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Test code for machine tools —

Part 3: Determination of thermal effects

Code d'essai des machines-outils —

Partie 3: Évaluation des effets thermiques

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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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 of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

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

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This third edition cancels and replaces the second edition (ISO 230-3:2007), which has been technically revised. The main changes compared to the previous edition is the addition of Clause 8 for checking thermal effects of machine tool rotating heads and tables.

A list of all parts in the ISO 230 series can be found on the ISO website.

Introduction

The purpose of the ISO 230 series is to standardize methods of testing the accuracy of machine tools, excluding portable power tools.

This document specifies test procedures to determine thermal effects caused by a variety of heat inputs resulting in the distortions of a machine tool structure or the positioning system. It is a recognized fact that the ultimate thermo-elastic deformation of a machine tool is closely linked to the operating conditions. The test conditions described in this document are not intended to simulate the normal operating conditions but are to facilitate performance estimation and to determine the effects of environment on machine tool performance. For example, use of coolants can significantly affect the actual thermal behaviour of the machine tool. Therefore, these tests are considered only as the preliminary tests towards the determination of actual thermo-elastic behaviour of the machine tool if such determination becomes necessary for machine characterization purposes. The tests are designed to measure the relative displacements between the component that holds the tool and the component that holds the workpiece as a result of thermal expansion, contraction, or distortion of relevant structural elements.

The tests described in this document can be used either for testing different types of machine tools (type testing) or testing individual machine tools for acceptance purposes. When the tests are required for acceptance purposes, it is up to the user to choose, in agreement with the supplier/manufacturer, those tests relating to the properties of the components of the machine, which are of interest. A simple reference to this part of the test code for the acceptance tests, without agreement on the tests to be applied and the relevant charges, cannot be considered as binding for any contracting party. One significant feature of this document is its emphasis on environmental thermal effects on all the performance tests described in other parts of the ISO 230 series related to linear displacement measurements (such as linear positioning accuracy, repeatability and the circular tests). The suppliers/manufacturers are expected to provide 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 supplier/manufacturer's thermal guidelines or otherwise accepting reduced performance. An example of environmental thermal guidelines is given in Annex C.

A relaxation in accuracy expectations is required if the thermal environment causes excessive uncertainty or variation in the machine tool performance and does not meet the supplier/manufacturer's thermal guidelines. If the machine does not meet the performance specifications, the analysis of the combined standard thermal uncertainty provides help identifying sources of problems. Combined standard thermal uncertainty is defined in 3.13 as well as in ISO/TR 16015.

Test code for machine tools —

Part 3: Determination of thermal effects

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document defines four tests:

— an environmental temperature variation error (ETVE) test;

— a test for thermal distortion caused by rotating spindles;

— a test for thermal distortion caused by moving linear axes;

— a test for thermal distortion caused by rotary motion of components.

The tests for thermal distortion caused by moving linear axes (see Clause 7) are applicable to numerically controlled (NC) machines only and are designed to quantify the effects of thermal expansion and contraction as well as the angular deformation of structures. For practical reasons, the test methods described in Clause 7 apply to machines with linear axes up to 2 000 mm in length. If they are used for machines with axes longer than 2 000 mm, a representative length of 2 000 mm in the normal range of each axis is chosen for the tests.

The tests correspond to the drift test procedure as described in ISO/TR 16015:2003, A.4.2, applied for machine tools with special consideration of thermal distortion of moving linear components and thermal distortion of moving rotary components. On machine tools equipped with compensation for thermal effects these tests demonstrate any uncertainty in nominal thermal expansion due to uncertainty of coefficient of thermal expansion and any uncertainty of length due to temperature measurement.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

3 Terms and definitions

For the purposes of this document, the terms and definitions in ISO 230-1:2012 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
machine scale
measurement system integrated into a machine providing the linear or rotary position of the machine's axis

EXAMPLE Linear and rotary encoders are typical machine scales.

3.2
coefficient of thermal expansion
α
ratio of the fractional change of length to the change in temperature

Note 1 to entry: For the purpose of this document, a range of temperature from 20 °C to any temperature, T, is considered. Formula (1) is used:

$$\alpha(20,T)=\frac{L_T-L_{20}}{L_{20}\times(T-20)} \tag{1}$$

where

T is the temperature of the object in °C;

L_{20} is the length of a measured object or of a portion of the scale of a length test equipment at temperature T = 20 °C;

L_T is the length of a measured object or of a portion of the scale of a length test equipment at temperature T.

[SOURCE: ISO/TR 16015:2003, 3.1.1, modified — Note 1 to entry has been changed and the where clause has been added.]

3.3
nominal coefficient of thermal expansion
α_n
approximate value for the *coefficient of thermal expansion* (3.2) over a range of temperature from 20 °C to T

3.4
uncertainty of coefficient of thermal expansion
u_α
parameter that characterizes the dispersion of the values that can reasonably be attributed to the *coefficient of thermal expansion* (3.2)

3.5
thermal expansion
Δ_E
change in the length of a measured object or a portion of the scale of a length test equipment in response to a temperature change

3.6
nominal thermal expansion
Δ_{NE}
estimate of the *thermal expansion* (3.5) of a measured object or a portion of the scale of a length test equipment from 20 °C to their average temperatures at the time of measurement

Note 1 to entry: This estimate is based on nominal coefficients of thermal expansion [see Formula (2)]:

$$\Delta_{NE}=\alpha_n\times L\times(T-20) \tag{2}$$

where

α_n is the *nominal coefficient of thermal expansion* (3.3) of the object's material;

L is the length of the object;

T is the average temperature of the object (°C).

3.7
uncertainty in nominal thermal expansion due to uncertainty in $\boldsymbol{\alpha}$
$\boldsymbol{u_{\Delta,\mathrm{NE}}}$
uncertainty in the *nominal thermal expansion* (3.6) arising from *uncertainty of coefficient of thermal expansion* (3.4)

Note 1 to entry: This uncertainty can be calculated by Formula (3):

$$u_{\Delta,\mathrm{NE}} = L \times (T - 20) \times u_\alpha \tag{3}$$

where

L is the length of the object;

T is the temperature of the object (°C);

u_α is *uncertainty of coefficient of thermal expansion* (3.4).

3.8
uncertainty of length due to temperature measurement
$\boldsymbol{u_{\mathrm{TM}}}$
uncertainty in a measured length due to the uncertainty of the temperature at which the length measurement was conducted

3.9
nominal differential thermal expansion
NDE
difference between the estimated expansion of a measured object and that of the test equipment owing to their temperatures deviating from 20 °C

3.10
uncertainty of nominal differential thermal expansion
$\boldsymbol{u_{\mathrm{NDE}}}$
combined uncertainty caused by the uncertainties of *thermal expansion* (3.5) of the measured object and that of the test equipment

Note 1 to entry: It is obtained as the square root of the sum of the squares of the uncertainties of nominal expansions of the measured object and the test equipment [see Formula (4)].

$$u_{\mathrm{NDE}} = \sqrt{u_{\mathrm{EM}}^2 + u_{\mathrm{ET}}^2} \tag{4}$$

where

u_{EM} is the uncertainty of nominal expansion of the measured object;

u_{ET} is the uncertainty of nominal expansion of the test equipment.

Note 2 to entry: For evaluation of uncertainty see ISO/TR 16015:2003, 5.3.

3.11
environmental temperature variation error
***E*$_{TVE}$**
estimate of the maximum possible measurement variation induced solely by the variation of the environment temperature during any time period while performance measurements are carried out on a machine tool

EXAMPLE The notation E_{TVE}(Z, 8 °C) indicates that the E_{TVE} value is obtained along the Z direction and the value corresponds to an environmental temperature variation of 8 °C.

3.12
uncertainty due to environmental temperature variation error
***u*$_{ETVE}$**
standard measurement uncertainty contribution in performance measurements carried out on a machine tool caused by the effects of environmental temperature changes

Note 1 to entry: It can be calculated as the square root of the square of E_{TVE} divided by 12 [see Formula (5) and ISO/TR 230-9]:

$$u_{ETVE} = \sqrt{\frac{E_{TVE}^2}{12}} \tag{5}$$

Note 2 to entry: The basis for the estimation of this uncertainty for a machine tool is the environment test according to Clause 5.

3.13
combined standard thermal uncertainty
***u*$_{CT}$**
combined uncertainty in length measurements caused by an environment with a temperature other than a constant and uniform 20 °C

Note 1 to entry: This term is equivalent to *combined standard dimensional uncertainty due to thermal effects* as defined in ISO/TR 16015.

Note 2 to entry: It is a combination by square root of sum of squares of *uncertainty due to environmental temperature variation error* (3.12), u_{ETVE}, length uncertainty due to uncertainty of temperature measurements, u_{TM}, and the *uncertainty of nominal differential thermal expansion* (3.10), u_{NDE} [see Formula (6)]:

$$u_{CT} = \sqrt{u_{ETVE}^2 + u_{TM}^2 + u_{NDE}^2} \tag{6}$$

Note 3 to entry: A detailed description of estimating the combined standard thermal uncertainty is given in ISO/TR 16015.

3.14
thermal distortion of moving rotary component
***d*(*E*$_{\alpha 0\beta}$)$_{xx,t}$**
range of linear or angular displacement of moving rotary component along rotary axis β or of axis average line of spindle β in the direction of α within (the first) t min of the tests (at position xx)

EXAMPLE The notation $d(E_{X0C})_{P1,60}$ indicates that the thermal distortion, within the first 60 min, of axis average line of axis C in X direction at position P1 (away from the spindle nose) is referenced.

Note 1 to entry: Possible notations for α are: X, Y, Z, A, B, C. Possible notations for β are: C, C1, A, B, or any spindle axis. Possible notations for xx are: P1 (position P1, away from the spindle nose) and P2 (position P2, close to spindle nose); position reference xx is omitted for values of linear displacement in the Z direction and angular displacements (A, B, and C).

Note 2 to entry: For notation $E_{\alpha 0\beta}$, see ISO 230-7.

Note 3 to entry: $d(E_{ROT})$ is a special case of this thermal distortion indicating radial expansion of the rotary component T. Similarly, $d(E_{ZOT})$ is the thermal growth of the rotary component rotating around C in the axial direction.

3.15
thermal distortion of moving linear component
$d(E_{\alpha\gamma})_{xx,t}$
range of linear or angular displacement, in the direction of α, of moved machine component along linear axis γ within (the first) t min of the tests for thermal distortion caused by moving linear axis (at position xx)

EXAMPLE The notation $d(E_{BX})_{P1,60}$ indicates that the thermal distortion, within the first 60 min, of linear axis X in B direction (rotation around Y) at target position P1 (e.g. right position in Figure 8) is referenced.

Note 1 to entry: Possible notations for *α* are: X, Y, Z, A, B, C. Possible notations for *γ* are: X, X1, Y, Z, W or any linear axis. Possible notations for xx are: P1 and P2, xx can also be expressed in words, e.g. left and right.

4 Preliminary remarks

4.1 Measuring units

In this document, all linear dimensions and deviations are expressed in millimetres. All angular dimensions are expressed in degrees. Angular deviations are, in principle, expressed in ratios but in some cases, micro-radians or arc-seconds may be used for clarification purposes. Formula (7) should always be kept in mind:

$$0{,}010/1\,000 = 10\,\mu\text{rad} \approx 2'' \qquad (7)$$

The temperatures are expressed in degrees Celsius (°C).

4.2 Reference to ISO 230-1

To apply this document, reference shall be made to ISO 230-1, especially for the installation of the machine before testing and for the recommended measurement uncertainty of the test equipment.

4.3 Recommended instrumentation and test equipment

The measuring instruments recommended in this subclause are examples. Other instruments capable of measuring the same quantities and having the same or smaller measurement uncertainty may be used. The following instrumentation and test equipment are recommended for Clauses 5, 6, 7 and 8.

4.3.1 Displacement measuring system, with adequate range, resolution, thermal stability, and measurement uncertainty (e.g. laser interferometer for thermal distortion caused by moving linear axes, capacitive, inductive or retractable contacting displacement sensors for environment testing and thermal distortion caused by rotating spindles and rotary components).

4.3.2 Temperature sensors (e.g. thermocouple, resistance or semiconductor thermometer), with adequate resolution and measurement uncertainty.

4.3.3 Data acquisition equipment, such as a multi-channel chart recorder which continuously monitors and plots all channels, or a computer-based system in which all channels are sampled at least once every 5 min[1], and data is stored for subsequent analysis.

NOTE Manual data processing is possible if a computer system is not available.

1) Some temperature compensation systems exhibit cycle times shorter than 5 min. In such cases, the frequency for monitoring can be increased to five readings per cycle if possible.

4.3.4 Test mandrel, respectively precision sphere for rotary components, preferably made of steel with the design to be specified in the relevant machine-specific standards or agreed between supplier/manufacturer and user (see ISO/TR 230-11:2018, 6.3 and 6.4).

End surface of test mandrel needs proper flatness and squareness to axis of mandrel as these deviations influence measurement uncertainty directly. To minimize such uncertainty, spherical ended mandrel or precision spheres can be used.

When selecting the test mandrel, maximum safe rotational speed needs to be considered.

4.3.5 Fixture in which to mount the displacement sensors, preferably made of steel, with the design to be specified in the relevant machine-specific standards or agreed between supplier/manufacturer and user.

The design should minimize local distortions caused by temperature gradients in the fixture.

When evaluating angular deviations, the distance between displacement sensors has to be selected in order to achieve adequate range, resolution and measurement uncertainty.

When necessary and practicable, the axial displacement sensor (see Figures 1, 2 and 3) may be placed directly against the spindle nose to eliminate the effect of the thermal expansion of the test mandrel.

Long-term accuracy of the measuring equipment shall be verified, for example, by transducer temperature stability test (cap test, see A.5).

The measuring instruments shall be thermally stabilized before starting the tests.

4.4 Machine tool conditions prior to testing

The machine tool shall be completely assembled and fully operational in accordance with the supplier's/manufacturer's instructions which shall be recorded. All necessary levelling operations, geometric alignment and functional checks shall be completed satisfactorily before starting the tests.

