INTERNATIONAL STANDARD

ISO 230-3

Second edition
2007-08-15

Test code for machine tools —

Part 3: Determination of thermal effects

Code d'essai des machines-outils —

Partie 3: Évaluation des effets thermiques

Reference number
ISO 230-3:2007(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword iv
Introduction v
1 Scope 1
2 Normative references 1
3 Terms and definitions 2
4 Preliminary remarks 5
4.1 Measuring units 5
4.2 Reference to ISO 230-1 5
4.3 Recommended instrumentation and test equipment 5
4.4 Machine conditions prior to testing 6
4.5 Test sequence 6
4.6 Test environment temperature 6
5 ETVE test 7
5.1 General 7
5.2 Test method 10
5.3 Interpretation of results 11
5.4 Presentation of results 14
6 Thermal distortion caused by rotating spindle 15
6.1 General 15
6.2 Test method 15
6.3 Interpretation of results 17
6.4 Presentation of results 19
7 Thermal distortion caused by linear motion of components 19
7.1 General 19
7.2 Test method 20
7.3 Presentation of results 26
Annex A (informative) Linear displacement sensors 30
Annex B (informative) Guidelines on the required number of linear displacement sensors 35
Annex C (informative) Guidelines for machine tool thermal environment 38
Annex D (informative) Alternative measurement devices and set-ups 40
Bibliography 44

Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 230-3 was prepared by Technical Committee ISO/TC 39, *Machine tools*, Subcommittee SC 2, *Test conditions for metal cutting machine tools*.

This second edition cancels and replaces the first edition (ISO 230-3:2001), which has been technically revised.

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

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

— *Part 2: Determination of accuracy and repeatability of positioning 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 9: Estimation of measurement uncertainty for machine tool tests according to series 230, basic equations* [Technical Report]

The following part is under preparation:

— *Part 8: Determination of vibration levels* [Technical Report]

Determination of the measuring performance of a machine tool is to form the subject of a future part 10.

Introduction

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

This part of ISO 230 specifies test procedures for determining 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 part of ISO 230 are not intended to simulate the normal operating conditions, but to facilitate performance estimation and the determination of the effects of environment on machine performance. For example, use of coolants may significantly affect the actual thermal behaviour of the machine. Therefore, these tests should be 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 or contraction of relevant structural elements.

The tests specified in this part of ISO 230 can be used either for testing different types of machine tool (type testing) or 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. The mere reference to this part of the test code for the acceptance tests, without agreement on the parts to be applied and the relevant charges, cannot be considered as binding for one or other of the contracting parties. One significant feature of this part of ISO 230 is its emphasis on environmental thermal effects on all the performance tests described in other parts of ISO 230 related to linear displacement measurements (such as linear displacement accuracy, repeatability and the circular tests). The supplier/manufacturer will need to provide thermal specifications for the environment in which the machine can be expected to perform with the specified accuracy. The machine user will be responsible for providing a suitable test environment by meeting the supplier's/manufacturer's thermal guidelines or otherwise accepting reduced performance. An example of environmental thermal guidelines is given in 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 supplier's/manufacturer's thermal guidelines. If the machine does not meet the performance specifications, the analysis of the combined standard thermal uncertainty provides help in identifying sources of problems. Combined standard thermal uncertainty is defined in 3.6, as well as in ISO/TR 16015.

Test code for machine tools —

Part 3: Determination of thermal effects

1 Scope

This part of ISO 230 defines three tests for the determination of thermal effects on machine tools:

— 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.

The test for thermal distortion caused by moving linear axes (see Clause 7) is applicable to numerically controlled (NC) machines only and is designed to quantify the effects of thermal expansion and contraction as well as the rotational deformation of structure. For practical reasons, it is applicable to machines with linear axes up to 2 000 mm in length. If used for machines with axes longer than 2 000 mm, it will be necessary to choose a representative length of 2 000 mm in the normal range of each axis for the tests.

The tests correspond to drift tests according to ISO/TR 16015 and define the evaluation and the detailed procedure for machine tools.

NOTE It is not foreseen that numerical tolerances will be determined for the tests specified in this part of ISO 230.

2 Normative references

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

ISO 1:2002, *Geometrical Product Specifications (GPS) — Standard reference temperature for geometrical product specification and verification*

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

ISO/TR 16015:2003, *Geometrical product specifications (GPS) — Systematic errors and contributions to measurement uncertainty of length measurement due to thermal influences*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TR 16015 and the following apply.

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

3.2
coefficient of thermal expansion
α
ratio of the fractional change of the length of a measured object or of the scale of length test equipment to the change in temperature

NOTE For the purposes of this part of ISO 230, a range of temperature from 20°C to T is considered; the following expression is used:

$$\alpha(20,T) = \frac{L_T - L_{20}}{L_{20} \cdot (T - 20)}$$

where L is the length of a measured object or of a portion of the scale of a length test equipment.

