to be calculated. The expanded measurement uncertainty due to the temperature measurement of the machine tool remains a contributor to the length measurement uncertainty [see Formula (A.5)].

With linear scales, if the thermal expansion coefficient of the scale is the same as the machine tool (or the workpiece), the compensation for temperatures other than 20 °C is also done automatically, due to the expansion of the linear scale. The only error is the temperature difference between the workpiece-holding device of the machine tool and the linear scale. Some minutes after mounting the linear scale on the machine tool, this difference is typically smaller than 0,1 °C. This possible temperature difference can be used as the temperature range in Formula (A.5) for the uncertainty due to the temperature measurement of the machine tool, $U_{\text{M, MACHINE TOOL}}$. The temperature of the linear scale has not to be measured, therefore the expanded measurement uncertainty due to the temperature measurement of the device, $U_{\mathrm{M,\ DEVICE}}$, can be set to zero [see Formula (A.6)].

$$U_{\mathrm{M,\ MACHINE\ TOOL}} = 0{,}6 \cdot \alpha \cdot L \cdot R(\Theta) \tag{A.5}$$

where

$U_{\mathrm{M,\ MACHINE\ TOOL}}$	is the expanded measurement uncertainty due to temperature measurement of the machine tool, in micrometres (µm);
α	is the expansion coefficient of the machine tool, in respect of the axis under test, in micrometres per metre degree Celsius [µm/(m·°C)];
L	is the measurement length, in metres (m);
$R(\Theta)$	is the possible range of temperature due to uncertainty of measurement, or the temperature difference between the workpiece holding device of the machine tool and the (mechanical) measuring device, in degrees Celsius (°C).

$$U_{\mathrm{M,\ DEVICE}} = 0{,}6 \cdot \alpha \cdot L \cdot R(\Theta) \tag{A.6}$$

where

$U_{\mathrm{M,\ DEVICE}}$	is the expanded measurement uncertainty due to temperature measurement of the measuring device, in micrometres (µm), and which can be set to zero if the uncertainty statement of the measuring device includes the uncertainty due to the temperature measurement of the device (or the uncertainty of the compensation for measurements at temperatures other than 20 °C), or if the measuring device adopts the temperature of the machine tool (or the workpiece);
α	is the expansion coefficient of the measuring device, in micrometres per metre degree Celsius [µm/(m·°C)];
L	is the measurement length, in metres (m);
$R(\Theta)$	is the possible range of temperature due to uncertainty of measurement, in degrees Celsius (°C).

A.2.4.3 Expanded uncertainty due to expansion coefficient

The formulae used in this subclause are based on ISO/TR 230-9:2005, Formula (C.7).

In practice, the expansion coefficient of the machine tool and of the measuring device are taken from handbooks or brochures. The effective coefficient of expansion might differ from these data. The difference is stated by a range in micrometres per metre degree Celsius [µm/(m·°C)]. Typically, this range is 2 µm/(m·°C) for linear scales of machine axis; compound materials could show larger deviations from the nominal values.

NOTE A range of 2 µm/(m·°C) corresponds to the expression ±1 µm/(m·°C).

Table A.3 shows the relation of the uncertainty of the thermal expansion coefficient and the temperature of the length measurement for axes lengths of 1 m. Measurements at 20 °C show no uncertainty due to the expansion coefficient, because no compensation is needed in this case.

The expanded uncertainty due to the possible error in the expansion coefficient of the machine tool (or workpiece), $U_{\mathrm{E,\ MACHINE\ TOOL}}$ [see Formula (A.7)], and the expanded uncertainty due to the possible error of the expansion coefficient of the measuring device, $U_{\mathrm{E,\ DEVICE}}$ [see Formula (A.8)], should be evaluated.

If the uncertainty statement for the measuring device includes the uncertainty of the compensation of measurements at temperatures other than 20 °C, $U_{\mathrm{E,\ DEVICE}}$ can be set to zero.

Table A.3 — Measurement uncertainty due to the uncertainty of the thermal expansion coefficient

Temperature °C	**Coefficient for U_E** µm/m				
	Error range in expansion coefficient µm/(m·°C)				
	1 (±0,5)	2 (±1,0)	3 (±1,5)	4 (±2,0)	6 (±3,0)
5	9	17	26	35	52
10	6	12	17	23	35
15	3	6	9	12	17
18	1	2	3	5	7
19	1	1	2	2	3
20	0	0	0	0	0
21	1	1	2	2	3
22	1	2	3	5	7
25	3	6	9	12	17
30	6	12	17	23	35
35	9	17	26	35	52

NOTE 1 U_E = coefficient × L.

NOTE 2 U_E is expressed in µm.