The machine tool shall be powered up with auxiliary services operating and axes in “Hold” position, with no spindle rotation, for a period sufficient to stabilize the effects of internal heat sources as specified by the supplier/manufacturer or as indicated by the test instrumentation. The machine tool and the measuring instruments shall be protected from draughts and external radiation such as those from overhead heaters or sunlight, etc.

All tests shall be carried out with the machine tool in the unloaded condition. Where a machine tool involves rotating both the workpiece and the cutting tool on separate spindles, the tests described in Clauses 5 and 6 shall be carried out for each spindle with respect to a common fixed location on the machine tool structure. If any hardware- or software-based compensation capability or facilities for minimizing thermal effects, such as air or oil showers, are available on the machine tool they shall be used during the tests and the usage of these facilities shall be recorded.

4.5 Testing sequence

The tests described in Clauses 5, 6, 7 and 8 may be used either singly or in any combination.

4.6 Test environment temperature

According to ISO 1, unless otherwise specified, all dimensional measurements shall be made when the measuring instruments and the measured objects (for example machine tool) are in equilibrium with the environment where the temperature is kept at 20 °C. If the environment is at a temperature other than 20 °C, nominal differential thermal expansion (NDE) correction between the measurement system and the measured object (machine tool) shall be made to correct the results to correspond to 20 °C (or to the specified reference temperature). For example, in a typical linear displacement measurement using laser interferometer, ambient temperature around the laser beam and the temperature of machine scale should be recorded during the measurements. The expected length change of the laser interferometer (due to change in laser wavelength as a function of the ambient temperature and pressure) and that of the machine scale (as a response to its temperature) shall be calculated. The difference between these two length expansions is calculated as NDE and used to correct the raw measurement data from the laser interferometer to determine the linear displacement deviations at 20 °C. However, in this document, since the aim is to identify the machine's behaviour under possibly varying environmental temperature conditions, the requirement for NDE corrections is relaxed. NDE correction is allowed only between the test equipment and the part of the machine where the workpiece is usually located. Built-in NDE correction used for the normal operation of machine tool shall be used. Additional NDE correction just for the measurements shall not be used to correct the thermal distortions of machine scales.

4.7 Uncertainty due to temperature effects

The ETVE test (Clause 5), along with the uncertainty due to environmental temperature variation error, u_{ETVE}, and the tests (Clauses 6 to 8) for thermal distortions [$d(E_{\alpha 0\beta})_{xx,t}$, $d(E_{\alpha\gamma})_{xx,t}$], provide the temperature effects that contribute to the uncertainty of performance and/or performance evaluation of machine tools.

In addition to these test results, other contributors to the uncertainty are the uncertainty in nominal thermal expansion due to uncertainty of coefficient of thermal expansion (u_{α}, $u_{\Delta,NE}$) and the uncertainty of length due to temperature measurement, u_{TM}. All contributors are to be considered to estimate the combined standard thermal uncertainty, u_{CT}, or any other combined thermal uncertainties.

5 Environmental temperature variation error (ETVE) test

5.1 General

Environmental temperature variation error (ETVE) tests are designed to reveal the effects of environmental temperature changes on the machine tool and to estimate the thermally induced error during other performance measurements. They shall not be used for machine tool comparison. E_{TVE} shall be determined using the procedure described in 5.2. If the correct operation of the measuring instrument requires compensation for environment factors such as air temperature and pressure, then these shall be used. If the measuring instrument incorporates facilities for NDE correction then these facilities should be used, provided that the material temperature sensor is placed on the part of the machine tool where the workpiece is normally located. The use of such facilities shall be recorded.

It is recommended that the supplier/manufacturer offer guidelines regarding the thermal environment, which can be considered as acceptable for the machine tool to perform with the specified accuracy. Such general guidelines can 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 (see Annex C). It is the user's responsibility 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 supplier/manufacturer, the responsibility for machine performance according to the specifications reverts to the machine supplier/manufacturer.

The total uncertainty in the performance measurements of the machine tool caused by the thermal effects is defined as the combined standard thermal uncertainty. The combined standard thermal uncertainty (see 3.13) can be estimated with the help of the described test, when the environmental conditions during the performance measurement and the ETVE test are comparable. It shall not exceed an amount that is mutually agreed between the user and the supplier/manufacturer.

According to 4.4 the machine tool axes shall be powered up and in “Hold” position. On some machine designs, especially on a vertical or slant axis, the axis may warm up in “Hold” position. If this is the case, the ETVE test may be carried out with the machine completely shut off. By mutual agreement between the manufacturer/supplier and the user, ETVE test may also be preceded by an appropriate warm-up period. This condition shall be stated in the test report.

5.2 Test method

Figures 1, 2 and 3 show examples of typical measurement setups for a vertical- and horizontal-spindle machining centre and a turning centre, respectively. The fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating workholding or tool-holding component of the machine tool to measure:

a) the relative displacements between the component that holds the cutting tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine. The exact position of the measurement setup shall be recorded along with the test results;

b) the tilt or rotation around the X and Y axes of the machine tool.

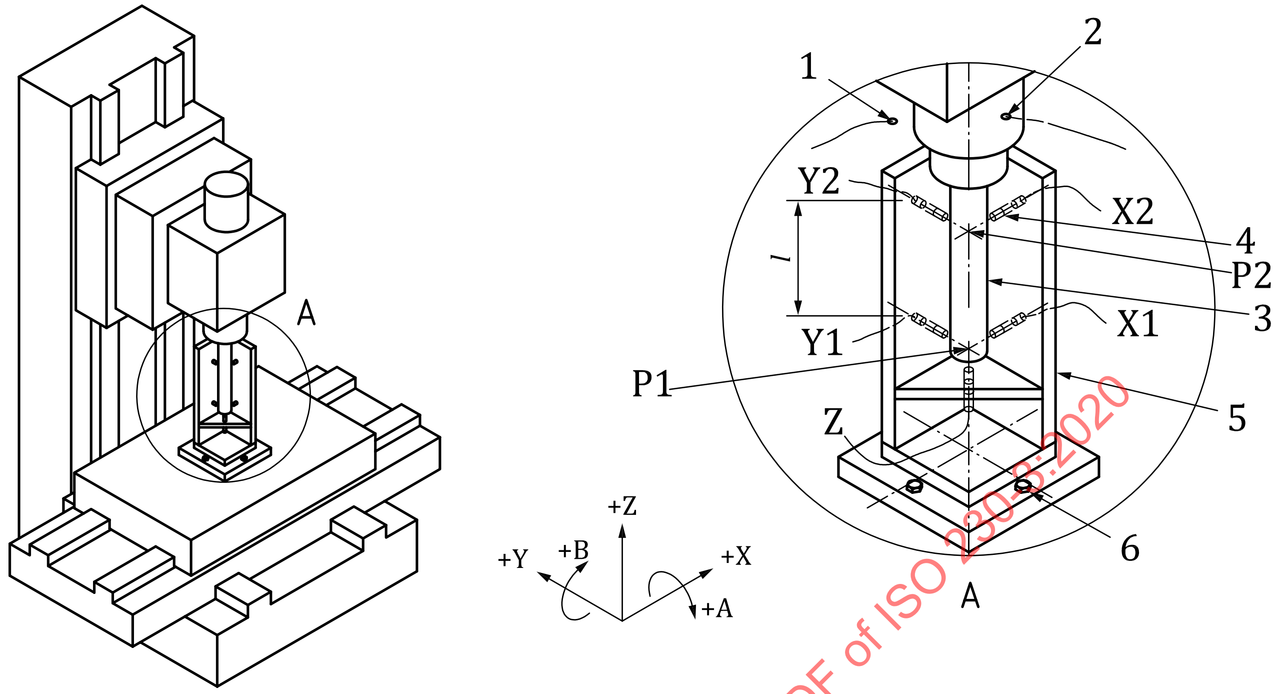
WARNING — Figures 1 to 3 show test mandrels that need end surfaces with proper flatness and squareness to the axis of the mandrel as these deviations influence the measurement uncertainty directly. To minimize such uncertainty, spherical ended mandrel or precision spheres can be used.

The temperature of the machine tool structure, as close as possible to the front spindle bearing or at a point agreed between the supplier/manufacturer and the user, and the ambient air temperature in the close vicinity of the machine (if the machine is enclosed, then the temperature sensor should be placed outside this enclosure) and at the same height as the spindle nose should be monitored at least once every 5 min[2)]. It is important to measure the ambient (environmental) air temperature at a suitable distance from the machine to avoid any influence by the heating up of the machine (for example by hydraulic components) on the ambient air temperature. Although the measured temperatures do not exactly correlate to the measured displacements, they are indications of the thermal changes in the environment and the machine tool structure.

NOTE To ensure the consistency of the ETVE results, the ETVE testing process is monitored in such a way that significant changes in measurement conditions including environmental conditions are recognizable.

Once set up, the ETVE test should be allowed to continue as long as possible, with a minimum deviation from normal performance measurement conditions. In situations where a periodic pattern of activity (such as periodic resetting of test equipment with respect to a measurement reference) is observed, the test duration should be over some period of time during which most events are repeated, or any other duration agreed by the supplier/manufacturer and the user.

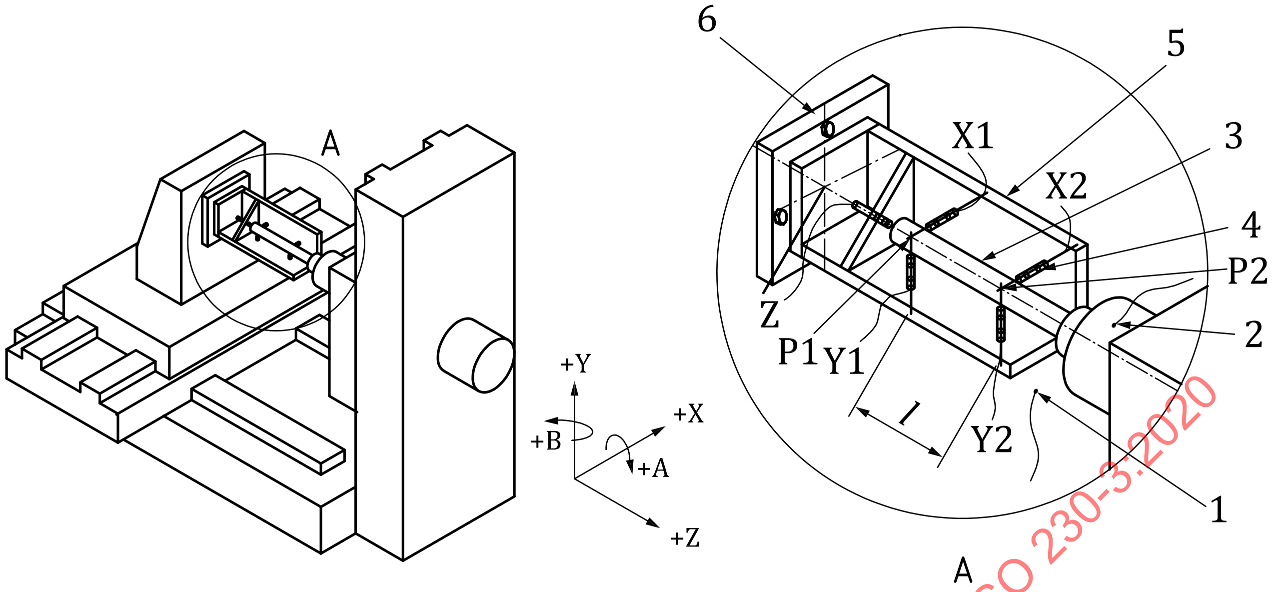
2) Some temperature compensation systems exhibit cycle times shorter than 5 min. In such cases, the frequency for monitoring can be increased to five readings per cycle if possible.



Key

1	ambient air temperature sensor	P1	measuring position 1
2	spindle bearing temperature sensor	P2	measuring position 2
3	test mandrel	*l*	distance between measuring positions P1 and P2
4	linear displacement sensors	X1	sensor measuring displacement along X-direction at measuring position 1
5	fixture	X2	sensor measuring displacement along X-direction at measuring position 2
6	fixture bolted to table	Y1	sensor measuring displacement along Y-direction at measuring position 1
		Y2	sensor measuring displacement along Y-direction at measuring position 2
		Z	sensor measuring displacement along Z-direction

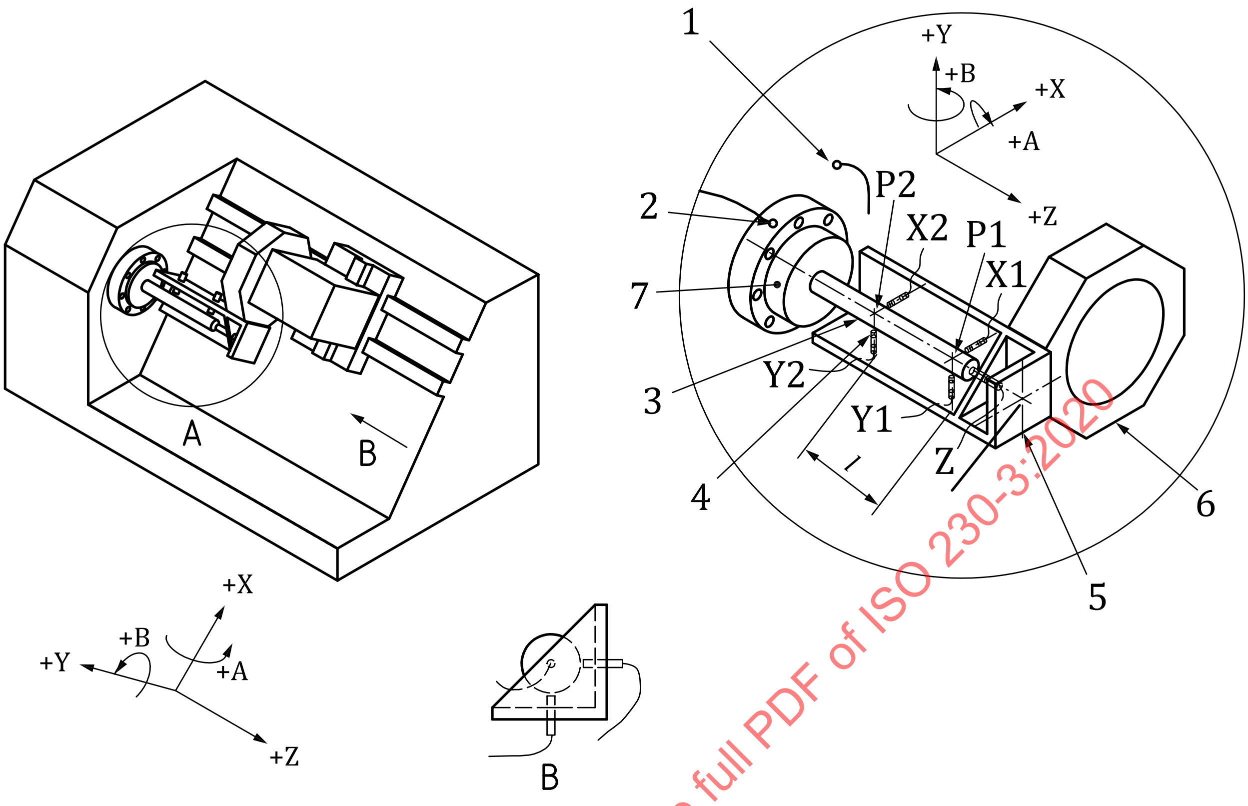
Figure 1 — Typical setup for tests of ETVE and thermal distortion of structure caused by rotating spindle and thermal distortion caused by moving linear axis on a vertical machining centre