3.3
nominal coefficient of thermal expansion
α_n
approximate value for the coefficient of thermal expansion 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 could reasonably be attributed to the coefficient of thermal expansion

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

3.6
nominal thermal expansion
Δ_NE
estimate of the thermal expansion of a measured object or a portion of the scale of length test equipment from 20°C to their average temperatures at the time of measurement

NOTE This estimate is based on nominal coefficients of thermal expansion:

$$\Delta_\mathrm{NE} = \alpha_n \cdot L \cdot (T - 20)$$

3.7
uncertainty in nominal thermal expansion due to uncertainty in α
u_{Δ_NE}
uncertainty in the nominal thermal expansion arising from uncertainty in the coefficient of thermal expansion

NOTE This uncertainty can be calculated by

$$u_{\Delta_\mathrm{NE}} = L \cdot (T - 20) \cdot u_\alpha$$

3.8
uncertainty of length due to temperature measurement
u_{TM}
uncertainty in a measured length due to the uncertainty of the temperature at which the length measurement was made

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
u_{NDE}
combined uncertainty caused by the uncertainties of thermal expansion of the measured object and that of the test equipment

NOTE 1 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:

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

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 For evaluation of uncertainly, see ISO/TR 16015:2003, 5.3.4.

3.11
environmental temperature variation error
ETVE
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 ETVE(Z, 8 °C) indicates that the ETVE value is obtained along the Z direction and the value corresponds to an environmental temperature variation of 8 °C.

NOTE It is recognized that ISO terminology normally requires the term *deviation* instead of *error* in this term. However, due to the long history of ETVE usage, it was decided to treat it as an exception.

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 It is calculated as the square root of the square of ETVE divided by 12 (see ISO TR 230-9):

$$u_{ETVE} = \sqrt{\frac{\text{ETVE}^2}{12}}$$

NOTE 2 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 This term is equivalent to *combined standard dimensional uncertainty due to thermal effects* as defined in ISO/TR 16015.

NOTE 2 It is a combination by square root of sum of squares of uncertainty of environmental temperature variation error (u_{ETVE}), length uncertainty due to temperature measurements (u_{TM}) and the uncertainty of nominal differential thermal expansion (u_{NDE}):

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

NOTE 3 A detailed description of the estimation of the combined standard thermal uncertainty is given in ISO/TR 16015.

3.14
drift $d(\alpha O \beta)_{xx,60}$
range of linear or angular displacement of axis average line of spindle β in the direction of α within the first 60 min of the tests for thermal distortion caused by rotating spindle (at position xx)

EXAMPLE The notation $d(XOC)_{P1,60}$ indicates that the drift of axis average line of spindle C in direction X at position P1 (away from the spindle nose) is referenced.

NOTE 1 Possible notations for α are X, Y, Z, A, B. 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 and B).

NOTE 2 For notation $\alpha O \beta$, see ISO 230-7.

3.15
drift $d(\alpha O \beta)_{xx,t}$
range of linear or angular displacement of axis average line of spindle β in direction of α within the total spindle running period, t, of the tests for thermal distortion caused by rotating spindle (at position xx)

EXAMPLE The notation $d(XOC)_{P1,t}$ indicates that the drift of axis average line of spindle C in direction X at position P1 (away from the spindle nose) is referenced.

NOTE 1 Possible notations for α are X, Y, Z, A, B. 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 and B).

NOTE 2 For notation $\alpha O \beta$, see ISO 230-7.

3.16
drift $d(\alpha O \gamma)_{xx,60}$
range of linear or angular displacement, in the direction of α, of moved machine component along linear axis γ within the first 60 min of the tests for thermal distortion caused by moving linear axis (at position xx)

EXAMPLE The notation $d(BOX)_{1,60}$ indicates that the drift of linear axis X in direction B (rotation around Y) at target position 1 (right position in Figure 8) is referenced.

NOTE 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: 1 and 2, xx might be also expressed in words, e.g. left and right.

3.17
drift $d(\alpha O \gamma)_{xx,t}$
range of linear or angular displacement of moved machine component along linear axis γ in direction α within the total moving period, t, of the tests for thermal distortion caused by moving linear axis

EXAMPLE The notation $d(\text{BOX})_{1,t}$ indicates that the drift of linear axis X in direction B (rotation around Y) at target position 1 (right position in Figure 8) is referenced.

NOTE 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 1 and 2; xx might be also expressed in words, e.g. left and right.

4 Preliminary remarks

4.1 Measuring units

In this part of ISO 230, 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. The equivalent of the following expressions should always be kept in mind:

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

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

4.2 Reference to ISO 230-1

For the application of this part of ISO 230, refer to ISO 230-1, especially for the installation of the machine before testing and for accuracy of test equipment.