NOTE 3 L is expressed in m.

$$U_{\mathrm{E,\ MACHINE\ TOOL}} = 0{,}6 \cdot \Delta T \cdot L \cdot R(\alpha) \quad \text{(A.7)}$$

where

$U_{\mathrm{E,\ MACHINE\ TOOL}}$	is the expanded measurement uncertainty due to the possible error in the thermal expansion coefficient of the machine tool (or the workpiece), in micrometres (µm);
ΔT	is the difference to 20 °C, in degrees Celsius, $\Delta T = (T - 20)$ °C;
T	is the temperature of machine tool or workpiece, in degrees Celsius (°C);
L	is the measurement length, in metres (m);
$R(\alpha)$	is the error range of the expansion coefficient of the machine tool (or workpiece), in micrometres per metre degree Celsius [µm/(m·°C)].

$$U_{\mathrm{E,\,DEVICE}} = 0{,}6 \cdot \Delta T \cdot L \cdot R(\alpha) \qquad \text{(A.8)}$$

where

$U_{\mathrm{E,\,DEVICE}}$	is the expanded measurement uncertainty due to the possible error in the thermal expansion coefficient of the length measuring device, in micrometres (µm), and which can be set to zero, if the uncertainty statement of the measuring device includes the uncertainty due to the temperature measurement of the device (or the uncertainty of the compensation of measurements at temperatures other than 20 °C);
ΔT	is the difference to 20 °C, in degrees Celsius, $\Delta T = (T - 20)$ °C;
T	is the temperature of the measuring device, in degrees Celsius (°C);
L	is the measurement length, in metres (m);
$R(\alpha)$	is the error range of the expansion coefficient of the measuring device, in micrometres per metre degree Celsius [µm/(m·°C)].

A.2.5 Expanded uncertainty due to environmental variation error, E_{VE}, U_{EVE}

The formula used in this subclause is based on ISO/TR 230-9:2005, C.2.5, and Formula (C.9).

During most measurements, temperature changes can be observed that might influence the machine tool and the measuring device. The effects of these changes shall be kept to a minimum according to 4.1 and 4.3.

The remaining effects are checked by a simple test. Before starting the length measurements, the length measuring device shall be set up in order to read the largest distance of the axis under test, whereas the set-up shall not be influenced by any environmental variation errors of the machine tool, e.g. direct set-up on or near the machine bed with all components of the device being fixed. During the approximate time needed for the length measurement, the readout of the measuring device is recorded. The range of the readout, E_{VE}, is the remaining environmental variation error that is used to estimate the corresponding uncertainty according to Formula (A.9).

If the effect of the environmental variation on the machine table is known to be irrelevant, in the direction of the length measurement, over the approximate duration for the measurement, the length measuring device can be fixed to the table for this test. In this case, the length measuring device is set up to measure relative motion between the machine that carries the cutting tool and the component that carries the workpiece, moved to the extreme position (largest distance), and the test on environmental variation error is carried out in this position.

$$U_{\mathrm{EVE}} = 0{,}6 \cdot E_{\mathrm{VE}} \qquad \text{(A.9)}$$

where

U_{EVE}	is the expanded measurement uncertainty due to environmental variation, in micrometres (µm);
E_{VE}	is the range from the environmental variation error test, in micrometres (µm).

A.2.6 Correction of repeatability values due to environmental variation errors

This subclause is applicable only to measurements up to 2 000 mm. Its formulae are based on Clause 4 and A.2.4, and on ISO/TR 230-9:2005, C.2.5. Any environmental variation error, E_{VE}, will increase the standard deviation calculated from the repeated measurements of the axis, and therefore increase the repeatability values R, $R\uparrow$, and $R\downarrow$. If an environment variation error test is carried out and if the repeatability values are valid for longer measurement lengths of the axis under test, the repeatability values can be corrected using Formula (A.10):

$$s_{i,\text{corrected}}\uparrow = \sqrt{s_i\uparrow^2 - \left(\frac{U_{\text{EVE}}}{2}\right)^2}$$

$$s_{i,\text{corrected}}\downarrow = \sqrt{s_i\downarrow^2 - \left(\frac{U_{\text{EVE}}}{2}\right)^2}$$

$$R_{i,\text{corrected}}\uparrow = 4\cdot s_{i,\text{corrected}}\uparrow$$

$$R_{i,\text{corrected}}\downarrow = 4\cdot s_{i,\text{corrected}}\downarrow$$

$$R_{i,\text{corrected}} = \max.\left[2\cdot s_{i,\text{corrected}}\uparrow + 2\cdot s_{i,\text{corrected}}\downarrow + |B_i|;\ R_{i,\text{corrected}}\uparrow;\ R_{i,\text{corrected}}\downarrow\right]$$

$$R_{\text{corrected}}\uparrow = \max.[R_{i,\text{corrected}}\uparrow]$$

$$R_{\text{corrected}}\downarrow = \max.[R_{i,\text{corrected}}\downarrow]$$

$$R_{\text{corrected}} = \max.[R_{i,\text{corrected}}] \qquad \text{(A.10)}$$

where

$s_{i,\text{corrected}}\uparrow,\downarrow$	is the corrected estimator for the standard deviation of unidirectional axis positioning repeatability, s_i, correction due to environmental influences;
s_i	is the estimator of the standard deviation of unidirectional axis positioning repeatability (see 3.16);
U_{EVE}	is the expanded measurement uncertainty due to environmental variations;
$R_{i,\text{corrected}}\uparrow,\downarrow$	is the corrected unidirectional positioning repeatability at a position *i*, correction due to environmental influences;
$R_{i,\text{corrected}}$	is the corrected bi-directional positioning repeatability at a position *i*, correction due to environmental influences;
$R_{\text{corrected}}\uparrow,\downarrow$	is the corrected unidirectional positioning repeatability, correction due to environmental influences;
$R_{\text{corrected}}$	is the corrected bi-directional positioning repeatability, correction due to environmental influences.