Key

1 ambient air temperature sensor
2 spindle bearing temperature sensor
3 test mandrel
4 linear displacement sensors
5 fixture
6 fixture bolted to workholding pallet
P1 measuring position 1
P2 measuring position 2
l distance between measuring positions P1 and P2
X1 sensor measuring displacement along X-direction at measuring position 1
X2 sensor measuring displacement along X-direction at measuring position 2
Y1 sensor measuring displacement along Y-direction at measuring position 1
Y2 sensor measuring displacement along Y-direction at measuring position 2
Z sensor measuring displacement along Z-direction

Figure 2 — Typical setup for tests of ETVE and thermal distortion of structure caused by rotating spindle and thermal distortion caused by moving linear axis on a horizontal machining centre



Key

1	ambient air temperature sensor		P1	measuring position 1
2	spindle bearing temperature sensor		P2	measuring position 2
3	test mandrel		*l*	distance between measuring positions P1 and P2
4	linear displacement sensors		X1	sensor measuring displacement along X-direction at measuring position 1
5	fixture		Y1	sensor measuring displacement along Y-direction at measuring position 1
6	turret		X2	sensor measuring displacement along X-direction at measuring position 2
7	chuck		Y2	sensor measuring displacement along Y-direction at measuring position 2
			Z	sensor measuring displacement along Z-direction

Figure 3 — Typical setup for tests of ETVE and thermal distortion of structure caused by rotating spindle and thermal distortion caused by moving linear axis on a slant bed turning centre

5.3 Interpretation of results

As a general rule, the results are plotted in graphs of thermal distortion and temperature versus time as shown in the examples given in Figure 4. However, this resultant plot shall not be used for the purposes of machine comparison. The E_{TVE} values obtained from such a plot are used for considering the combined standard thermal uncertainty in measurements such as linear positioning error along each machine axis or the circular measurements in the three orthogonal planes of the machine work zone. In order to apply the combined standard thermal uncertainty to any performance measurement, the ambient temperature should be recorded continuously during that particular performance measurement process. If the recording shows a significant change of conditions compared to the conditions in which E_{TVE} values were obtained, the ETVE test results are null and void for that measurement process. In these cases, a re-evaluation of E_{TVE} should be conducted, or conditions corrected to those for which the E_{TVE} applies[3)]. In addition, measuring instruments shall be thermally stabilized.

Measurements in different directions should use different E_{TVE} values obtained from the same plot. For example, positioning error measurements along the Z axis of the machine tool should use the maximum range of thermal distortion in the Z direction for the period of time it takes to carry out the positioning error measurements as the E_{TVE}(Z) value. The E_{TVE}(Y) and E_{TVE}(X) values can be determined in the same way for the two other directions. In the case of measurements involving more than one axis movement, such as the circular measurements in the XY-plane for example, the maximum value of E_{TVE}(X) and E_{TVE}(Y) is generally taken as the E_{TVE} value.

For angular deviation measurement, ETVE values are obtained by calculating the maximum range of the tilts around X and Y axes for the period of time it takes to carry out the angular deviation measurements. The tilt angles *A* and *B* according to ISO 841, at any given time, are calculated by dividing the difference between the two displacement sensor readings along an axis divided by the distance, *l*, between these two transducers sensing in the same direction. Formulae (8) to (11) are used for these calculations:

$$A=(\mathrm{Y1}-\mathrm{Y2})/l \tag{8}$$

$$B=(\mathrm{X1}-\mathrm{X2})/l \tag{9}$$

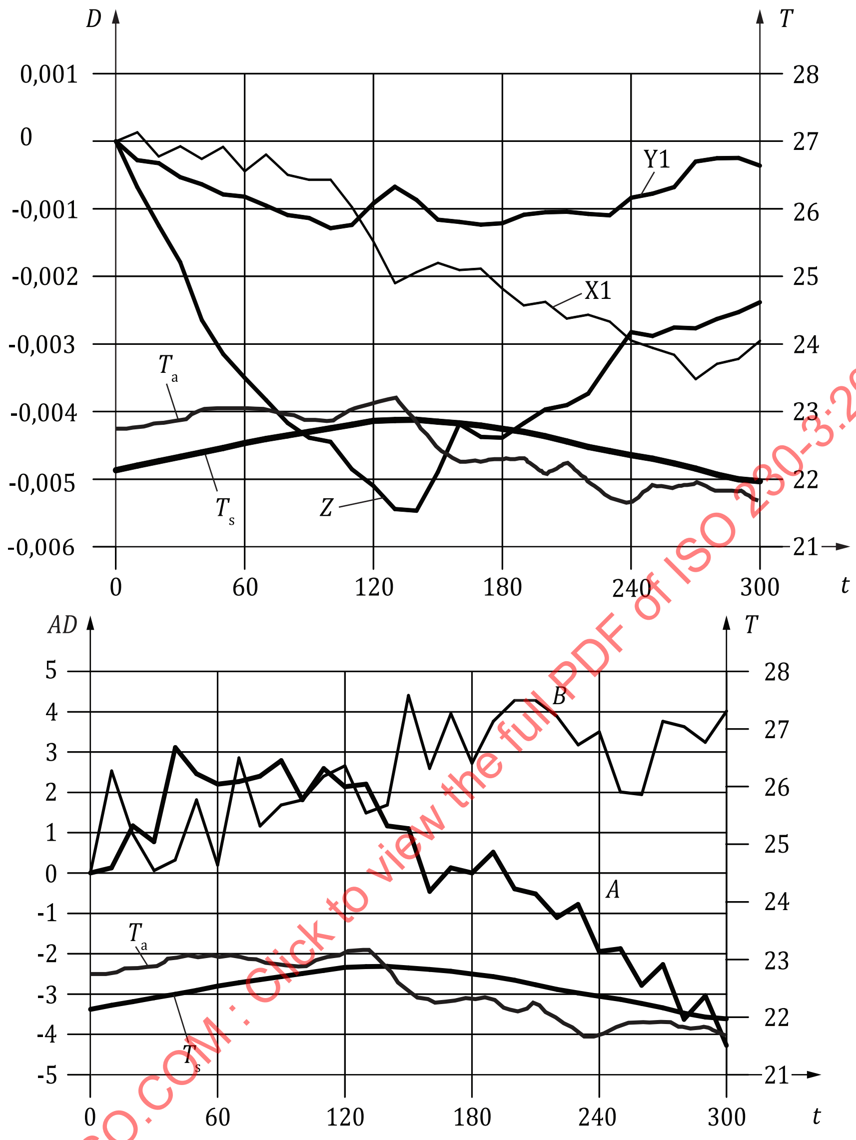
$$E_{\mathrm{TVE}}(\mathrm{A})=\text{maximum range of } A \tag{10}$$

$$E_{\mathrm{TVE}}(\mathrm{B})=\text{maximum range of } B \tag{11}$$

NOTE The resulting values are represented according to ISO 841 sign convention.

In order to determine E_{TVE} for a given performance test (for example for a given direction of measurement) on a machine tool, one has to look for an interval on the E_{TVE} plot that is as long as the time period corresponding to that performance test and that has the maximum slope. The maximum variation observed within that time interval becomes the effective E_{TVE} value for that test. For example, referring to Figure 4, E_{TVE}(X) for the test of linear positioning error of a machine tool that lasts about 1 hour is determined by the time interval 90 min to 150 min on the time scale. The E_{TVE} value for this test obtained from the plot in that interval is 0,001 5 mm.

3) Maximum variations of ambient temperature measured during machine performance tests are expected to be smaller or equal to the change of ambient temperature measured during ETVE tests (Clause 5).



Key

t time in min

T temperature in °C

D linear distortion in mm

AD angular distortion in arcsec

T_a ambient temperature in °C

T_s spindle temperature in °C

X1 linear displacement along X axis at position P1 in mm

Y1 linear displacement along Y axis at position P1 in mm

Z linear displacement along Z axis in mm

A rotation around X in arcsec

B rotation around Y in arcsec

Figure 4 — Temperature and distortion versus time for ETVE test

EXAMPLE For a test that takes 1 hour, the following E_{TVE} values are obtained from the above graphs (Figure 4):

E_{TVE}(X; 1,1 °C) = 0,001 5 mm (90 min to 150 min) E_{TVE}(A; 1,1 °C) = 3 arcsec (110 min to 170 min)

E_{TVE}(Y; 0,6 °C) = 0,000 8 mm (230 min to 290 min) E_{TVE}(B; 1,1 °C) = 3 arcsec (110 min to 170 min)

E_{TVE}(Z; 0,4 °C) = 0,003 5 mm (0 min to 60 min)

5.4 Presentation of results

As a general rule, the measurement data are plotted in graphs of distortion and temperature versus time as shown in Figure 4. The E_{TVE} values for each direction should be recorded to indicate the amount of temperature variation during the observation period, for example E_{TVE}(Z; 1,2 °C) = 0,005 5 mm.

The following information should also be reported with the results of the test (see Figures 4 and 5):

a) location of the measurement setup (coordinates of position P1, see Figure 5);

b) distance between spindle face and P1;

c) locations of temperature sensors;

d) types of sensors;

e) design and material of the test mandrels and fixtures;

f) thermal compensation procedures/ facilities used;

g) any special test procedures agreed on;

h) time and date of the test;

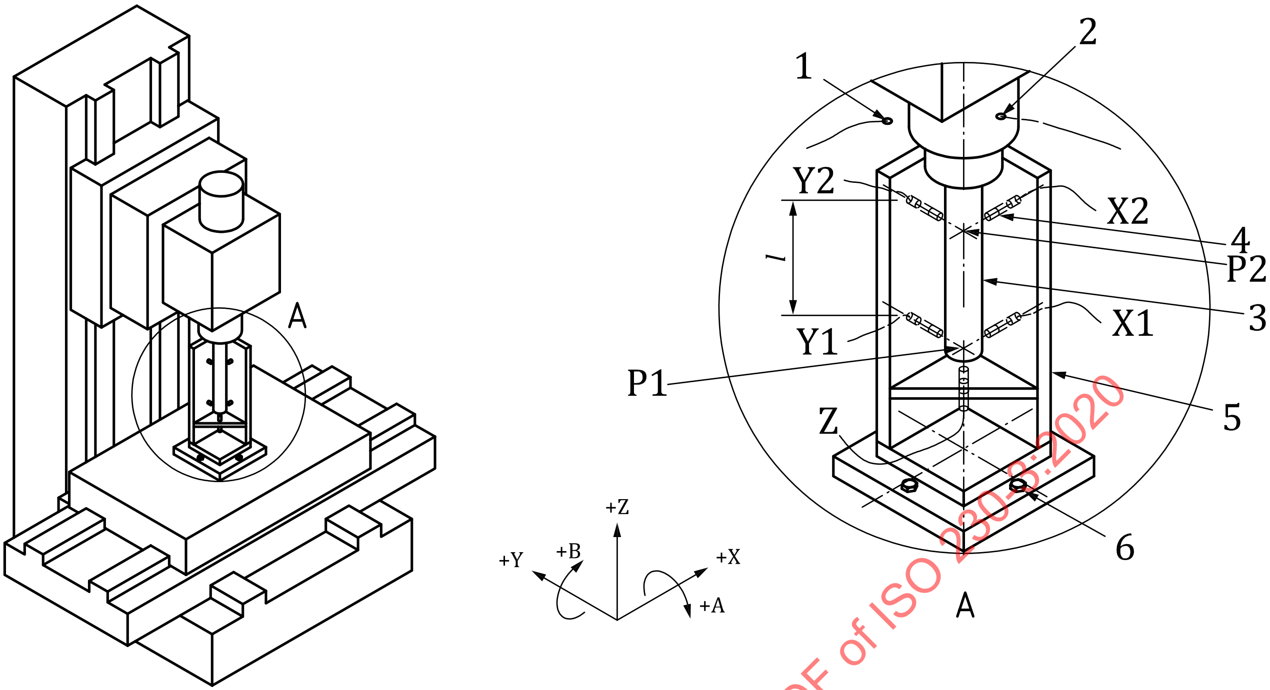
i) machine preparation procedure prior to testing (including the time period for operating auxiliary services prior to testing);

j) positive direction of deviations in X, Y, Z, A, B if different from the coordinate systems shown in Figures 1, 2, 3 and 5;

k) control mode for machine axis (hold or off);

l) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers.