4.3 Recommended instrumentation and test equipment

The measuring instruments recommended here are only 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 application of Clauses 5 to 7:

a) 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);

b) temperature sensors (e.g. thermocouple, resistance or semiconductor thermometer) with adequate resolution and measurement uncertainty;

c) 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 permissible if a computer system is not available.

d) test mandrel, preferably made of steel, with the design to be specified in machine-specific standards or agreed between supplier/manufacturer and user, see ISO 230-1:1996, A.3;

---

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

e) fixture in which to mount the displacement sensors, preferably made of steel, with the design to be specified in machine-specific standards or agreed between the supplier/manufacturer and the user, and with a design that should minimize local distortions caused by temperature gradients in the fixture;

f) 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 drift tests (see A.5).

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

4.4 Machine conditions prior to testing

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

The machine shall be powered up with auxiliary services operating and axes in the "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 and the measuring instruments shall be protected from draughts and external radiation such as those from overhead heaters or sunlight.

All tests shall be carried out with the machine in the unloaded condition. Where testing a machine involves rotating both the workpiece and the tool on separate spindles, the tests in accordance with Clauses 5 and 6 shall be carried out for each spindle with respect to a common fixed location on the machine 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 their usage recorded.

4.5 Test sequence

The tests given in Clauses 5 to 7 may be used either singly or in any combination.

4.6 Test environment temperature

In accordance with ISO 1, all dimensional measurements shall be made when the measuring instruments and the measured objects (for example, a machine tool) are in equilibrium with the environment, with the temperature maintained 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 in order to correspond with those for 20 °C. 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, since the aim in this part of ISO 230 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 the machine tool shall be used; additional NDE correction only for the measurements shall not be used to correct the thermal distortions of machine scales.

5 ETVE test

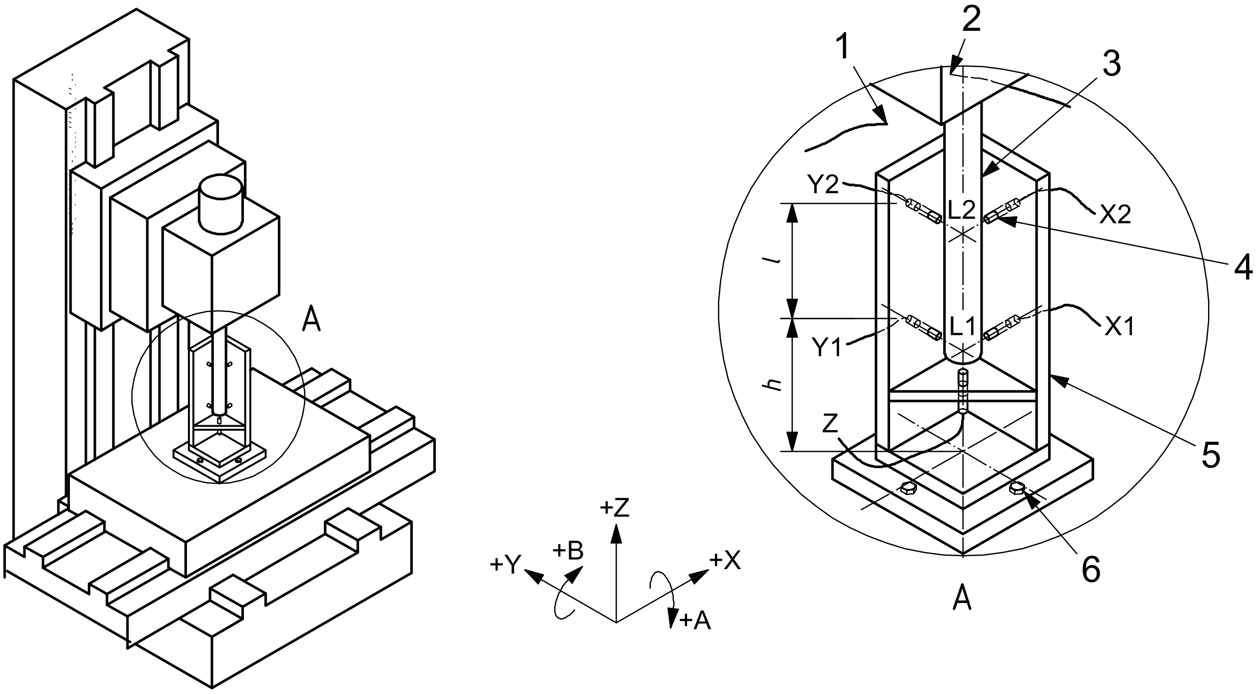
5.1 General

An ETVE test is designed to reveal the effects of environmental temperature changes on the machine and to estimate the thermally induced error during other performance measurements. Such tests shall not be used for machine comparison. The ETVE shall be determined by the drift test using the procedure given 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 where the workpiece is normally located. The use of such facilities shall be recorded.