A.3 Estimation of expanded uncertainty of parameters A, $A\uparrow$, $A\downarrow$, E, $E\uparrow$, $E\downarrow$, R, $R\uparrow$, $R\downarrow$, B

A.3.1 General

The formulae used in A.3.2 to A.3.6 are based on Clause 3 and on ISO/TR 230-9:2005, C.4. For linear axes up to 2 000 mm, five runs in positive direction and five runs in negative direction are assumed; for linear axes exceeding 2 000 mm, only one run in positive and negative directions.

The following main contributors to the measurement uncertainty are taken into account: measuring device, misalignment of the device to the machine axis under test, temperature measurement for machine tool and measuring device, thermal expansion coefficient of machine tool and measuring device, and environmental variation error (E_{VE}).

A.3.2 Expanded uncertainty estimation for unidirectional repeatability, $U(R\uparrow, R\downarrow)$

This subclause is applicable only to measurements up to 2 000 mm. The formula used is based on ISO/TR 230-9:2005, C.4.3, and Formula (A.14):

$$U(R\uparrow, R\downarrow) = 2 \cdot U_{\mathrm{EVE}} \tag{A.11}$$

where

$U(R\uparrow, R\downarrow)$ is the expanded uncertainty of the unidirectional repeatability, $k = 2$, for five measurement runs, in micrometres (µm).

A.3.3 Expanded uncertainty estimation for reversal error, $U(B)$

The formulae used in this subclause are based on ISO/TR 230-9:2005, C.4.2, and Formula (C.14).

a) For axes up to 2 000 mm

$$U(B) = 0{,}9 \cdot U_{\mathrm{EVE}} \tag{A.12}$$

where

$U(B)$ is the expanded measurement uncertainty of reversal error, $k = 2$, for five measurement runs, in micrometres (µm).

b) For axes exceeding 2 000 mm

$$U(B) = 2 \cdot U_{\mathrm{EVE}} \tag{A.13}$$

where

$U(B)$ is the expanded measurement uncertainty of reversal error, $k = 2$, for one measurement run, in micrometres (µm).

A.3.4 Expanded uncertainty of bi-directional repeatability, $U(R)$

This subclause is applicable only to measurements up to 2 000 mm. Its formula is based on ISO/TR 230-9:2005, C.4.4, and Formula (C.15).

$$U(R) = 2{,}2 \cdot U_{\mathrm{EVE}} \tag{A.14}$$

where

$U(R)$ is the expanded measurement uncertainty of bi-directional repeatability, $k = 2$, for five measurement runs, in micrometres (µm).

A.3.5 Expanded uncertainty of systematic errors, $U(M, E, E\uparrow, E\downarrow)$

The formulae used in this subclause are based on ISO/TR 230-9:2005, C.4.5, and Formula (C.16).

a) For axes up to 2 000 mm

$$U(E, E\uparrow, E\downarrow) =$$

$$\sqrt{U_{\mathrm{DEVICE}}^{2}+U_{\mathrm{MISALIGNMENT}}^{2}+U_{\mathrm{M,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{M,\ DEVICE}}^{2}+U_{\mathrm{E,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{E,\ DEVICE}}^{2}+\frac{1}{5}\cdot U_{\mathrm{EVE}}^{2}} \tag{A.15}$$

where

$U(E, E\uparrow, E\downarrow)$ is the expanded measurement uncertainty of systematic errors, $k = 2$, for five measurement runs, in micrometres (μm).

$$U(M) =$$

$$\sqrt{U_{\mathrm{DEVICE}}^{2}+U_{\mathrm{MISALIGNMENT}}^{2}+U_{\mathrm{M,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{M,\ DEVICE}}^{2}+U_{\mathrm{E,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{E,\ DEVICE}}^{2}+\frac{1}{10}\cdot U_{\mathrm{EVE}}^{2}} \tag{A.16}$$

where

$U(M)$ is the expanded measurement uncertainty of the mean positioning deviation M, $k = 2$, for five measurement runs, in micrometres (μm).

b) For axes exceeding 2 000 mm

$$U(E, E\uparrow, E\downarrow) =$$

$$2\cdot\sqrt{u_{\mathrm{DEVICE}}^{2}+u_{\mathrm{MISALIGNMENT}}^{2}+u_{\mathrm{M,\ MACHINE\ TOOL}}^{2}+u_{\mathrm{M,DEVICE}}^{2}+u_{\mathrm{E,\ MACHINE\ TOOL}}^{2}+u_{\mathrm{E,\ DEVICE}}^{2}+u_{\mathrm{EVE}}^{2}} \tag{A.17}$$

where

$U(E, E\uparrow, E\downarrow)$ is the expanded measurement uncertainty of systematic errors, $k = 2$, for one measurement run, in micrometres (μm).

$$U(M) =$$

$$\sqrt{U_{\mathrm{DEVICE}}^{2}+U_{\mathrm{MISALIGNMENT}}^{2}+U_{\mathrm{M,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{M,\ DEVICE}}^{2}+U_{\mathrm{E,\ MACHINE\ TOOL}}^{2}+U_{\mathrm{E,\ DEVICE}}^{2}+\frac{1}{2}\cdot U_{\mathrm{EVE}}^{2}} \tag{A.18}$$

where

$U(M)$ is the expanded measurement uncertainty of mean positioning deviation, M, $k = 2$, for one measurement run, in micrometres (μm).