Date of test: Machine:	YY/MM/DD AAA, vertical machining centre/ X = 1 000, Y = 600, Z = 800
Temperature sensor/position (ambient):	thermocouple/from the spindle axis of rotation Y = 300 (front), X = 200 (right)
Test mandrel: Fixture:	steel, 11×10^{-6} °C^{-1}, diameter: 60 mm, length: 200 mm, No. 40 taper steel, $11 \times 10^{-6} \cdot$ °C^{-1}, 100 mm × 100 mm × 400 mm, fixed on the table centre
Thermal compensation used: Warm-up procedures: Axes slide position: Measuring position P1: Distance between spindle face and P1: Sensor distance, *l* (P1, P2):	oil cooler with spindle temperature sensor cold start X = 500 mm, Y = 300 mm, Z = 400 mm, C = 0 X = 500 mm, Y = 300 mm, Z = 220 mm (height from table surface) 175 mm 150 mm



Key

1	ambient air temperature sensor	P1	measuring position 1
2	spindle bearing temperature sensor	P2	measuring position 2
3	test mandrel	*l*	distance between measuring positions P1 and P2
4	linear displacement sensors	X1	sensor measuring displacement along X-direction at measuring position 1
5	fixture	X2	sensor measuring displacement along X-direction at measuring position 2
6	fixture bolted to table	Y1	sensor measuring displacement along Y-direction at measuring position 1
		Y2	sensor measuring displacement along Y-direction at measuring position 2
		Z	sensor measuring displacement along Z-direction

NOTE Dimensions of test mandrel and fixture are for examples only.

Figure 5 — Typical presentation of setup information for the tests of ETVE and thermal distortion caused by rotating spindle and thermal distortion caused by moving linear axis

6 Thermal distortion caused by rotating spindle

6.1 General

This test is carried out to identify the effects of the internal heat generated by rotation of the spindle and the resultant temperature gradient along the structure on the distortion of the machine tool structure observed between the workpiece and the cutting tool. Since it is related to the heat generation by the spindle, this test is carried out on machines with rotating spindles only.

6.2 Test method

Figures 1, 2 and 3 show typical measurement setups for vertical- and horizontal-spindle machining centres and a turning centre, respectively. The fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating workholding or tool-holding component of the machine tool to measure:

a) the relative displacements between the component that holds the cutting tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine tool [e.g. for a C-axis, $d(E_{X0C})$, $d(E_{Y0C})$, and $d(E_{Z0C})$]; the exact position of the measurement setup shall be recorded along with the test results.

NOTE The specific location of the measurement setup in the work zone is provided in the relevant machine-specific standards.

b) the tilt or rotation around the X and Y axes of the machine tool [e.g. for a C-axis, $d(E_{A0C})$ and $d(E_{B0C})$].

The temperature of the machine tool structure, as close as possible to the front spindle bearing, and the ambient air temperature in the close vicinity of the machine tool and at the same elevation of the spindle nose should be monitored at least once every 5 min[4]. It is important to measure the ambient air temperature at a suitable distance from the machine tool to avoid any influence by the heating up of the machine tool (for example by hydraulic components) on the ambient temperature. Although these temperatures do not exactly correlate to the measured displacements, they are indications of the thermal changes in the environment and the machine tool structure.

The test procedure should follow one of the two specified spindle speed regimes described below:

— variable speed spectrum, for instance, as shown in Figure 6;

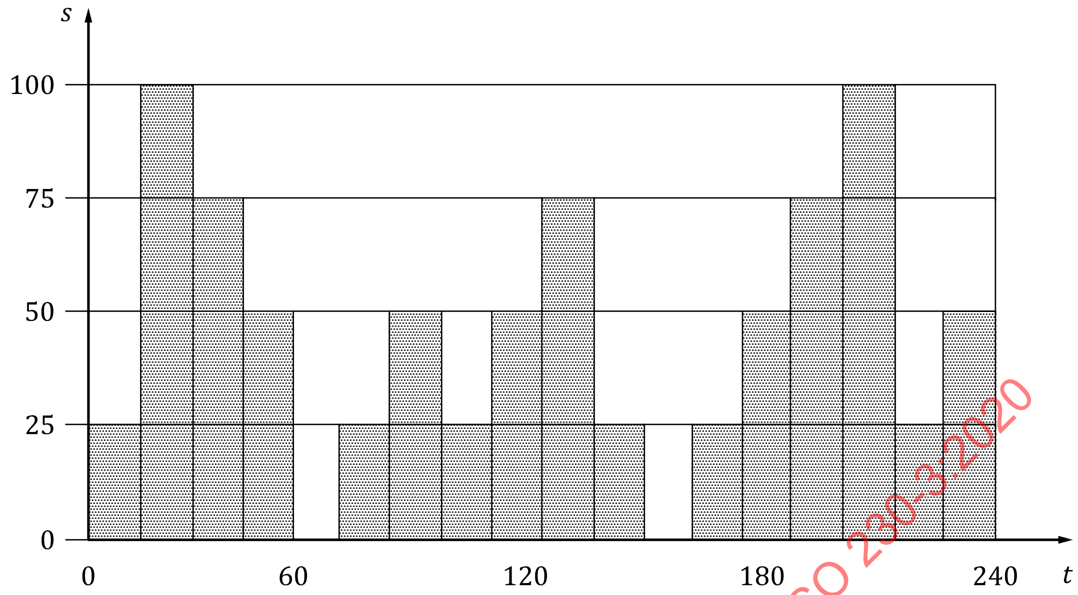
— constant speed as a percentage of maximum speed.

The choice of the test procedure with spindle speed spectrum and the percentages shall be specified in machine-specific standards. If necessary, the supplier/manufacturer and user may agree on a different, special test schedule (for example a certain warm-up cycle before the test) corresponding to their own special requirements. The spindle speed spectrums selected generally reflect practical usage of the machine tool. For example, for machining centres, a spindle speed spectrum consisting of different spindle speeds over 2 min to 30 min for each spindle speed, with periodic stops of 1 min to 30 min in between may be selected to represent typical machining conditions.

All sensor outputs shall be monitored for a period of 4 h. Alternatively, shortening or extending the measurement period is allowed until the distortion change during the last 60 min is less than 15 % of the maximum distortion registered over the first hour of the test. Other conditions may be agreed between the user and the supplier/manufacturer. Then, the spindle is stopped for a minimum period of 1 h while monitoring the sensors is continued. The effects of test mandrel runout should be eliminated[5] during the tests when the spindle is rotating.

4) Some temperature compensation systems exhibit cycle times shorter than 5 min. In such cases, the frequency for monitoring can be increased accordingly.

5) The elimination of the effects of test mandrel runout can be achieved by low-pass filters, averaging, or by synchronizing data acquisition with spindle orientation (see ISO 230-7).



Key

t time in s

S spindle speed in % of maximum spindle speed

Figure 6 — Sample spindle speed spectrum for thermal distortion tests

6.3 Interpretation of results

The measurement results should be plotted in graphs of thermal distortion and temperatures (ambient and spindle bearing temperatures) versus time as shown in Figure 7.

The effects of warming up the machine tool structure on the ability of the machine tool to maintain the position of the cutting tool relative to the workpiece can be assessed from these graphs. It should be noted that the starting and stopping of the spindle can cause offsets in the plots due to the effect of test mandrel runout. These effects should be ignored during the evaluation of thermal deflection.

The graph for angular distortion (see Figure 7) is generated by calculating tilt angles A and B as described in 5.3.

6.4 Presentation of results

The range of displacements along each machine tool axis within the first 60 min [$d(E_{X0C})_{P1,60}$, $d(E_{Y0C})_{P1,60}$, $d(E_{Z0C})_{60}$, $d(E_{A0C})_{60}$, $d(E_{B0C})_{60}$] and during the total spindle running period [$d(E_{X0C})_{P1,t}$, $d(E_{Y0C})_{P1,t}$, $d(E_{Z0C})_t$, $d(E_{A0C})_t$, $d(E_{B0C})_t$, where t is the time at the end of the spindle running period], shall be recorded along with the distance, l, between the two linear displacement sensors sensing in the same direction (see Figures 1, 2 and 3). These values, as shown in Table 1, shall be presented with the graphs of temperature and distortion versus time, as shown in the example given in Figure 7. The following parameters should also be reported with the results of the test as shown in Figure 5:

a) location of the measurement setup (coordinates of position P1, see Figure 1);

b) distance between spindle face and P1;

c) locations of temperature sensors;

d) type of sensors;

e) design and material of the test mandrel and fixture;

f) thermal compensation procedures/facilities used;

g) spindle speed regime;

h) any special test procedures agreed on;

i) time and date of the test;

j) machine preparation procedure prior to testing (including the time period for operating);

k) positive directions of deviations X, Y, Z, A, B if different from the coordinate system shown in Figures 1, 2, 3 and 5;

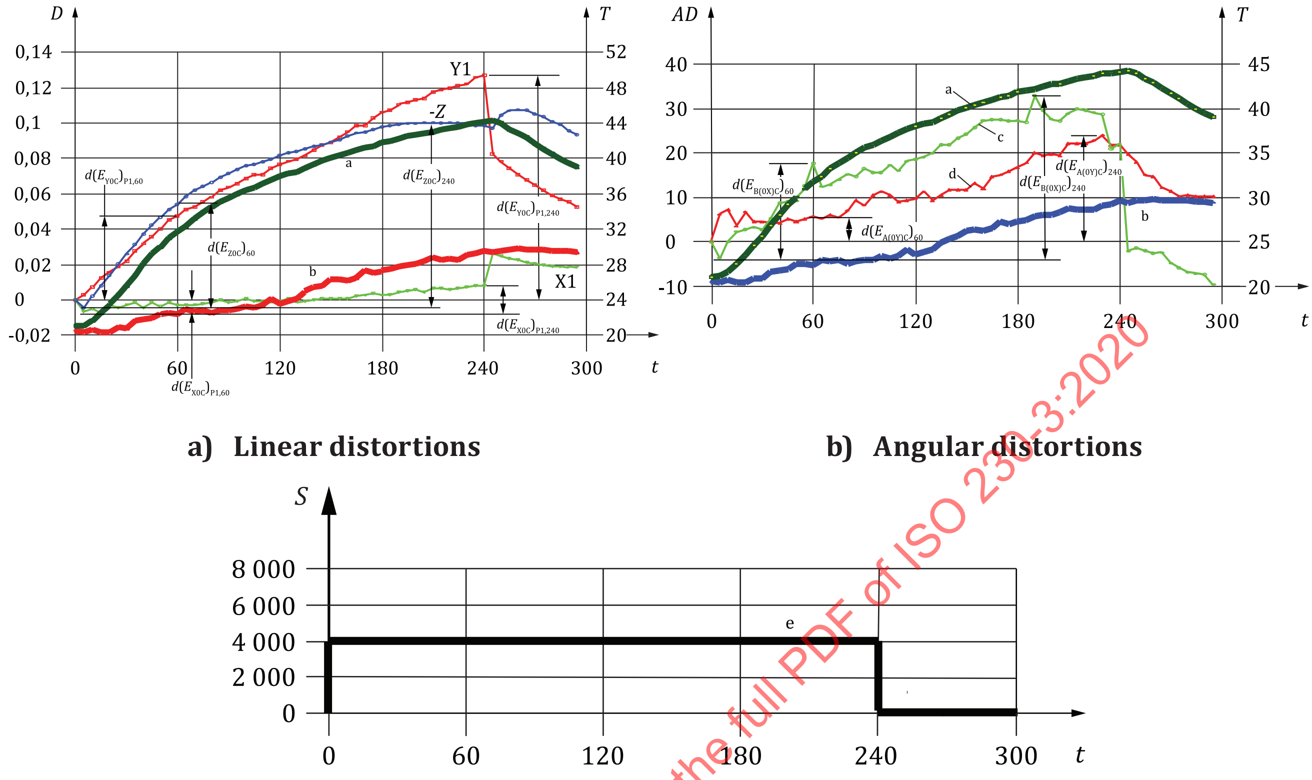
l) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers.

Table 1 — Typical presentation of results from tests of thermal distortion caused by rotating spindle

	X1	Y1	Z	A	B
During the first 60 min	$d(E_{X0C})_{P1,\,60}$	$d(E_{Y0C})_{P1,\,60}$	$d(E_{Z0C})_{\,60}$	$d(E_{A0C})_{\,60}$	$d(E_{B(0X)C})_{\,60}$
During the spindle running period, t	$d(E_{X0C})_{P1,\,t}$	$d(E_{Y0C})_{P1,\,t}$	$d(E_{Z0C})_{\,t}$	$d(E_{A0C})_{\,t}$	$d(E_{B0C})_{\,t}$
Distance, l	The value is given in the example in Figure 7.				

EXAMPLE For a test that takes 5 h, the following values are obtained from Figure 7.

	X1 (mm)	Y1 (mm)	Z (mm)	A (arcsec)	B (arcsec)
First 60 min	$d(E_{X0C})_{P1,60} = 0{,}008$	$d(E_{Y0C})_{P1,60} = 0{,}048$	$d(E_{Z0C})_{P1,60} = 0{,}061$	$d(E_{A0C})_{60} = 6$	$d(E_{B0C})_{60} = 22$
Full running period (t = 240 min)	$d(E_{X0C})_{P1,240} = 0{,}020$	$d(E_{Y0C})_{P1,240} = 0{,}124$	$d(E_{Z0C})_{P1,240} = 0{,}108$	$d(E_{A0C})_{240} = 24$	$d(E_{B0C})_{240} = 38$
Distance, l	150 mm				



a) Linear distortions

b) Angular distortions

c) Spindle speed

Key

a	machine structure temperature in °C	t	time in min
b	ambient temperature in °C	T	temperature in °C
c	rotation about Y ($E_{B(0X)C}$) in arcsec	X1	sensor reading at P1 along X direction in mm
d	rotation about X ($E_{A(0Y)C}$) in arcsec	Y1	sensor reading at P1 along Y direction in mm
e	spindle speed (maximum spindle speed = 6 000 min^{-1})	Z	sensor reading along Z direction in mm
S	spindle speed in min^{-1}	D	thermal distortion in mm
		AD	thermal angular distortion in arcsec

NOTE Negative Z data shown in (a) is for graphical clarity.

Figure 7 — Example thermal linear and angular distortions caused by rotating spindle of a machining centre versus time

7 Thermal distortion caused by linear motion of components

7.1 General

This test is carried out to identify the effects of internal heat generated by the machine linear positioning system and by guideway friction on the distortion of the machine tool structure observed between the workpiece and the cutting tool. The test indicates the amount of the change in position and orientation of the moving component at two positions along a machine tool linear axis, due to thermal elongation of machine tool scales and deformations (twist and bend) of the machine tool structure caused by local generation of heat during the warm-up period. This test is carried out on numerically controlled (NC) machines tools only.