It is recommended that the supplier/manufacturer offer guidelines on the thermal environment which can be considered as acceptable for the machine to perform in with the specified accuracy. Such general 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 (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, u_{CT}, 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 upon between the user and the supplier/manufacturer.

It is a requirement that the machine axes be powered up and in the “Hold” position (see 4.4.). 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. This condition shall be stated in the test report.



Key

1 ambient air temperature sensor

2 spindle bearing temperature sensor

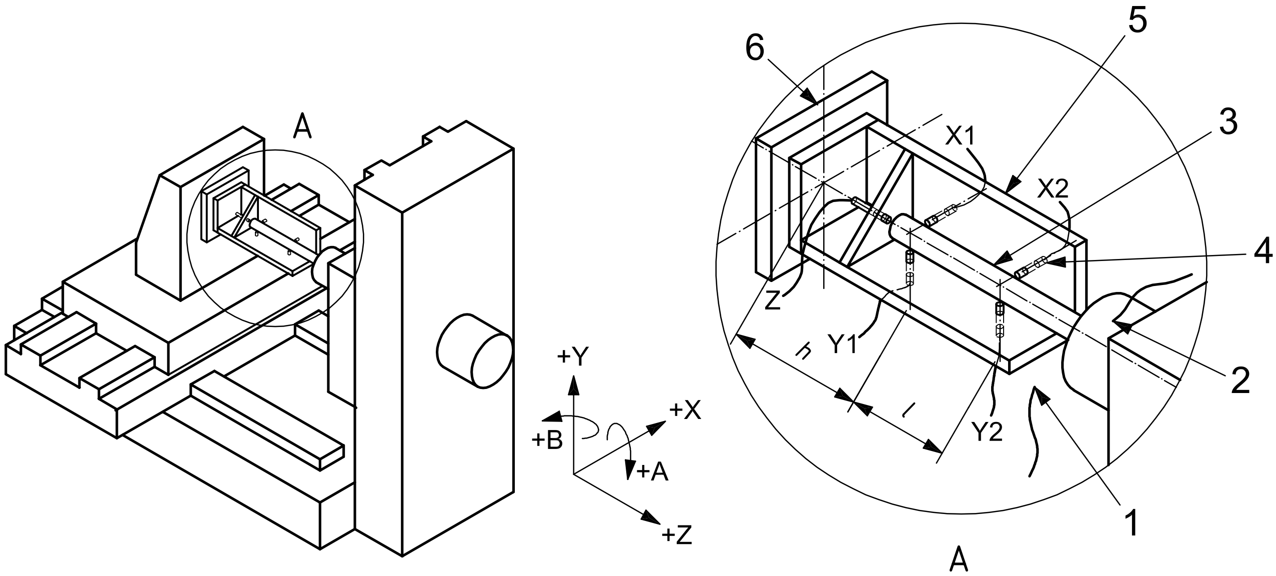
3 test mandrel

4 linear displacement sensors

5 fixture

6 fixture bolted to table

Figure 1 — Typical set-up for testing ETVE and thermal distortion of structure caused by rotating spindle and by moving linear axis on vertical spindle machining centre