A.3.6 Expanded uncertainty of positioning error, $U(A, A\uparrow, A\downarrow)$

The formula used in this subclause is based on ISO/TR 230-9:2005, C.4.6, and Formula (C.17).

$$U(A,A\uparrow,A\downarrow)=\sqrt{U(E)^{2}+U(R\uparrow,R\downarrow)^{2}} \tag{A.19}$$

where

$U(A, A\uparrow, A\downarrow)$ is the expanded measurement uncertainty of positioning error, $k = 2$, for five measurement runs, in micrometres (μm).

A.4 Examples of expanded uncertainty estimation

This clause provides four examples for expanded measurement uncertainty estimations: two for laser interferometer measurements and two for linear scale measurements; for both measuring devices, the estimation is done for average industrial conditions and for improved conditions.

Average industrial conditions are defined as (see Table A.4 and Table A.6):

- the measuring device is not calibrated;
- alignment:
  - for the laser interferometer, the return beam has sufficient intensity (not recommended),
  - for the linear scale, aligned via a side surface within 0,5 mm;
- temperature in the workshop is 20 °C ± 5 °C;
- temperature measurement:
  - for the laser interferometer, the range of error of temperature measurement of the machine tool is 0,7 °C,
  - for the linear scale, the difference to machine temperature is 0,1 °C (generally reached after some minutes);
- possible error of thermal expansion coefficients is 2 µm/(m·°C);
- environmental variation error, E_{VE}, is 1,7 µm.

Improved industrial conditions are defined as (see Table A.5 and Table A.7):

- the measuring device is calibrated;
- alignment:
  - for the laser interferometer, the return beam is aligned within 1 mm (recommended procedure),
  - for the linear scale, aligned via a side surface within 0,5 mm;
- temperature in the workshop is 20 °C ± 1 °C;
- temperature measurement:
  - for the laser interferometer, the range of error of temperature measurement of the machine tool is 0,2 °C,
  - for the linear scale, the difference to machine temperature is 0,05 °C (generally reached after less than 10 min);
- possible error of thermal expansion coefficients is 2 µm/(m·°C);
- environmental variation error, E_{VE}, is 1,7 µm, although improved industrial conditions will show smaller E_{VE} values.

Under average industrial conditions, the expanded measurement uncertainty for the positioning error, $U(A)$, is 15 µm for laser interferometer and linear scale, for an axis length of 1 750 mm, and for the conditions stated (see Tables A.4 and A.6). The statement for the positioning error A should be $A = 6$ µm ± 15 µm ($k = 2$).

Under improved industrial conditions, the expanded measurement uncertainty for the positioning error, $U(A)$, is 4 µm for laser interferometer and linear scale, for an axis length of 1 750 mm, and for the conditions stated (see Table A.5 and Table A.7). The statement for the positioning error A should be $A = 6$ µm ± 4 µm ($k = 2$).

The example for the correction of repeatability values due to uncertainty associated with environmental variation error is shown in Table A.8.

Table A.4 — Sample estimation of expanded measurement uncertainty for laser positioning measurement using laser interferometer under average industrial conditions

Positioning measurement					
Estimation of expanded measurement uncertainty, laser interferometer measurement					
Simplified method					
Average industrial conditions					
Contributors	**Parameter**	**Unit**	U	**Unit**	**Formula**
Device					
measurement length	1 751,000	mm			
error range	3,400	µm/m			
U_{DEVICE}			**3,6**	**µm**	**A.3**
Alignment					
beam alignment					
alignment, assumed	4,000	mm			
measurement length	1 751,000	mm			
$U_{\text{MISALIGNMENT}}$			**2,7**	**µm**	**A.4**
Compensation of workpiece temperature					
measurement length	1 751,000	mm			
thermal expansion coefficient	12,000	µm/(m·°C)			
difference to 20 °C, maximum	5,000	°C			
temperature measurement					
deviation, maximum	0,700	°C			
$U_{\text{M, MACHINE TOOL}}$			**8,8**	**µm**	**A.5**
$U_{\text{M, DEVICE}}$	zero, included in U_{DEVICE}				
error range $R(\alpha)$ of expansion coefficient	2,000	µm/(m·°C)			
$U_{\text{E, MACHINE TOOL}}$			**10,5**	**µm**	**A.7**
$U_{\text{E, DEVICE}}$	zero, included in U_{DEVICE}				
E_{VE}, environmental variation					
E_{VE}	1,700	µm			
U_{EVE}			**1,0**	**µm**	**A.9**
$U_{R+,R-}$			**2**	**µm**	**A.11**
U_B			**1**	**µm**	**A.12**
U_R			**2**	**µm**	**A.14**
$U_{E,E+,E-}$			**14**	**µm**	**A.15**
U_M			**14**	**µm**	**A.16**
U_A			**15**	**µm**	**A.19**

Table A.5 — Sample estimation of expanded measurement uncertainty for laser positioning measurement using laser interferometer under improved industrial conditions