A machine tool component can maintain its shape while warming up only if the thermal expansion can be exactly the same in all the points of its structure, i.e. if there were only temperature gradients in time not in space and if the coefficient of thermal expansion (CTE) is the same. But, in practice, there is always a temperature gradient in the machine tool structure in the presence of local heat sources such as electric motors, friction in ballscrew bearings and nut, and hydraulics.

Due to thermal gradients, different machine tool components expand in different amounts creating stresses and angular distortions as twist and bend of the structure.

Measurements described in this clause reveal the effect of all thermal distortions mentioned above.

7.2 Test method

7.2.1 Measurement positions

The target positions should be selected close to the end points of travel, where applicable, and generally not further than 2 m from each other. Each target position is only approached from the other target position, thus including the reversal error of the linear motion in the measurements. It is assumed that changes in the reversal error are not significant.

For ballscrew/rotary encoder type systems, reversal values (both linear and angular) can change with temperature. In these cases, bi-directional measurements are to be taken, if possible.

7.2.2 Setup of instruments

Three examples of typical measurement setups are shown as follows. The first is composed of two fixtures, with five linear displacement sensors each, and a test mandrel. The test mandrel shall be mounted on the spindle and two fixtures, shall be securely fixed on the table at each end of the selected stroke (see Figure 8).

The linear displacement sensors shall be set to measure the changes in position and orientation of the test mandrel at each target position (P1 and P2). From the corresponding displacement sensor readings at each target position, the change in distance traversed by the moving component under test as well as the two orthogonal linear deviations and two angular deviations at each target position (all corresponding to the relative motion between the cutting tool and the work sides of the machine tool) are calculated. These calculations are done using Formulae (12) to (21) (using the setup and nomenclature shown in Figure 8):

$$d(E_{XX})_{P1,t} = (P_{x11})_t - (P_{x11})_{t0} \quad (12)$$

$$d(E_{XX})_{P2,t} = -(P_{x21})_t - (P_{x21})_{t0} \quad (13)$$

$$d(E_{YX})_{P1,t} = (P_{y11})_t - (P_{y11})_{t0} \quad (14)$$

$$d(E_{YX})_{P2,t} = -(P_{y21})_t - (P_{y21})_{t0} \quad (15)$$

$$d(E_{ZX})_{P1,t} = -\left[(P_{z1})_t - (P_{z1})_{t0}\right] \quad (16)$$

$$d(E_{ZX})_{P2,t} = -\left[(P_{z2})_t - (P_{z2})_{t0}\right] \quad (17)$$

$$d(E_{AX})_{P1,t} = \left[(P_{y11} - P_{y12})_t - (P_{y11} - P_{y12})_{t0}\right] / l_1 \quad (18)$$

$$d(E_{AX})_{P2,t} = -\left[(P_{y21} - P_{y22})_t - (P_{y21} - P_{y22})_{t0}\right]/l_2 \quad (19)$$

$$d(E_{BX})_{P1,t} = \left[(P_{x12} - P_{x11})_t - (P_{x12} - P_{x11})_{t0}\right]/l_3 \quad (20)$$

$$d(E_{BX})_{P2,t} = -\left[(P_{x22} - P_{x21})_t - (P_{x22} - P_{x21})_{t0}\right]/l_4 \quad (21)$$

where

l_1 to l_4 are the distances between the two displacement sensors measuring in the same direction;

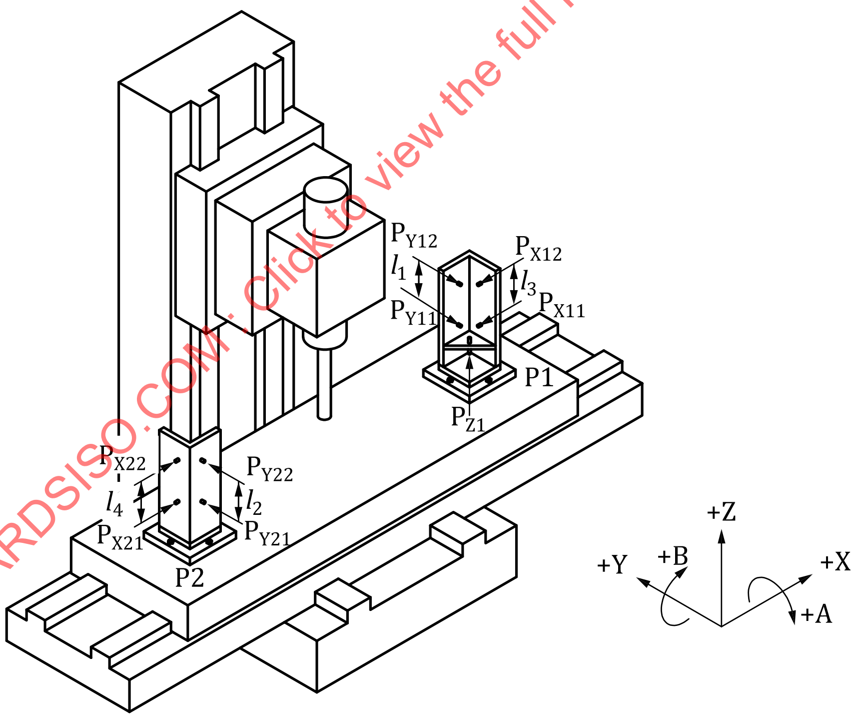
t0 indicates the beginning of the test period;

t indicates the end of the axis cycling time period;

P_{x21} indicates the reading of the first displacement sensor in the direction of X-axis located at position P_2.

NOTE 1 $d(E_{CX})_{P1}$ and $d(E_{CX})_{P2}$ cannot be calculated with the measurement setup of Figure 8.

NOTE 2 The sign convention in Formulae (12) to (21) is such that motion of the spindle relative to the workpiece in the positive direction causes positive reading of the linear displacement sensor.



Key

l_1, l_2, l_3, l_4 distances between sensors used to calculate angular distortions

Figure 8 — Typical setup for measurement of thermal distortions due to moving X-axis table of a machining centre

The second example is composed of one fixture with seven displacement sensors, and two target blocks. It is shown in Figure 9. In such a setup, a sensor fixture is mounted on the spindle. Two target blocks are mounted at each end of the travel. This setup allows the simultaneous measurement of six components of the thermal distortion, one in the direction of travel, two in the orthogonal directions and three angular components around three linear axes using Formulae (22) to (33) (using the setup and nomenclature shown in Figure 9).

$$d(E_{XX})_{P1,t} = (P_{x1})_t - (P_{x1})_{t0} \tag{22}$$

$$d(E_{XX})_{P2,t} = -\left[(P_{x2})_t - (P_{x2})_{t0}\right] \tag{23}$$

$$d(E_{YX})_{P1,t} = (P_{y11})_t - (P_{y11})_{t0} \tag{24}$$

$$d(E_{YX})_{P2,t} = (P_{y21})_t - (P_{y21})_{t0} \tag{25}$$

$$d(E_{ZX})_{P1,t} = -\left[(P_{z13})_t - (P_{z13})_{t0}\right] \tag{26}$$

$$d(E_{ZX})_{P2,t} = -\left[(P_{z23})_t - (P_{z23})_{t0}\right] \tag{27}$$

$$d(E_{AX})_{P1,t} = \left[((P_{z11} + P_{z12})/2 - P_{z13})_t - ((P_{z11} + P_{z12})/2 - P_{z13})_{t0}\right]/l_1 \tag{28}$$

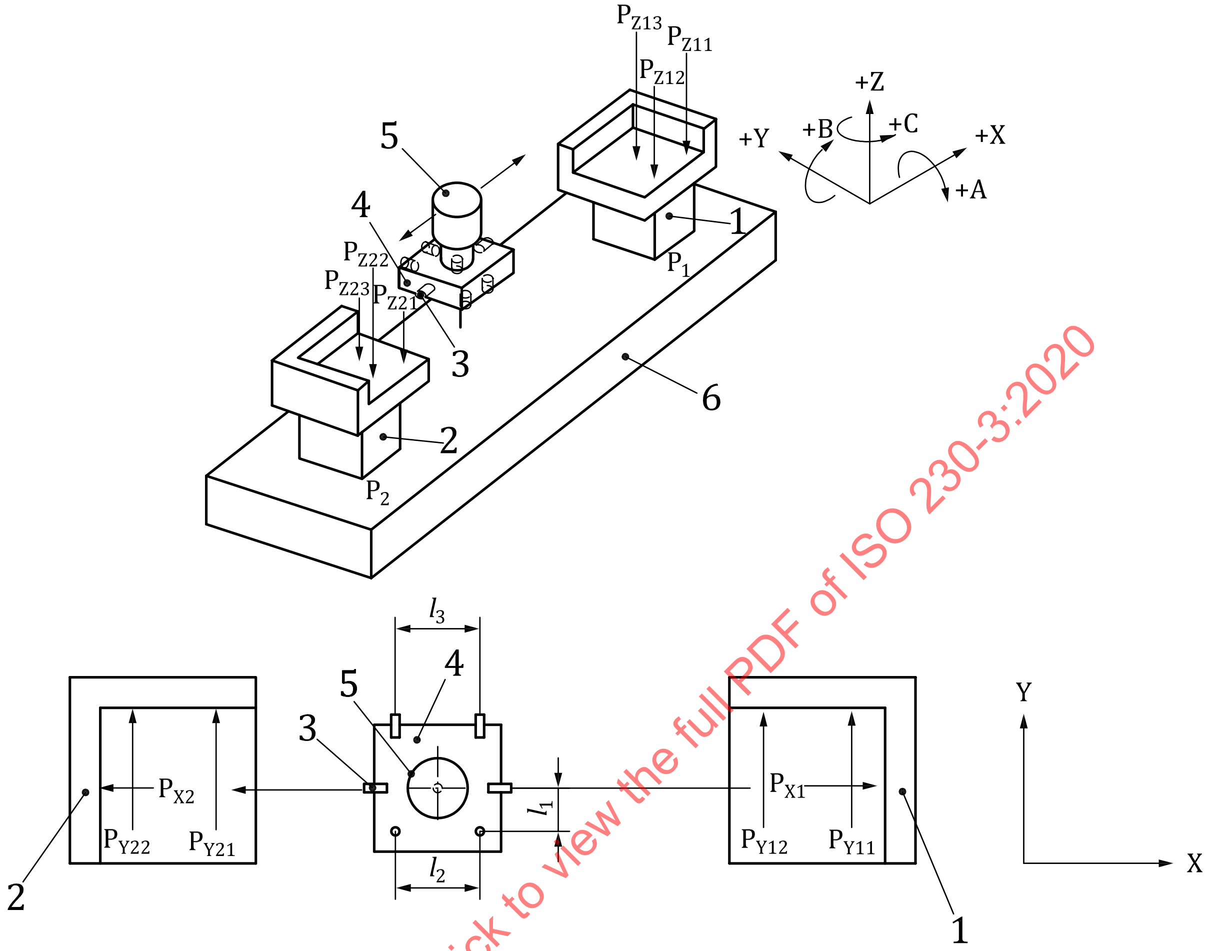
$$d(E_{AX})_{P2,t} = \left[((P_{z21} + P_{z22})/2 - P_{z23})_t - ((P_{z21} + P_{z22})/2 - P_{z23})_{t0}\right]/l_1 \tag{29}$$

$$d(E_{BX})_{P1,t} = \left[(P_{z11} + P_{z12})_t - (P_{z11} + P_{z12})_{t0}\right]/l_2 \tag{30}$$

$$d(E_{BX})_{P2,t} = \left[(P_{z21} - P_{z22})_t - (P_{z21} - P_{z22})_{t0}\right]/l_2 \tag{31}$$

$$d(E_{CX})_{P1,t} = \left[(P_{y11} + P_{y12})_t - (P_{y11} + P_{y12})_{t0}\right]/l_3 \tag{32}$$

$$d(E_{CX})_{P2,t} = \left[(P_{y21} - P_{y22})_t - (P_{y21} - P_{y22})_{t0}\right]/l_3 \tag{33}$$



Key

1 target right
2 target left
3 gap sensor
4 sensor fixture
5 machine spindle
6 machine table
l_1, l_2, l_3 distances between sensors used to calculate angular distortions

Figure 9 — Alternative setup for measurement of thermal distortion caused by moving X-axis slide of a machining centre

For most turning centres, the sensor fixture (with 6 transducers) is mounted to the tool-holding part of the machine tool and a special artefact, with reference surfaces aligned against those sensors, is mounted on the workholding spindle as shown in Figure 10. For such a setup the thermal distortion can be calculated using Formulae (33) to (42) (using the setup and nomenclature shown in Figure 10).

$$d(E_{ZZ})_{P1,t} = (P_{z1})_t - (P_{z1})_{t0} \tag{33}$$

$$d(E_{ZZ})_{P2,t} = -\left[(P_{z2})_t - (P_{z2})_{t0}\right] \tag{34}$$

$$d(E_{ZX})_{P1,t} = \left[(P_{x11})_t - (P_{x11})_{t0}\right] \tag{35}$$

$$d(E_{XZ})_{P2,t} = -\left[(P_{x21})_t - (P_{x21})_{t0}\right] \tag{36}$$

$$d(E_{YZ})_{P1,t} = -\left[\left(P_{y11}\right)_t - \left(P_{y11}\right)_{t0}\right] \quad (37)$$

$$d(E_{YZ})_{P2,t} = -\left[\left(P_{y21}\right)_t - \left(P_{y21}\right)_{t0}\right] \quad (38)$$