Key

1 ambient air temperature sensor

2 spindle bearing temperature sensor

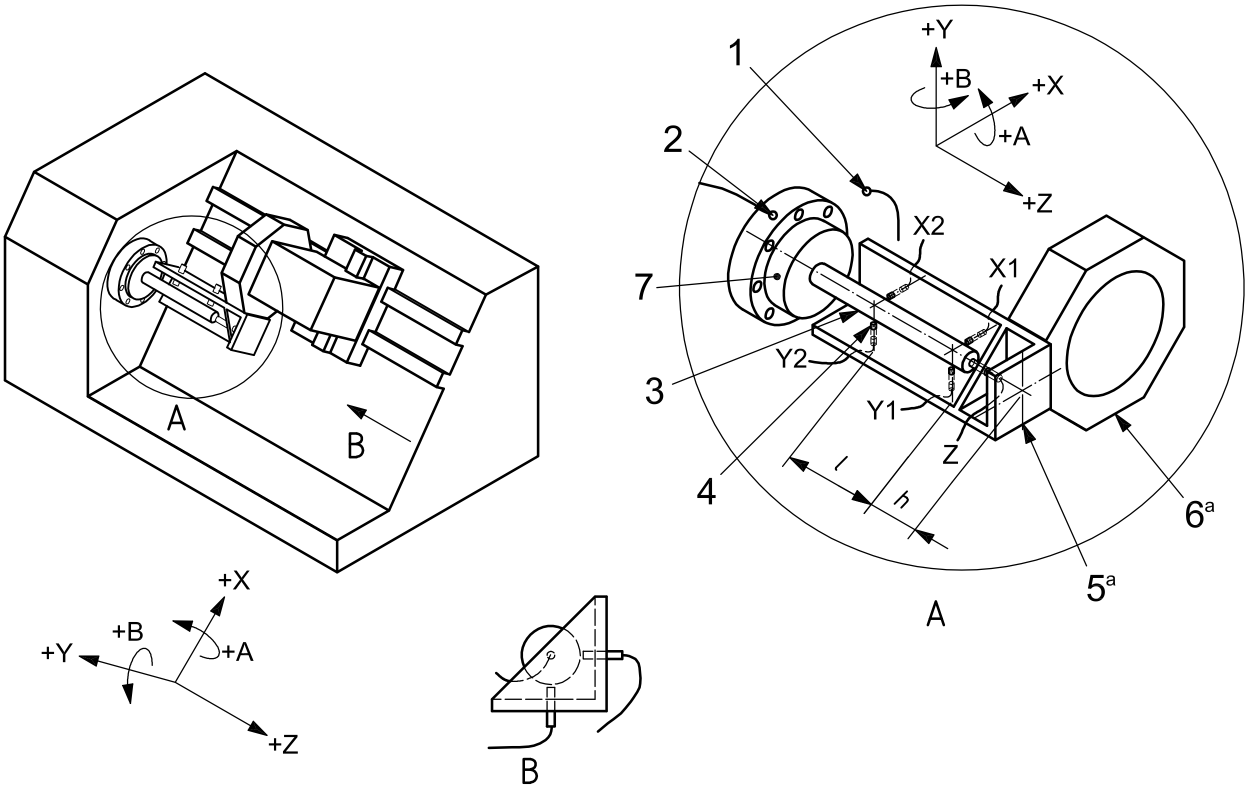
3 test mandrel

4 linear displacement sensors

5 fixture

6 fixture bolted to table

Figure 2 — Typical set-up for testing of ETVE and thermal distortion of structure caused by rotating spindle and by moving linear axis on horizontal spindle machining centre



Key

1 ambient air temperature sensor

2 spindle bearing temperature sensor

3 test mandrel

4 linear displacement sensors

5 fixture

6 turret

7 chuck

a Rotated for clarity.

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

5.2 Test method

Figures 1, 2 and 3 show typical measurement set-ups for a vertical- and horizontal-spindle machining centre and a turning centre, respectively. For this test, the fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating workholding or tool-holding zone of the machine so as to measure the following:

a) the relative displacements between the component that holds the 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 set-up shall be recorded along with the test results;

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

The temperature of the machine structure — as close as possible to the front spindle bearing or at a point agreed upon 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 structure.

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

Once set up, the drift 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.

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 example illustrated by Figure 4. However, this resultant plot shall not be used for the purposes of machine comparison. The ETVE values obtained from such a plot are used for considering the combined standard thermal uncertainty in measurements such as linear displacement accuracy 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 with the conditions in which ETVE values were obtained, the ETVE results are to be considered null and void for that measurement process. In these cases, a re-evaluation of ETVE should be conducted, or conditions corrected to those for which the ETVE applies [3]. In addition, measuring instruments shall be thermally stabilized.

Measurements in different directions should use different ETVE values obtained from the same plot. For example, linear displacement measurements along the Z axis of the machine should use the maximum range of thermal distortion in the Z direction for the period of time it takes to carry out the linear displacement measurements as the ETVE(Z) value. The ETVE(Y) and ETVE(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, the maximum value of ETVE(X) and ETVE(Y) is generally taken as the ETVE 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, 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 facing the same direction. The following formulae are used for these calculations:

$$A = (Y1 - Y2)/l$$

$$B = (X1 - X2)/l$$

ETVE(A) = maximum range of A

ETVE(B) = maximum range of B

The resulting values should be represented according to the ISO 841 sign convention.

In order to determine ETVE for a given performance test (for example, for a given direction of measurement) on a machine tool, an interval on the ETVE plot that is as long as the time period corresponding to that

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

3) Maximum variations of ambient temperature measured during machine performance tests should be smaller or equal to the change of ambient temperature measured during ETVE tests.

performance test and that has the maximum slope must be identified. The maximum variation observed within that time interval becomes the effective ETVE value for that test. For example, referring to Figure 4, ETVE(X) for the linear positioning test of a machine tool that lasts about 1 h is determined by the time interval 90 min to 150 min on the time scale. The ETVE value for this test obtained from the plot in that interval is 0,001 5 mm.

