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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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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.

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).

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

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

This 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. $E_{XX,A\uparrow}$ (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

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

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 $k = 2$

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

and

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

3.20
bi-directional positioning repeatability at a position
R_i
$R_i = \max.\left[2s_i\uparrow + 2s_i\downarrow + |B_i|; R_i\uparrow; R_i\downarrow\right]$

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

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

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

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

$$R = \max.\left[R_i\right]$$

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

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

and

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

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

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

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

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

3.26
unidirectional positioning error of an axis
unidirectional positioning accuracy of an axis
A↑ or *A*↓
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):

$$P_i = (i - 1)p + r \quad (1)$$

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.

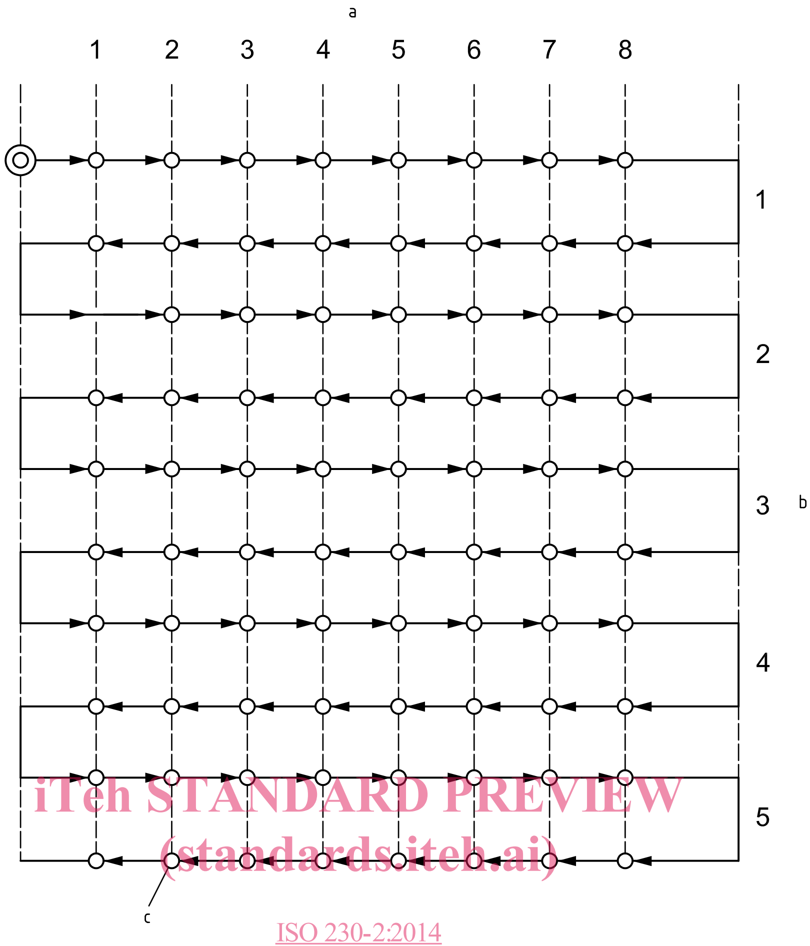
The position of the measuring instruments and reference artefacts, if any, shall be recorded on the test report.

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.