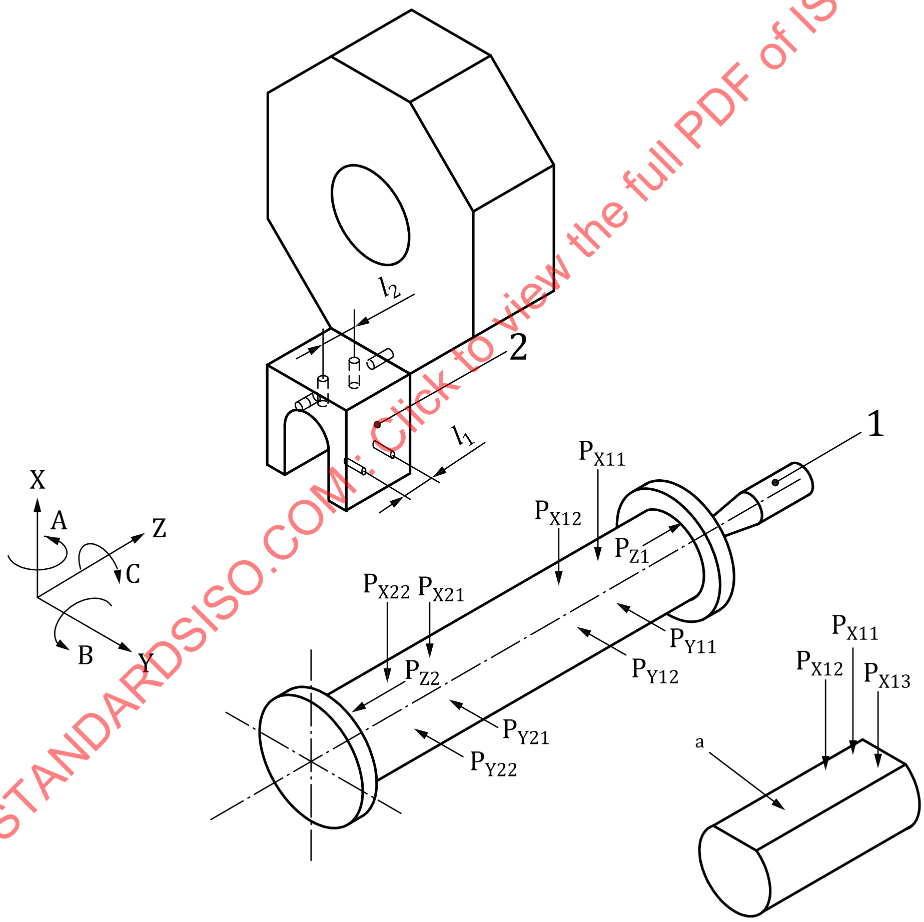
$$d(E_{AZ})_{P1,t} = \left[\left(P_{y11} - P_{y12}\right)_t - \left(P_{y11} - P_{y12}\right)_{t0}\right] / l_1 \quad (39)$$

$$d(E_{AZ})_{P2,t} = \left[\left(P_{y21} - P_{y22}\right)_t - \left(P_{y21} - P_{y22}\right)_{t0}\right] / l_1 \quad (40)$$

$$d(E_{BZ})_{P1,t} = \left[\left(P_{x12} - P_{x11}\right)_t - \left(P_{x12} - P_{x11}\right)_{t0}\right] / l_2 \quad (41)$$

$$d(E_{BZ})_{P2,t} = \left[\left(P_{x22} - P_{x21}\right)_t - \left(P_{x22} - P_{x21}\right)_{t0}\right] / l_2 \quad (42)$$

NOTE 3 $d(E_{CZ})$ cannot be calculated with the measurement setup of Figure 10.



Key

1 machine tail stock

2 sensor holding bracket

l_1, l_2 distances between sensors to calculate angular distortions

a Optional flat surface for $d(E_{CZ})$ calculation.

NOTE Coordinate axes rotated for clarity purposes

Figure 10 — A typical setup for measurement of thermal distortions due to moving Z-axis carriage of a turning centre

The third example is composed of machine tool's touch-trigger probe (if available) and two target blocks. The two target blocks are mounted at each end of the travel as shown in Figure 11. Ideally, by touching six points on each artefact (as shown in Figure 11) and recording the machine tool X, Y, and Z positions corresponding to those points all six components of the thermal distortion can be calculated using Formulae (43) to (54) (using the setup, nomenclature and the machine tool structure shown in Figure 11).

$$d(E_{XX})_{P1,t} = (P_{x11})_t - (P_{x11})_{t0} \tag{43}$$

$$d(E_{XX})_{P2,t} = -\left[(P_{x21})_t - (P_{x21})_{t0}\right] \tag{44}$$

$$d(E_{YX})_{P1,t} = (P_{y11})_t - (P_{y11})_{t0} \tag{45}$$

$$d(E_{YX})_{P2,t} = (P_{y21})_t - (P_{y21})_{t0} \tag{46}$$

$$d(E_{ZX})_{P1,t} = (P_{z11})_t - (P_{z11})_{t0} \tag{47}$$

$$d(E_{ZX})_{P2,t} = (P_{z21})_t - (P_{z21})_{t0} \tag{48}$$

$$d(E_{AX})_{P1,t} = \left[(P_{y11} - P_{y12})_t - (P_{y11} - P_{y12})_{t0}\right]/l_1 \tag{49}$$

$$d(E_{AX})_{P2,t} = \left[(P_{y21} - P_{y22})_t - (P_{y21} - P_{y22})_{t0}\right]/l_1 \tag{50}$$

$$d(E_{BX})_{P1,t} = \left[(P_{x11} - (P_{x12} + P_{x13})/2)_t - (P_{x11} - (P_{x12} + P_{x13})/2)_{t0}\right]/l_2 \tag{51}$$

$$d(E_{BX})_{P2,t} = -\left[(P_{x21} - (P_{x22} + P_{x23})/2)_t - (P_{x21} - (P_{x12} + P_{x23})/3)_{t0}\right]/l_2 \tag{52}$$

$$d(E_{CX})_{P1,t} = \left[(P_{x12} - P_{x13})_t - (P_{x12} - P_{x13})_{t0}\right]/l_3 \tag{53}$$

$$d(E_{CX})_{P2,t} = \left[(P_{x22} - P_{x23})_t - (P_{x22} - P_{x23})_{t0}\right]/l_3 \tag{54}$$

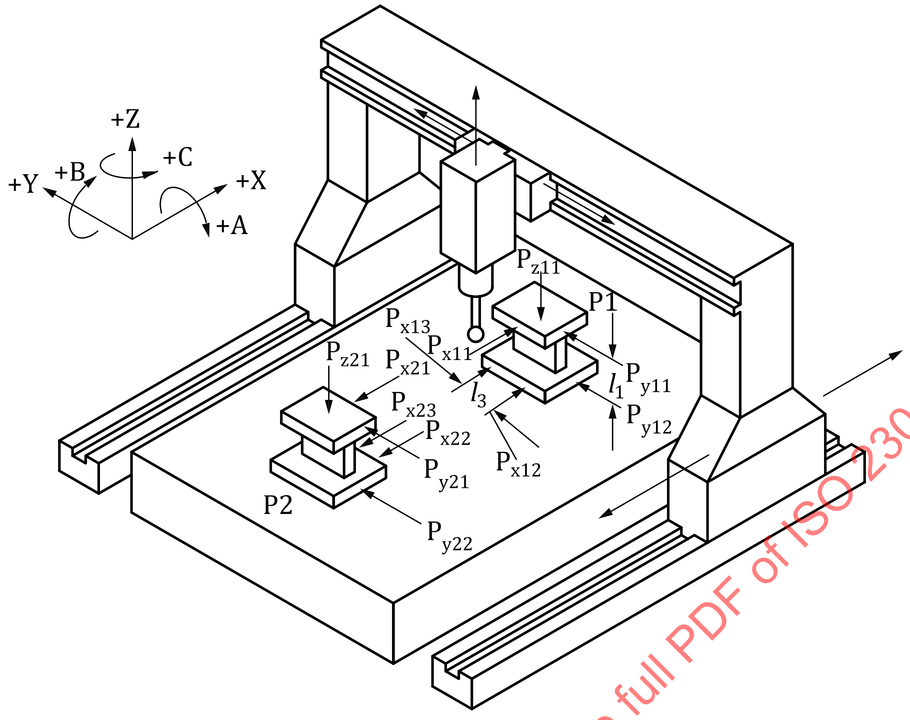
where

l_1, l_2, and l_3	are the distances between the two probing locations in the same direction;
t0	indicates the beginning of the axis cycling period;
t	indicates the end of the axis cycling period.

It should be noted that an angular distortion of a machine tool component can only be estimated if it causes a difference in the measured thermal distortion at two probed points. Care should be taken in the selection of the probing points to ensure that all angular distortions of interest yield such a difference. For example, only the angular deviation of X-axis slide is captured by $d(E_{CX})$ calculations, the angular deviations of the Y-axis slide (a part of E_{CY}) and Z-axis slide (a part of E_{CZ}) are not included in the determination of overall distortions represented by the probing locations shown in Figure 11. So, if these probing points are used for the Y-axis or Z-axis tests, there can be some inconsistency with respect to the other alternative measurement setups mentioned previously.

NOTE 4 Identification of some angular distortions can require measurements with two different probe offsets to achieve this condition.

It should also be noted that using the above-mentioned setups requires zeroing of all readings at the start, and thus provides no absolute measurements of deviations, only their change in time.



Key

l_1, l_2, l_3 distances between probing points to calculate angular distortions

NOTE Same distances l_1, l_2 and l_3 apply to P2 artefact.

Figure 11 — Typical setup for measurement of thermal distortion caused by moving X-axis bridge of a machining centre using touch-trigger probe

NOTE 5 Repeatability of the touch-trigger probe affects the measurement results.

7.2.3 Test cycle

The test cycle is made of two periods of time, 4 h of axis cycling and 1 h cooling down. The measurements may be interrupted when the distortion change noted during the last 60 min is less than 15 % of the distortion registered over the first hour of the test. In situations where a set pattern of activity (for example periodic tool setting) is observed, the tests should be carried out over a period of time during which relevant events are repeated or over any other period of time agreed by the supplier/manufacturer and the user. Sufficient time should be allocated after each test to allow for the machine tool to cool down.

Starting from one of the target positions 1, where the machine tool remains at rest long enough (dwell time) to record the readings of the displacement sensors, the machine tool slide shall be programmed to move to the target position 2, where the second set of readings is taken. The motion is then reversed and the readings at target position 1 shall be measured and recorded again. This test sequence shall then be repeated until the end of the axis cycling period, recording data at the two target positions. The programmed traverse rate shall be a percentage of the maximum programmable feed speed. The dwell time at each target position shall be the minimum required for taking the readings. The percentage and the dwell time shall be specified in machine specific standards. Different dwell times and traverse rates have different heat input, and can consequently cause different amounts of thermal distortion. The dwell time and the traverse rate in these tests may be modified based on agreements reached between the user and the supplier/manufacturer.

If the measurement system can only record a limited amount of data, then the measurements at two target positions may be taken at set intervals, for example, at every 5 bi-directional motion of the machine slide. The exact procedure of the measurements should be reported.

At the end of the axis cycling period, the machine tool slide shall be stopped at the middle of its travel; every 5 min it shall be moved to both target positions to take readings, and then stopped again in the middle, until the end of the cool down period.

7.2.4 Temperature measurements

Useful positions for the temperature sensors can be selected as follows:

— position transducer (if possible);

— an area close to the friction sources (usually between the moveable element and the related fixed part, e.g. table/bed, head/column, the temperature grows due to friction in the slideways, in the ball screw support bearings, in the ball screw nut);

— an area in the opposite side of the machine tool structure (e.g. bottom of the bed);

— table;

— spindle head.

Ambient temperature should be monitored at least once every 5 min[6] during these tests.

7.2.5 Compensations

If the correct operation of the measuring instrument requires compensation for environmental factors such as air temperature and pressure, then these shall be used.

If the measuring instrument incorporates facilities for NDE correction, then these facilities shall not be used, because they hide the contribution to the overall thermal distortion given by the elongation of the axis scale.

7.3 Presentation of results

For each axis of the machine, the following plots versus time should be presented:

— two position plots of the target positions;

— four orthogonal linear distortion plots of the target positions;

— four or six angular distortion plots of the target positions (number depending on the type of measurement setup);

— in each of these plots the quantities of variations from the starting values as opposed to absolute values should be indicated.

In addition, the plots of the environment temperature and the machine tool temperatures measured during the test versus time should be provided. It should be noted that the results are influenced by the positioning repeatability of the machine tool axis under test.

An example set of such plots is shown in Figure 12 and Figure 13.

The following parameters shall be reported along with the plots as shown in Figure 12 and Figure 13:

a) traverse speed;

6) Some temperature compensation systems show cycle times shorter than 5 min. In such cases, the frequency for monitoring can be increased accordingly.

b) dwell times;

c) start and end point positions;

d) compensation capabilities and facilities used;

e) instrument and setup used;

f) temperature sensor location;

g) coefficient of thermal expansion used;

h) location of measurement line;

i) time and date of the test;

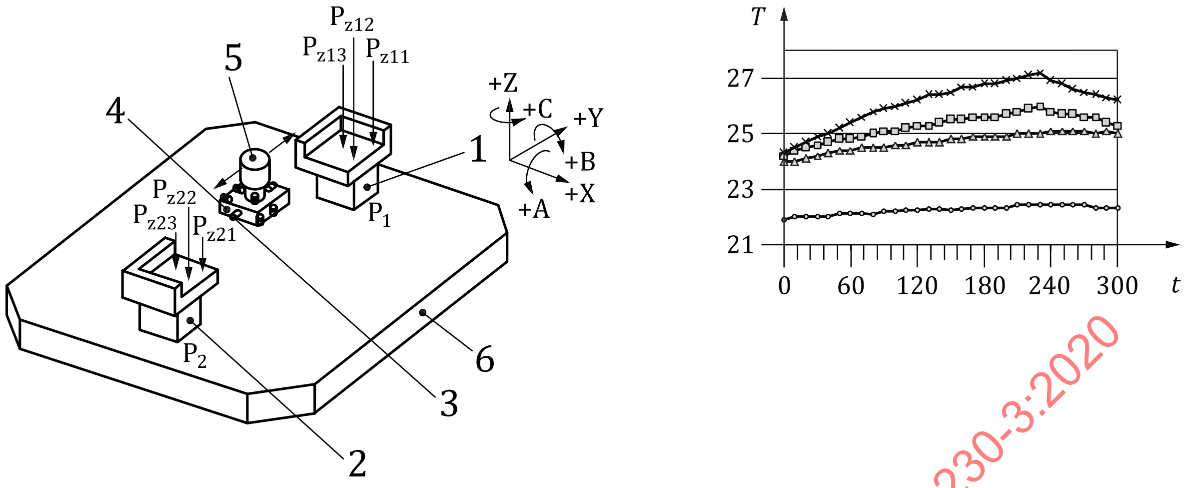
j) warm-up procedures (including the time period of warm-up procedures);

k) temperature of the measured object at the beginning and end of test;

l) positive direction of position drift, if different from the coordinate systems shown in Figures 1, 2, 3, 8 and 9;

m) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers.