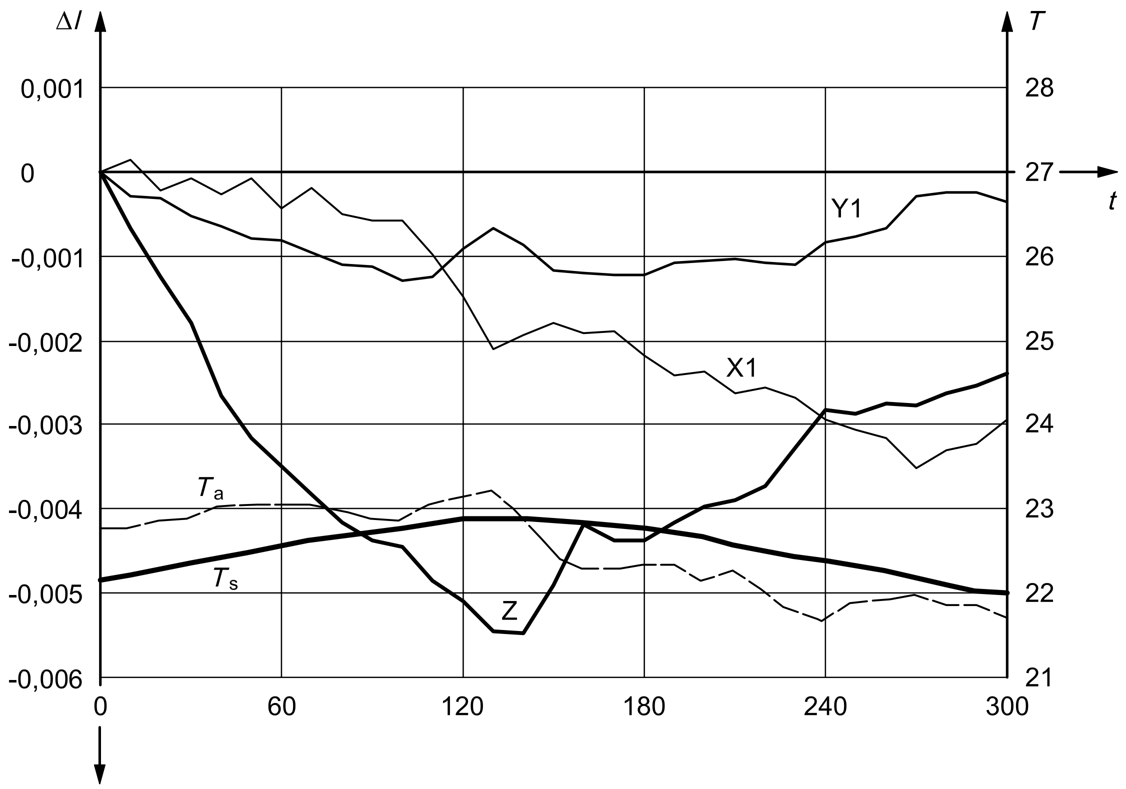
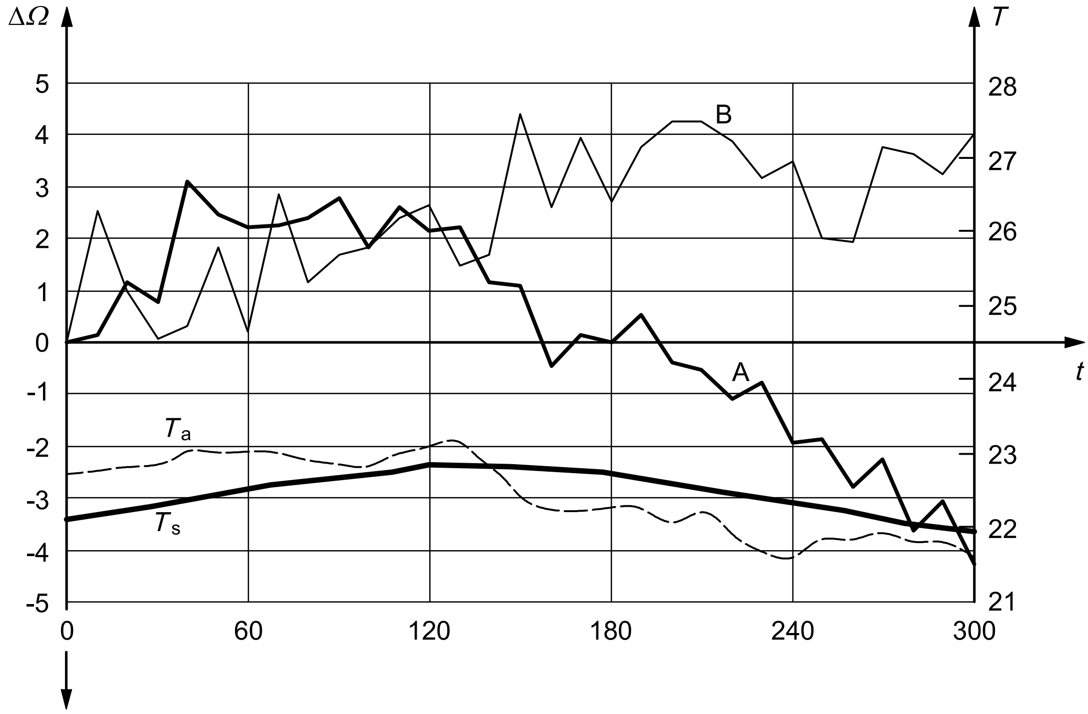