Positioning measurement					
Estimation of expanded measurement uncertainty, laser interferometer measurement					
Simplified method					
Improved industrial conditions					
Contributors	**Parameter**	**Unit**	U	**Unit**	**Formula**
Device					
measurement length	1 751,000	mm			
calibration uncertainty			1,0	µm/m	
U_{DEVICE}			**1,8**	**µm**	**A.2**
Alignment					
beam alignment					
alignment, assumed	1,000	mm			
measurement length	1 751,000	mm			
$U_{\text{MISALIGNMENT}}$			**0,2**	**µm**	**A.4**
Compensation of workpiece temperature					
measurement length	1 751,000	mm			
thermal expansion coefficient	12,000	µm/(m·°C)			
difference to 20 °C, maximum	1,000	°C			
temperature measurement					
deviation, maximum	0,200	°C			
$U_{\text{M, MACHINE TOOL}}$			**2,5**	**µm**	**A.5**
$U_{\text{M, DEVICE}}$	zero, included in U_{DEVICE}				
error range $R(\alpha)$ of expansion coefficient	2,000	µm/(m·°C)			
$U_{\text{E, MACHINE TOOL}}$			**2,1**	**µm**	**A.7**
$U_{\text{E, DEVICE}}$	zero, included in U_{DEVICE}				
E_{VE}, environmental variation					
E_{VE}	1,700	µm			
U_{EVE}					
$U_{R+,R-}$			**2,0**	**µm**	**A.11**
U_B			**0,9**	**µm**	**A.12**
U_R			**2,2**	**µm**	**A.14**
$U_{E,E+,E-}$			**3,7**	**µm**	**A.15**
U_M			**3,7**	**µm**	**A.16**
U_A			**4,2**	**µm**	**A.19**

Table A.6 — Sample estimation of expanded measurement uncertainty for linear positioning measurement using linear scale under average industrial conditions

Positioning measurement					
Estimation of expanded measurement uncertainty, linear scale measurement					
Simplified method					
Average industrial conditions					
Contributors	**Parameter**	**Unit**	U	**Unit**	**Formula**
Device					
measurement length	1 751,000	mm			
error range	2,000	µm/m			
U_{DEVICE}			**2,1**	**µm**	**A.3**
Alignment					
beam alignment					
alignment, assumed	0,500	mm			
measurement length	1 751,000	mm			
$U_{\text{MISALIGNMENT}}$			**0,0**	**µm**	**A.2**
Compensation of workpiece temperature					
measurement length	1 751,000	mm			
thermal expansion coefficient	12,000	µm/(m·°C)			
difference to 20 °C, maximum	5,000	°C			
temperature measurement					
deviation, maximum	0,100	°C			
$U_{\text{M, MACHINE TOOL}}$			**1,3**	**µm**	**A.5**
$U_{\text{M, DEVICE}}$	zero, device adopts temperature of machine				
error range $R(\alpha)$ of expansion coefficient	2,000	µm/(m·°C)			
$U_{\text{E, MACHINE TOOL}}$	2,000	µm/(m·°C)			
$U_{\text{E, DEVICE}}$			**10,5**	**µm**	**A.7**
E_{VE}, environmental variation			**10,5**	**µm**	**A.8**
E_{VE}	1,700	µm			
U_{EVE}			**1,0**	**µm**	**A.9**
$U_{R+,R-}$			**2**	**µm**	**A.11**
U_B			**1**	**µm**	**A.12**
U_R			**2**	**µm**	**A.14**
$U_{E,E+,E-}$			**15**	**µm**	**A.15**
U_M			**15**	**µm**	**A.16**
U_A			**15**	**µm**	**A.19**

Table A.7 — Sample estimation of expanded measurement uncertainty for linear positioning measurement using linear scale under improved industrial conditions

Positioning measurement					
Estimation of expanded measurement uncertainty, linear scale measurement					
Simplified method					
Improved industrial conditions					
Contributors	**Parameter**	**Unit**	U	**Unit**	**Formula**
Device					
measurement length	1 751,000	mm			
calibration uncertainty			1,8	µm	
U_{DEVICE}			**1,8**	**µm**	**A.1**
Alignment					
beam alignment					
alignment, assumed	0,500	mm			
measurement length	1 751,000	mm			
$U_{\text{MISALIGNMENT}}$			**0,0**	**µm**	**A.4**
Compensation of workpiece temperature					
measurement length	1 751,000	mm			
thermal expansion coefficient	12,000	µm/(m·°C)			
difference to 20 °C, maximum	1,000	°C			
temperature measurement					
deviation, maximum	0,050	°C			
$U_{\text{M, MACHINE TOOL}}$			**0,6**	**µm**	**A.5**
$U_{\text{M, DEVICE}}$	zero, device adopts temperature of machine				
error range $R(\alpha)$ of expansion coefficient	2,000	µm/(m·°C)			
$U_{\text{E, MACHINE TOOL}}$	2,000	°C			
$U_{\text{E, DEVICE}}$			**2,1**	**µm**	**A.7**
E_{VE}, environmental variation			**2,1**	**µm**	**A.8**
E_{VE}	1,700	µm			
U_{EVE}			**1,0**	**µm**	**A.9**
$U_{R+,R-}$			**2,0**	**µm**	**A.11**
U_{B}			**0,9**	**µm**	**A.12**
U_{R}			**2,2**	**µm**	**A.14**
$U_{E,E+,E-}$			**3,5**	**µm**	**A.15**
U_{M}			**3,5**	**µm**	**A.16**
U_{A}			**4,1**	**µm**	**A.19**