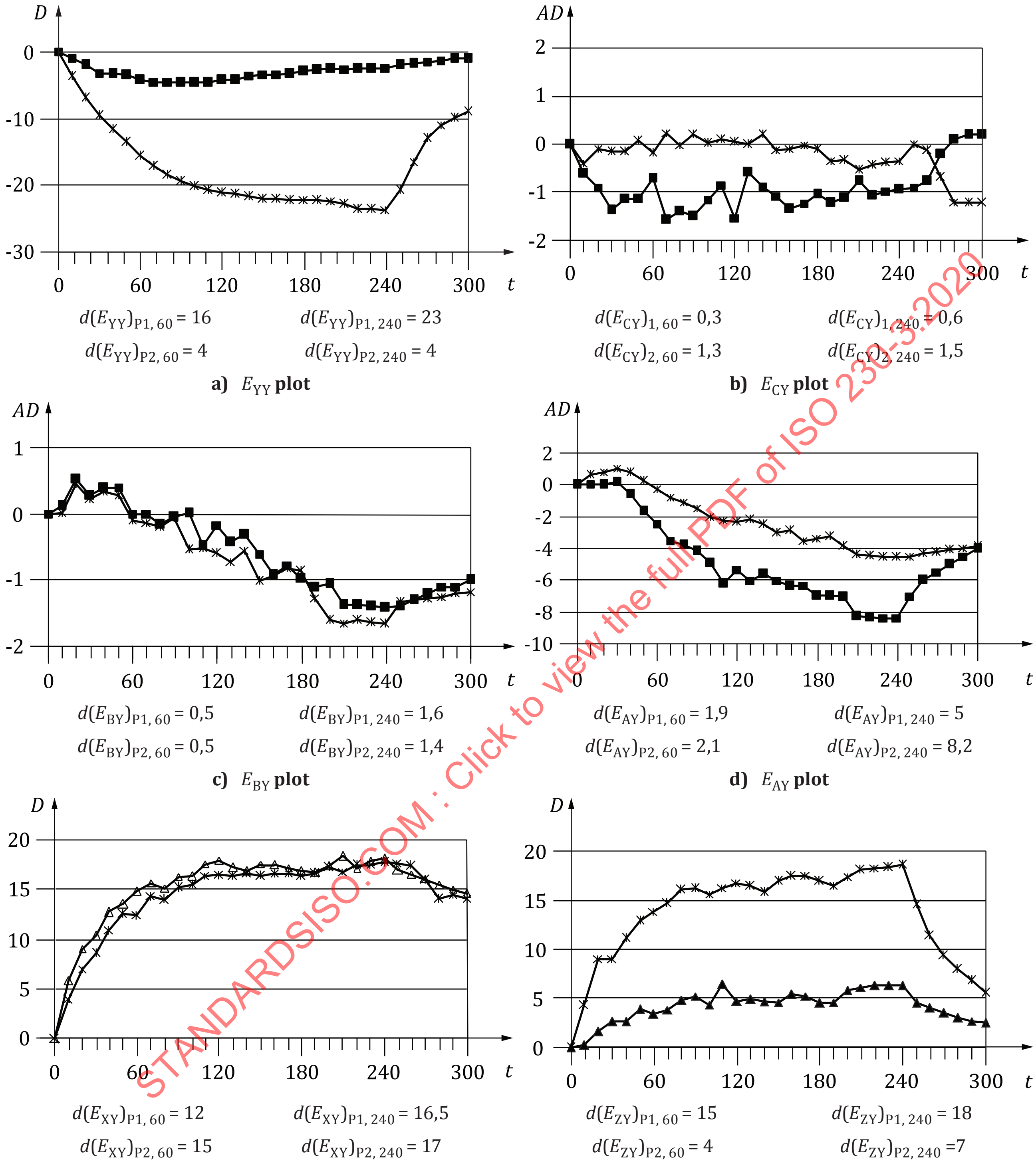
Date of test:	YY/MM/DD	
Machine:	AAA, vertical machining centre/X = 500, Y = 350, Z = 400	
Measuring instrument and serial No.:	BBB, 6 probes moved with spindle, 2 target fixture	
Tested axis and its location:	Y, X = 250, Z = 200	
Type of positioning scale:	Glass scale	
Coefficient of thermal expansion of scale:	8×10^{-6} °C^{-1}	
Thermal compensation used:	None	
Warm-up procedures:	machine is held in hold position over the last 6 hours	
Position axes not under test:	X = 250 mm; Z = 200 mm; C = 0	
Feed speed:	500 mm/min	
Start and end point:	Y, 0, 300 mm	
Dwell time at each target position:	5 s	
Interval circles for data taken	5	
Temperature sensor/position	(ambient): front, 200 mm X, 300 mm Y from spindle head (machine): table, X = 50 mm; linear scale; slide	
	Temperature at start in °C	Temperature at end in °C
— Machine temperature	24	25
— Ambient temperature	21,9	22,3



Key

1	target right	—○—	ambient temperature in °C
2	target left	—□—	Y scale temperature in °C
3	gap sensor	—△—	machine temperature in °C
4	sensor fixture	—×—	Y slide temperature in °C
5	machine spindle	*t*	time in min
6	machine table	*T*	temperature in °C

Figure 12 — Typical presentation of setup information for the tests of thermal distortion caused my moving linear slides



a) E_{YY} plot

b) E_{CY} plot

c) E_{BY} plot

d) E_{AY} plot

e) E_{XY} plot

f) E_{ZY} plot

Key

▲	P1	*AD*	angular distortion in arcsec
✳	P2	*D*	linear distortion in µm
		t	time in min

Figure 13 — Sample measurement results for measuring the thermal distortion caused by moving linear slides

8 Thermal distortion due to rotary motion of components

8.1 General

This test is carried out to identify the thermal distortion generated by the machine tool rotary positioning system observed between the workpiece and the cutting tool. The test indicates the amount of the change in position and orientation of the rotary component at two angular positions, due to thermal influences on machine tool scales and deformations (twist and bend) of the machine tool structure caused by local generation of heat during the warm-up period. This test is carried out on numerically controlled (NC) machine tools only.

A machine component can maintain its shape during temperature change only if the thermal expansion can be exactly the same in all the points of its structure, i.e. if there were only temperature gradients in time not in space and if the coefficient of thermal expansion (CTE) is the same. But, in practice, there is always a temperature gradient in the machine tool structure in the presence of local heat sources such as electric motors, friction in bearings, couplings, and hydraulics.

Due to thermal gradients, different machine tool components expand in different amounts creating stresses and angular distortions as twist and bend of the machine tool structure.

Measurements described in this clause reveal the influence of all thermal distortions mentioned above at specified position(s) in the work volume. These effects are quantified as the change in the position of a precision sphere mounted with a radial offset with respect to the axis average line of the rotary component.

8.2 Test method

8.2.1 Target positions

For rotary heads and rotary tables with a range of rotation less than 360°, three (equally-spaced) target positions are selected, two of them near the end points of rotary motion. For those with a range of travel more than 360°, four target positions 90° apart from each other are selected to detect:

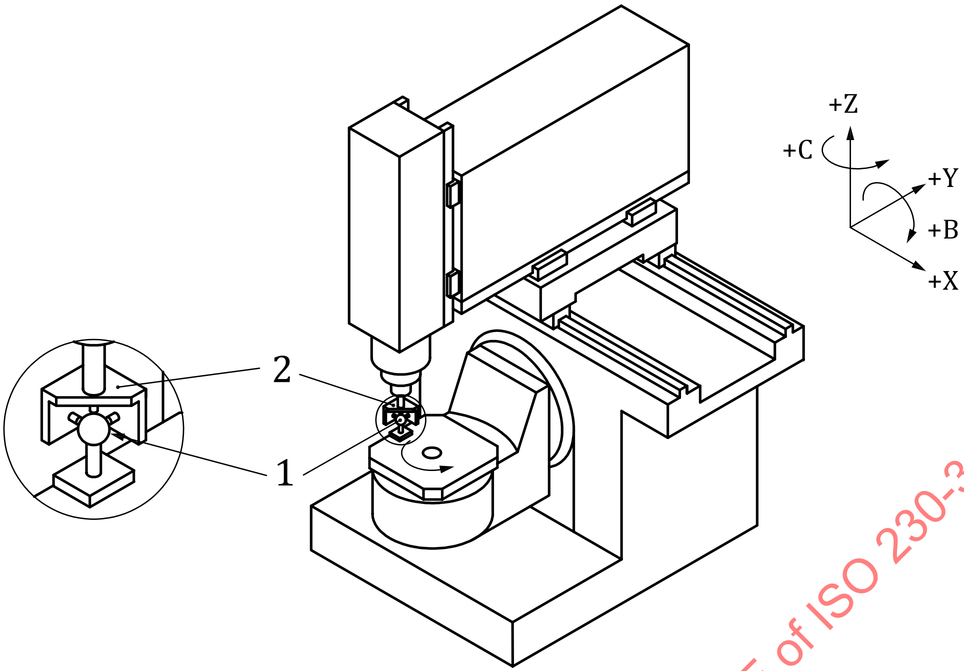
1) linear thermal distortions in X, Y, Z directions;

2) angular thermal distortions in A, B, C directions; and

3) radial thermal distortion.

8.2.2 Test setup

A precision sphere shall be mounted on the rotary component with a radial offset from the axis of rotation. A linear displacement sensor nest holding three sensors (aligned along the machine coordinate axes) shall be mounted at the opposite end of the structural loop to measure displacement between the cutting tool and the workpiece side of the machine tool at the sphere centre. See Figure 14 for an example of setup for rotary tables. Other setups providing similar information are also acceptable (see ISO 230-7).



Key

1 precision sphere

2 special fixture with sensor nest

Figure 14 — Typical setup for measuring thermal distortion caused by a rotary table

Measurements of changes in sphere locations corresponding to target positions of rotary axis, with a range of travel equal to or larger than 360° (P1, P2, P3, P4) shall be taken (see Figure 15). From the corresponding sensor readings at each target position, the change in location, orientation, and the radial and axial distortion of the rotary component are calculated. For a rotary axis along the C-direction, Formulae (55) to (62) can be used to calculate these distortions. It shall be noted that similar results can be obtained using measurement data corresponding to other combinations of target positions.

$$d(E_{\text{XOC}})_{\text{t}} = [(P_{\text{x}1} + P_{\text{x}2})/2]_{\text{t}} - [(P_{\text{x}1} + P_{\text{x}2})/2]_{\text{t}0} \quad (55)$$

$$d(E_{\text{YOC}})_{\text{t}} = [(P_{\text{y}1} + P_{\text{y}2})/2]_{\text{t}} - [(P_{\text{y}1} + P_{\text{y}2})/2]_{\text{t}0} \quad (56)$$

$$d(E_{\text{ZOT}})_{\text{t}} = [(P_{\text{z}1} + P_{\text{z}2})/2]_{\text{t}} - [(P_{\text{z}1} + P_{\text{z}2})/2]_{\text{t}0} \quad (57)$$

$$d(E_{\text{ROT}})_{\text{t}} = [(P_{\text{x}1} + P_{\text{x}2})/2]_{\text{t}} - [(P_{\text{x}1} + P_{\text{x}2})/2]_{\text{t}0} \quad (58)$$

$$d(E_{\text{AOC}})_{\text{t}} = [(P_{\text{z}3} - P_{\text{z}4})_{\text{t}} - (P_{\text{z}3} - P_{\text{z}4})_{\text{t}0}]/l \quad (59)$$

$$\text{or } d(E_{\text{AOC}})_{\text{t}} = [(P_{\text{z}3} - (P_{\text{z}1} + P_{\text{z}2})/2)_{\text{t}} - (P_{\text{z}3} - (P_{\text{z}1} + P_{\text{z}2})/2)_{\text{t}0}]/l' \quad (60)$$

$$d(E_{\text{BOC}})_{\text{t}} = -[(P_{\text{z}1} - P_{\text{z}2})_{\text{t}} - (P_{\text{z}1} - P_{\text{z}2})_{\text{t}0}]/l \quad (61)$$

$$d(E_{\text{COC}})_{\text{P1,t}} = [(P_{\text{y}1} - P_{\text{y}2})_{\text{t}} - (P_{\text{y}1} - P_{\text{y}2})_{\text{t}0}]/l \quad (62)$$

where

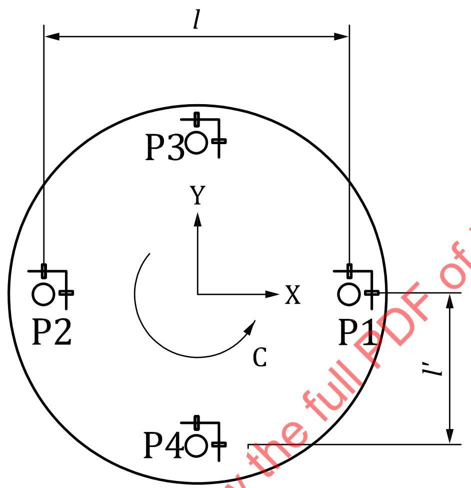
l and *l′* are the distances between the target positions used for angle calculations (e.g., P1 and P2);

t_0 is the beginning of the test period;

t is the end of the axis cycling period;

P_{x1} is the reading of the displacement sensor in the direction of X-axis located at target position P1.

NOTE Movements of other linear axes of the machine tool to bring the precision sphere to the sensor nest are necessary, therefore repeatability of these linear motions affect the measurement results.



Key

P1, P2, P3, P4 measurement target positions

l, *l′* distances between target positions used to calculate angular distortions

Figure 15 — Example setup for a rotary table with 360° rotation with four target positions P1 through P4 (only two sensors shown for the sensor nest)

8.2.3 Test cycle

The test cycle is made of two periods of time, 4 h of rotary axis cycling and 1 h cooling down. The measurements may be interrupted when the distortion change noted during the last 60 min is less than 15 % of the distortion registered over the first hour of the test. In situations where a set pattern of activity (for example periodic tool setting) is observed, the tests shall be carried out over a period of time during which relevant events are repeated or over any other period of time agreed between the supplier/manufacturer and the user. Sufficient time shall be allocated after each test to allow for the machine tool to cool down.