Figure 4 — Temperature and distortion versus time for ETVE test



Key

A rotation around X

B rotation around Y

Δl linear distortion, mm

$\Delta\Omega$ angular distortion, arcseconds (″)

X1 linear displacement along X axis at position L1

Y1 linear displacement along Y axis at position L1

T temperature, °C

T_a ambient temperature, °C

T_s spindle temperature, °C

t time, min

Z linear displacement along Z axis

EXAMPLE For a test that takes 1 h, the following ETVE values are obtained from the above graphs:

$ETVE_{X;\ 1,1\ °C}$ = 0,001 5 mm (90 min to 150 min)

$ETVE_{A;\ 1,1\ °C}$ = 3″ (110 min to 170 min)

$ETVE_{Y;\ 0,6\ °C}$ = 0,000 8 mm (230 min to 290 min)

$ETVE_{B;\ 1,1\ °C}$ = 3″ (110 min to 170 min)

$ETVE_{Z;\ 0,4\ °C}$ = 0,003 5 mm (0 min to 60 min)

Figure 4 *(continued)*

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 ETVE values for each direction should be recorded to indicate the amount of temperature variation during the observation period, for example ETVE(Z; 1,2 °C) = 0,001 mm.

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

a) location of the measurement set-up (coordinates of position L1, see Figure 5);

b) distance between spindle face and L1;

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 upon;

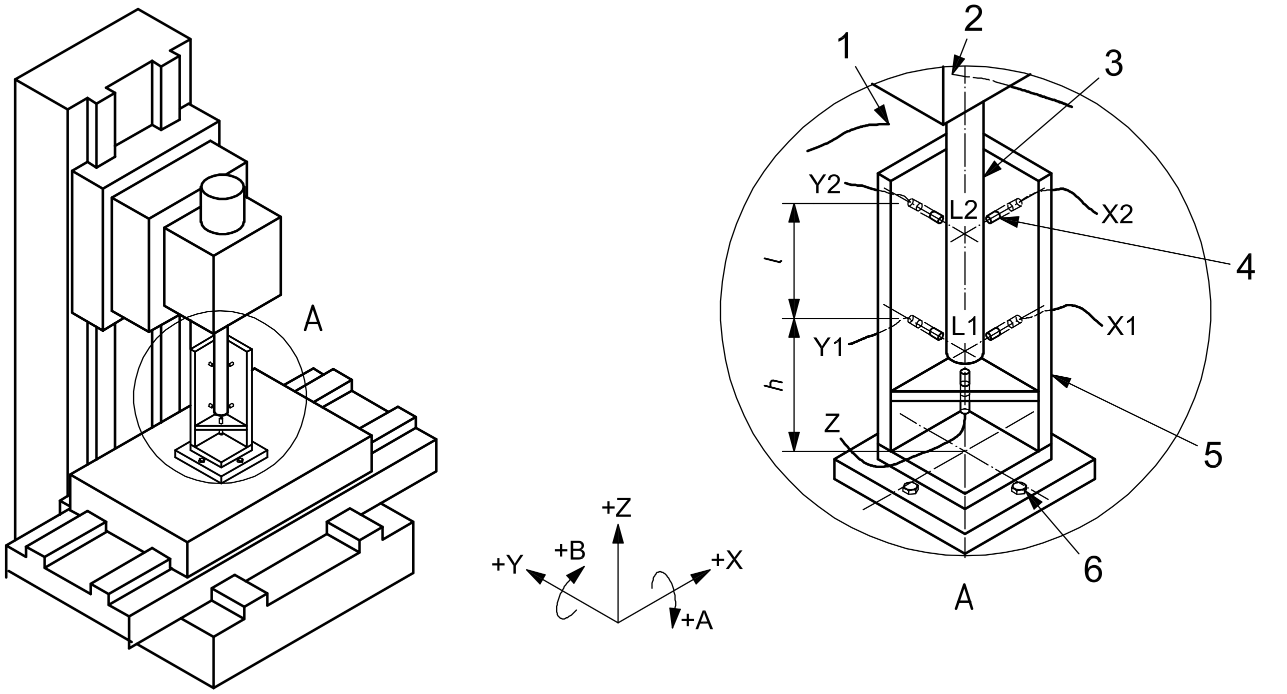
h) time and date of the test;

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).