Table A.8 — Example for the correction of repeatability values due to uncertainty associated with environmental variation error

Positioning measurement					
Correction of R values due to U_{EVE}					
	Parameters	**Unit**	U	**Unit**	**Formula**
E_{VE}, environmental variation					
E_{VE}	1,700	µm			
U_{EVE}			**1,0**	**µm**	**A.9**
Correction of repeatability values	**Uncorrected**	**Corrected**			
R+ according to Table 2, typical results	2,98	2,18	µm		**A.10**
R− according to Table 2, typical results	2,55	1,53	µm		**A.10**
s+ (at target 9) for R according to Table 2, typical results	0,746	0,544	µm		**A.10**
s− (at target 9) for R according to Table 2, typical results	0,638	0,383	µm		**A.10**
B (at target 9) for R according to Table 2, typical results	3,9		µm		
R according to Table 2, typical results	6,7	5,8	µm		**A.10**

Annex B
(informative)

Step cycle

This annex addresses the application of an optional test cycle: the step cycle (see Figure B.1).

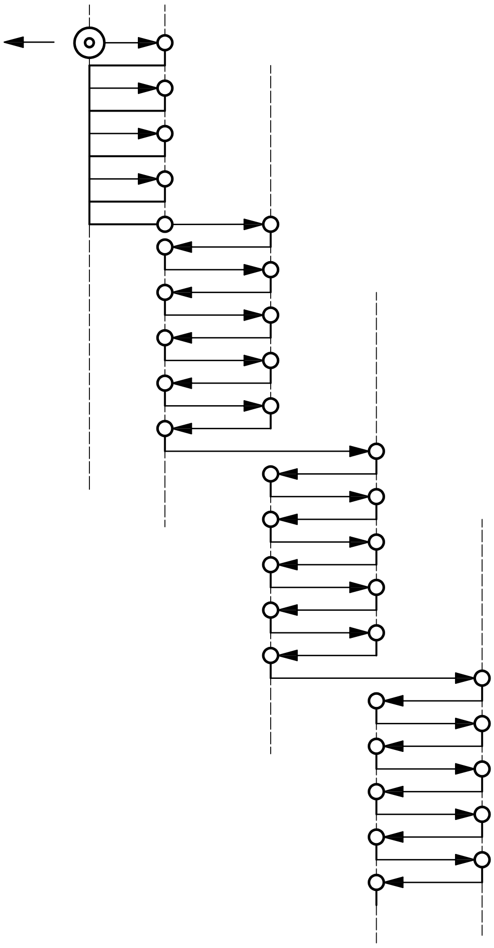


Figure B.1 — Step cycle

The results from tests made using this method could be different from those obtained from the standard test cycle shown in Figure 1 (see 5.3.2).

With the standard test cycle, the approach to the extreme target positions from opposing directions takes place with a large difference in time intervals. However, with the step cycle, the approach to the target positions from either direction takes place within shorter time intervals and a longer time is taken between the measurements of the first and the last target positions.

Measurements according to the standard test cycle could reflect thermal influences, which affect differently the various target positions along the axis under test. Here, thermal influences during the measurements could be evident in both the reversal errors, B, and the repeatability, R.

In the case of the step cycle, thermal influences could be evident in the range of the mean bi-directional positioning error, M, whereas the reversal errors and repeatability will be only slightly affected by the thermal behaviour of the machine.

Annex C

(informative)

Periodic positioning error

C.1 General

Positioning of numerically controlled axes could be affected by periodic errors such as errors associated to the pitch of ball screws and to the pitch of linear or rotary transducers.

According to 5.2, determination of the accuracy and repeatability of positioning of numerically controlled axes is performed at target positions that are selected adding a random number, *r*, to uniformly spaced intervals, which is used to ensure that the periodic positioning error deriving from possible periodic errors is adequately sampled.

This annex describes tests that could be performed (subject to specific agreement between manufacturer/supplier and user) to further investigate the magnitude of possible periodic errors associated with different types of linear or angular actuation and position feedback systems.

For position feedback systems where the position transducer directly measures the relative motion of the moving component, periodic positioning error is periodic over an interval that coincides with the transducer pitch (e.g. angular or linear encoder line spacing or wavelength of laser interferometer scales) and it would be adequately sampled by the investigation described in C.2.

For linear position feedback systems with ball screw and angular encoder directly connected to it, two periodic errors might be present: one associated with the ball screw pitch and one associated with the angular encoder line spacing. In this case, two separate investigations could be performed according to C.2, each one associated with the known possible periodic error interval.

For other linear (or angular) position feedback systems where more than two elements are involved in the position feedback loop (e.g. angular encoder on motor shaft, with gear or belt transmission from the shaft to the ball screw that drives the linear motion), additional periodic error sources can be present and can, in principle, be investigated separately (see Figure C.2). It is nevertheless considered that the specified performance of such systems is usually not stringent and extensive investigation for periodic error can be unjustified.

For angular position feedback systems applying angular encoders without integral bearings, the radial throw between the measuring scale grating and the axis of rotation to be controlled results in a periodic measurement error according to Formula (C.1):

$$\Delta\varphi = \pm 412 \cdot \frac{r}{D} \qquad \text{(C.1)}$$

where

$\Delta\varphi$ is the measurement error, in arcseconds (“);

r is the radial throw of the scale grating to the axis of rotation, in micrometres (µm);

D is the mean measuring scale grating diameter, in millimetres (mm).