Starting from target position P1, where the machine tool remains at rest long enough (dwell time) to record the readings of the displacement sensors, the rotary component shall be programmed to move to the target positions P2, and P3 (and P4 if applicable), where the corresponding set of displacement readings are taken after moving the sensor nest to these positions via linear axes motion. After the measurements in P1 are recorded, the sensor nest is disengaged from the target sphere and the rotary table is moved to target position P2. The sensor nest is then moved to this position via linear axes motion. The rotary component is then rotated continuously for a period of time after which displacement readings at target positions are taken. The period of continuous rotation is based on the agreement between the user and the supplier/manufacturer. This test sequence shall then be repeated until the end of the axis cycling period, recording data at the target positions. The programmed rotation speed shall be a percentage of the maximum programmable rotation speed. The dwell time at each target position shall be the minimum required for taking the readings. The percentage and the dwell time shall be specified in machine specific standards. Different dwell times and rotation speeds have different heat input, and can consequently cause different amounts of thermal distortion. The dwell time and the rotation speed in these tests may be modified based on agreements reached between the user and the supplier/manufacturer.

The exact procedure of the measurements shall be reported.

At the end of the axis cycling period, the rotary component shall be stopped at the first target position; every 5 min it shall be moved to all other target positions to take readings, and then stopped again at the first position, until the end of the cool down period.

8.2.4 Temperature measurements

Temperature measurements in some points of the machine tool can be helpful for the correct interpretation of the results. For example, the rotary component temperature increase can be mainly responsible for the linear expansion, whereas the temperature increase of the bearing surfaces and the consequent temperature gradient inside the fixed part (bed or column) can be mainly responsible for the bending distortions.

Useful positions for the temperature sensors can be selected as follows:

— angular position transducer (if possible);

— an area close to the friction sources (usually the temperature increases between the rotor and the stator, due to friction in the bearings);

— an area in the opposite side of the machine tool structure (e.g., bottom of the bed);

— table;

— spindle head.

Ambient temperature should be monitored at least once every 5 min[7)] during these tests.

8.2.5 Presentation of results

For each rotary axis of the machine tool, plots of the three linear and angular distortions (X, Y, Z, A, B, C), and radial distortion versus time (corresponding to the machine X-, Y-, and Z-axes) shall be presented.

In each of these plots, the quantities of variations from the starting values as opposed to absolute values shall be indicated.

In addition, the plots of the environment temperature and the machine temperatures measured during the test versus time shall be provided. The results are influenced by the positioning repeatability of the machine axis under test and the machine axes moved to take the measurements.

An example set of such plots is shown in Figure 16.

The following parameters shall be reported along with the plots:

a) rotary traverse speed;

b) dwell times;

c) start and end point positions;

d) radial offset of the target sphere;

e) axial offset of the target sphere (if applicable);

7) Some temperature compensation systems show cycle times shorter than 5 min. In such cases, the frequency for monitoring can be increased accordingly.

f) compensation capabilities and facilities used;

g) instrument and setup used;

h) temperature sensor location;

i) coefficient of thermal expansion used (if applicable);

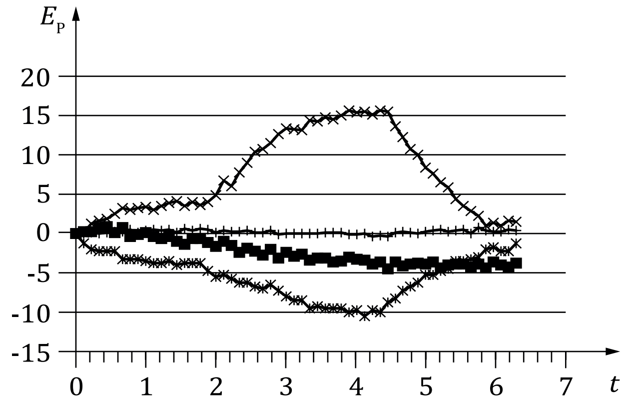
j) time and date of the test;

k) warm-up procedures (including the time period of warm-up procedures);

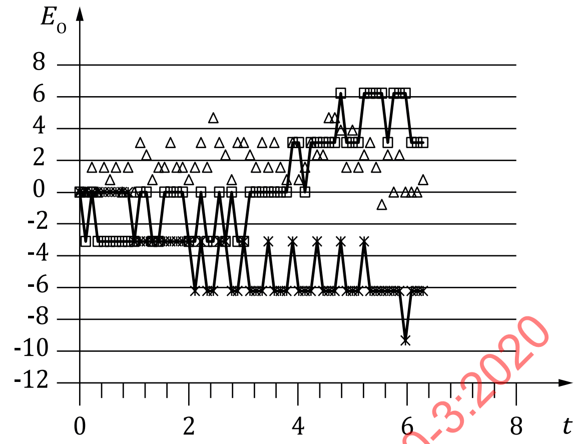
l) temperature of the measured object at the beginning and end of test;

m) positive direction of position deviation, if different from the coordinate systems shown in Figures 1, 2, 3, 8 and 9;

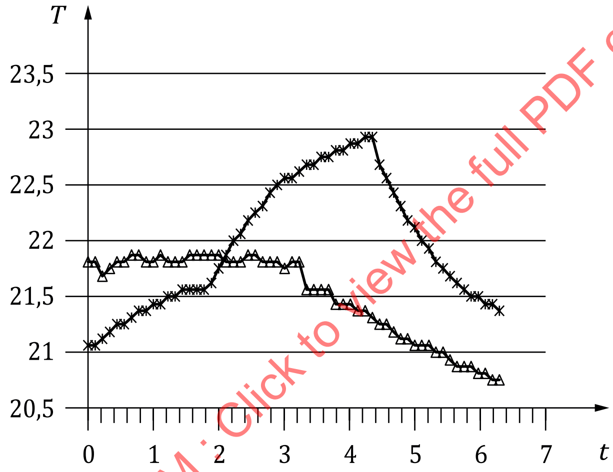
n) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers.



a) Position and size error due to thermal distortion



b) Orientation error due to thermal distortion



c) Temperature change during testing

Key

t	time in h	—+—	E_{X0C} position error of C axis in X direction
T	temperature in °C	—×—	E_{Y0C} position error of C axis in Y direction
—△—	TE environment temperature in °C	—✳—	E_{Z0T} displacement of the rotary table in axial direction
—×—	TW workspace temperature in °C	—■—	E_{R0T} expansion of rotary table in the radial direction
E_P	position error in µm	—□—	E_{A0C} orientation error of C axis around X axis
E_0	orientation error in µm/m	—✳—	E_{B0C} orientation error of C axis around Y axis
		—△—	E_{C0C} orientation error of C axis around C axis

Figure 16 — Sample measurement results for measuring thermal distortion caused by rotating machine components

Annex A
(informative)

Information on linear displacement sensors

A.1 General

There are three categories of linear displacement sensors that are commonly used to carry out the measurements described in this document: mechanical, electronic and optical sensors.

A.2 Mechanical sensors

A.2.1 General

Mechanical sensors consist of a body with a circular graduated dial and a contact point connected with a spiral or gear train, so that the hand on the dial face indicates the amount of movement of the contact point. Ordinary tests can be made with 0,01 mm resolution mechanical sensors but, for more precise tests, mechanical sensors with 0,001 mm resolution should be used.

A.2.2 Precautions in use

It is emphasized that the principal characteristics of these instruments are:

a) the non-linearity;

b) large hysteresis;

c) the extreme values of the measuring force at the beginning and end of the stroke of the stylus;

d) the maximum local variation of the measuring force (this force generally has different values for the in-and-out movements of the plunger at every position in the stroke);

e) the repeatability when used upside down.

Dial gauges with a short stroke are recommended and, in particular, those with low hysteresis and a light contact force.

If mechanical sensors are used for testing thermal distortion caused by rotating spindle, the test mandrel need to be centred, or the readings are always to be taken at the same angular position of the spindle.

A.3 Electronic sensors

A.3.1 General

Contact or non-contact type electronic sensors produce digital or analog output, which is proportional to the amount of movement of its gauge head or its target. Three common types of electronic sensors are linear variable differential transformers (LVDT), eddy current sensors and capacitance sensors. Electronic sensors with resolutions of 0,001 mm or better are used for the tests described in this document.

A.3.2 Contact-type electronic sensors

A.3.2.1 General

Contact type sensors require that sensor stylus touch the target surface, displacement of which is to be measured. Examples of such sensors are LVDTs and incremental length gauges. LVDT provides analog output proportional to the displacement of its stylus. Incremental length gauge uses a linear encoder (magnetic or optical) to measure the displacement of the stylus and provides digital output.

A.3.2.2 Precautions in use

Supports for mechanical and electronic probes are of sufficient stiffness to prevent unwanted errors. The stylus of the plunger type electronic probe is set perpendicular to the surface to be checked to avoid inaccuracies.

A.3.3 Non-contact-type electronic sensors

A.3.3.1 Eddy current sensors

A.3.3.1.1 General

The eddy current principle has a special place in the group of inductive measuring methods. The principle is based on the loss of energy from an oscillator circuit caused by the generation of eddy currents in an electrically conductive target. If a coil built into the sensor is fed with high frequency alternating current and the sensor is positioned in close proximity to a metal plate, the electromagnetic field of the sensor coil creates eddy currents in this target.

A.3.3.1.2 Precautions in use

Output signal and linearity is dependent on the electrical and magnetic properties of the test mandrel and its surface condition.

Individual linearization and calibration are required.

Due to the high oscillator frequency, the maximum length of the sensor cable is restricted to approximately 12 m to 18 m.

A.3.3.2 Capacitance sensors

A.3.3.2.1 General

Capacitive displacement measurement systems are based on the functioning of ideal plate capacitors. If the distance between the two capacitor electrodes varies, the voltage value of the capacitor changes accordingly. In a non-contact displacement measurement application, the two plate electrodes consist of the sensor and the target. If the sensor capacitor electrode is fed with an alternating current of constant frequency, then the amplitude of this alternating current is proportional to the distance from the sensor electrode to the target. The target functions as the ground electrode.

A.3.3.2.2 Precautions in use

This system is sensitive to changes of the dielectric in the measurement gap and is therefore useable in a clean and dry environment only.

The maximum sensor cable length is restricted by the influence of the cable on the oscillating circuit.

The measuring distance increases proportionally with the sensor diameter; the diameter of the measuring spot increases accordingly.

A.4 Optical sensors

A.4.1 Laser optical triangulation measurement sensors

A.4.1.1 General

A pulsed laser beam is projected onto the target surface and from there is reflected back to a receiver in the same housing as the transmitter.

A.4.1.2 Precautions in use

This system is somewhat dependent on the surface texture of the test object.

A clean environment is required for the transmission and reflection of the beam.

The dimensions of the sensor are important (compared to the eddy current and capacitive sensors).

A.4.2 Laser scanning micrometre

A.4.2.1 General

This instrument was originally designed to measure wire and tube diameters. The system consists of a laser light source, beam scanning prism, rotation angle measuring system, time base and two coupled CCD arrays that detect the beam position. The target diameter and its centre position are calculated from the beam position and prism rotating speed. One system can measure both the centre position of the mandrel and its diameter, so that it is possible to detect any change in the position of the machine tool spindle axis average line.

A.4.2.2 Precautions in use

The accuracy and its repeatability depend on the averaging numbers. If an accuracy better than 0,001 mm is requested, more than 100 measurements are required. The laser source requires warm-up time, preheating is also required for precise measurement.

A.5 Temperature stability test for linear displacement sensors

The temperature stability of sensors for thermal tests is important. Some displacement sensors are made up of different kinds of materials. This mixture generates complex thermal distortion of the sensors. Before using the sensor system for the thermal tests described in this document, the thermal behaviour of the sensor system itself is tested.

The basic test procedure (so-called cap test) is as follows:

a) prepare special jigs that hold the sensor body and its target rigidly. The material of the jigs should be of two types. The first jig, made of steel, is used for checking the sensor's distortion relative to steel components that are usually used for machine tool and measurement fixture construction. The second jig, made of low expansion material, is used to detect the sensor's absolute distortion;

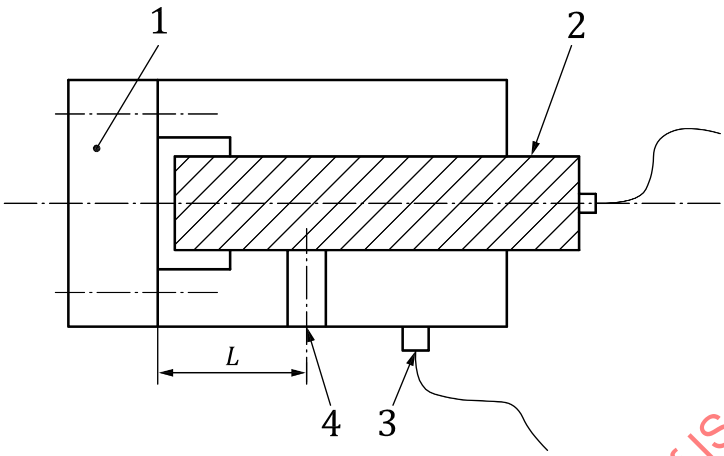
b) attach the sensor to be tested to the special jig. The distance, L, between the fixing point and the target surface should be the same as in the measurement setup to be used in actual test procedures (see Figure A.1). This distance directly affects the thermal distortion of the measurement system;

c) attach the temperature sensor onto the jig surface to measure its temperature change;

d) place the test system in an environmental chamber (an enclosure with variable controlled temperature) or any other temperature changeable environment;

e) artificially change the temperature and check the sensor output and temperature. The rate of change of temperature is set to be slow to allow all components of the tested system to reach the same temperature. Several temperature-changing cycles can be performed to identify the sensor's expansion coefficient, non-linearity and time lag;

f) in some cases, the amplifier unit of the sensors can also have some temperature influence. Therefore, it is useful to check the amplifier's performance by applying the same test procedure.



Key

1 target (CAP)

2 linear displacement sensor

3 temperature sensor

4 fixing bolt

L distance between fixing point of the linear displacement sensor and the target surface

Figure A.1 — Typical setup for sensor cap test