The measurement error, $\Delta\varphi$, is periodic over one full rotary axis revolution and will typically be detected by tests specified in 5.2.

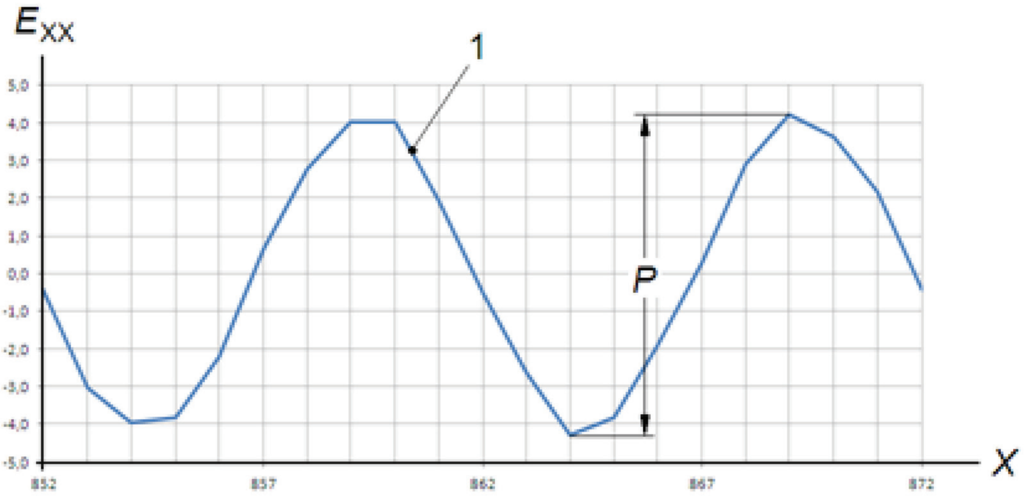
C.2 Periodic positioning error of known periodic interval(s)

In some cases, it can be advantageous to replace the random number, *r*, specified in 5.2, by a submultiple of the interval of the (known) periodic error component.

The set-up and instrumentation for this investigation can be identical to that used for the determination of positioning error and positioning repeatability described in 5.3.1.

A set of at least 21 evenly spaced target positions is selected over two periods of the expected periodic error. One unidirectional measurement is made at all the target positions.

The periodic linear positioning error, *P*, (for linear or angular errors) is the total range of the measured positioning deviations as shown in Figure C.1 that reports an example of periodic error measurement results for a machine tool with indirect measuring system and a ball screw with a 10 mm pitch.



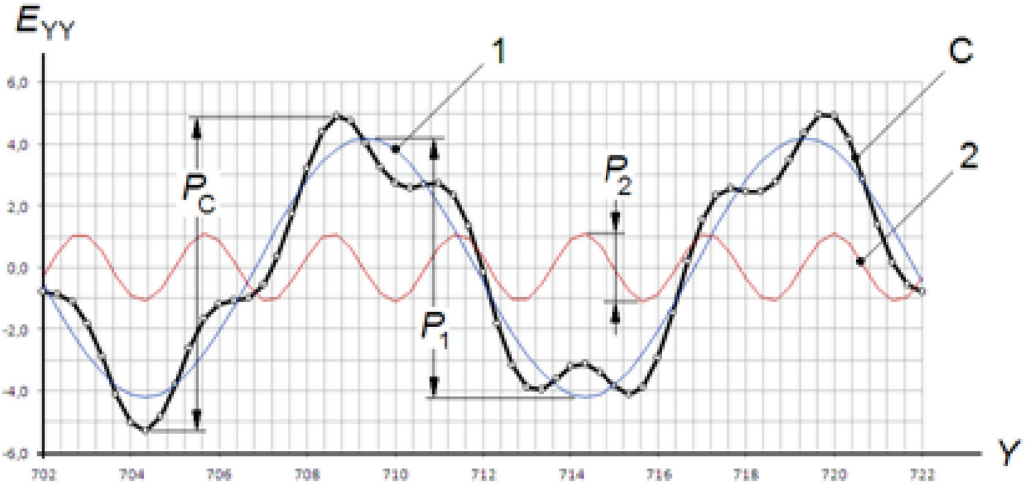
Key

X	x-axis position (mm)	1	measured deviations plot
E_{XX}	linear positioning error (µm)	*P*	periodic linear positioning error

Figure C.1 — Example of periodic linear positioning error for x-axis with 10 mm pitch ball screw, direct motor drive, and angular encoder on motor shaft

Where the position feedback loop includes angular encoder on motor shaft and gear or belt transmission from the shaft to the ball screw that drives the linear motion, additional periodic error sources are present.

Figure C.2 shows the periodic error resulting from imperfections in a 3,5:1 ratio gear or belt transmission combined with a 10 mm pitch ball screw periodic error.



Key

Y	y-axis position (mm)	C	combined measured deviations plot
E_{YY}	linear positioning error (µm)	P_1	periodic linear positioning error associated with ball screw
1	periodic error associated with ball screw	P_2	periodic linear positioning error associated with gear
2	periodic error associated with 3,5:1 gear ratio	P_C	combined periodic linear positioning error

Figure C.2 — Example of periodic linear positioning error for y-axis with 10 mm pitch ball screw, motor drive with 3,5:1 gear ratio, and angular encoder on motor shaft

Annex D
(informative)

Linear positioning error measurements using calibrated ball array or step gauge

D.1 General

The tests described in this annex rely on measurements of multiple distances in the machine's working volume. These measurements utilize reference artefacts with spheres located at known positions composing 1-D and 2-D ball arrays (see Figure D.1 and Figure D.2) or step gauges.

The positions of the artefact spheres in the machine coordinate system are determined using a displacement measuring or surface detection system, referred to as the "probing system", in conjunction with the machine position transducers. The measured positions of the artefact sphere centres are compared to the calibrated positions to determine deviations resulting from the machine error motions.

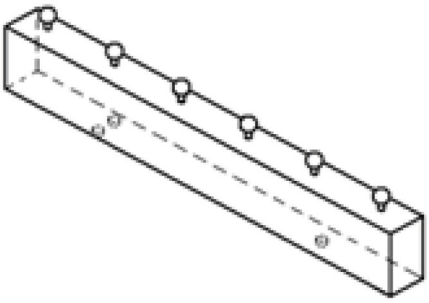


Figure D.1 — 1-D ball array

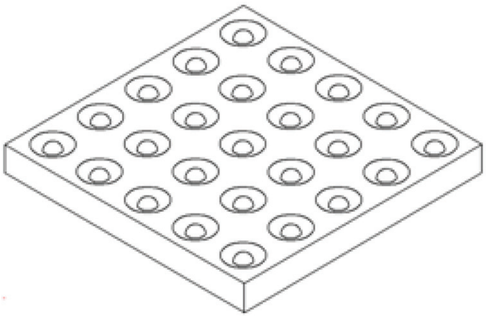


Figure D.2 — 2-D ball array

1-D and 2-D ball array artefacts are commercially available. Their calibration documentation typically includes the following data:

- centre position of individual spheres, with associated measurement uncertainty;
- sphere size and form measurement uncertainty;
- artefact coefficient of thermal expansion and (where available) associated estimated uncertainty.

The calibrated centre positions of each sphere are typically not exactly equally spaced, thus the requirement for the random component, *r*, prescribed in 5.2, is partially fulfilled.

Reference distances can also be materialised by calibrated step gauges.

The calibrated distances between steps can typically be considered as being exactly equally spaced, thus the requirement for the random component, *r*, prescribed in 5.2, is not necessarily fulfilled.

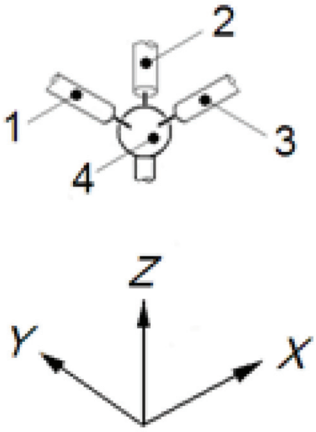
The reference artefact is connected to the component of the machine that holds the cutting tool and aligned to the axis of motion under test according to the manufacturer/supplier's instructions.

The measuring instruments for artefact-based measurement are touch-trigger probes, linear displacement sensor(s), and nests of linear displacement sensors (see Figure D.3).

D.2 Measurements with ball arrays and linear displacement sensors nest

Nests of linear displacement sensors (as depicted in Figure D.3) are commercially available. They are typically capable to determine the centre position of spheres of known size with respect to the nest predetermined reference point.

The sensor nest is connected and oriented to the component of the machine that holds the cutting tool in accordance with the manufacturer's/supplier's instructions. Within a specified measurement range, it provides the relative motion (in three orthogonal directions) between the sphere centre point and the sensors nest reference point.



Key

1, 2, 3	nest's linear displacement sensors (tool side)
4	test sphere on reference artefact (workpiece side)

Figure D.3 — Measurement with linear displacement sensors nest

During the measurement, the machine axes are programmed to move to the calibrated centre position of each sphere, according to the test sequence depicted in Figure 1 (see 5.3.2).

Positioning deviations are calculated and recorded by the sensors nest system and are presented in accordance with Clause 8.

Measurements with ball arrays and linear displacement sensor nest can also provide useful information on straightness deviations. Nevertheless, for the purpose of the test described in this annex, only the positioning deviations along the axis under test are considered.

Measurement uncertainties of the sensors in the nest should be considered for the estimation of overall measurement uncertainty, in combination with measurement uncertainties associated with the reference artefact.

D.3 Measurements with ball arrays or step gauges and touch-trigger probes

Information on positioning accuracy and repeatability of linear axes can also be obtained using touch-trigger probing systems in conjunction with reference ball arrays or step gauges.

The probing system performances are determined as specified in ISO 230-10.

Results are evaluated comparing measured positions with the calibrated reference artefact relevant positions.

Measurements performed with the touch-trigger probe do not provide information on bi-directional positioning error and bi-directional positioning repeatability.

Although valuable information on positioning error can be obtained by performing the test described in this Clause, results are not directly comparable with results obtained in accordance with specifications of Clause 5 and Clause 6.

When a step gauge is being used, a linear displacement sensor with a spherical tip, connected to the machine tool spindle side, can also be used.

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