Date of test:	YY/MM/DD
Machine:	AAA, vertical spindle 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:	steel, $11 \cdot 10^{-6}$ °C^{-1}, ∅ 60 mm, length 200 mm, No. 40 taper
Fixture:	steel, $11 \cdot 10^{-6}$ °C^{-1}, 400 × 100 × 100, fixed on the table centre
Thermal compensation used:	oil cooler with spindle temperature sensor
Warm-up procedures:	cold start
Axes slide position:	X = 500 mm, Y = 300 mm, Z = 400 mm, C = 0
Measuring position L1:	X = 500 mm, Y = 300 mm, Z = 220 mm (height from table surface)
Distance between spindle face and L1	175 mm
Sensor distance, l (L2, L2)	150 mm



Key

1 ambient air temperature sensor

2 spindle bearing temperature sensor

3 test mandrel

4 linear displacement sensors

5 fixture

6 fixture bolted to table

NOTE Dimensions of test mandrel and fixture are shown by way of example only.

Figure 5 — Typical presentation of set-up information for tests of ETVE and thermal distortion caused by rotating spindle and 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 structure observed between the workpiece and the 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 set-ups for a vertical- and horizontal-spindle machining centre and a turning centre, respectively. For this test, the fixture in which the linear displacement sensors are mounted shall be securely fixed to the non-rotating workholding or tool-holding zone of the machine so as to measure the following:

a) the relative displacements between the component that holds the tool and the component that holds the workpiece along the three orthogonal axes parallel to the axes of travel of the machine, e.g. for a C-axis, *d*(XOC), *d*(EYC), and *d*(ZOC); the exact position of the measurement set-up shall be recorded along with the test results; the specific location of the measurement set-up in the work zone should be provided in the machine-specific standards;

b) tilt or rotation around the X and Y axes of the machine tool, e.g. for a C-axis, *d*(AOC) and *d*(BOC).

The temperature of the machine structure, as close as possible to the front spindle bearing, and the ambient air temperature in the close vicinity of the machine 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 to avoid any influence by the heating up of the machine (e.g. 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 structure.

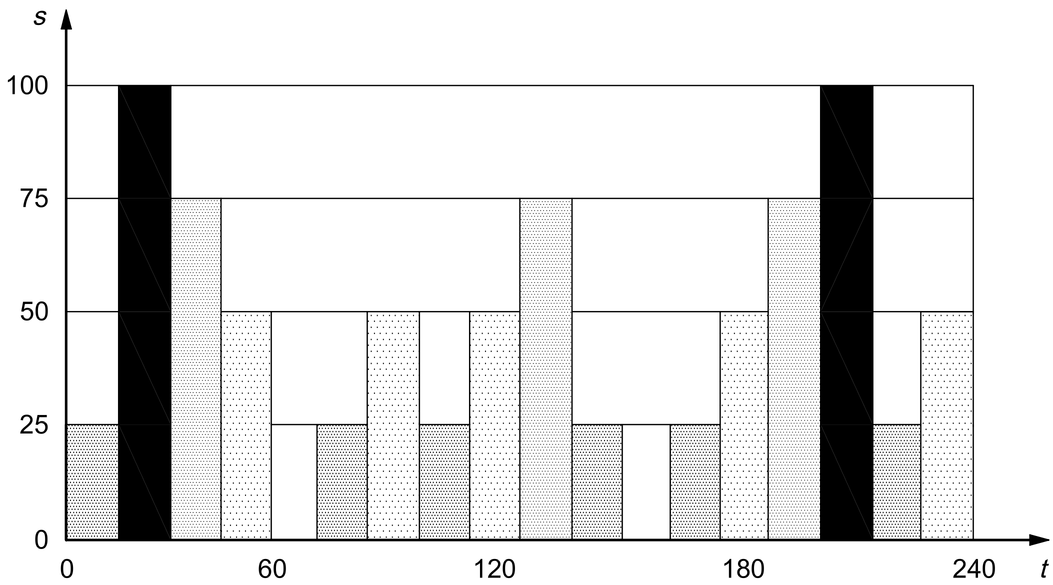
The test procedure should follow one or the other of the following two spindle speed regimes:

— variable speed spectrum, for example, 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 (e.g. a certain warm-up cycle before the test) corresponding to particular 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 transducer 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 transducers is continued. The effects of test mandrel runout should be eliminated[5] during the tests when the spindle is rotating.



Key

s spindle speed as percentage of max. spindle speed

t time, min

Figure 6 — Sample spindle speed spectrum for thermal distortion tests

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

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 the example illustrated in Figure 7.

The effects of warming up the machine structure on the ability of the machine to maintain the position of the tool relative to the workpiece can be assessed from such 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 (Figure 7) is generated by calculating tilt angles A and B as described in 5.3.

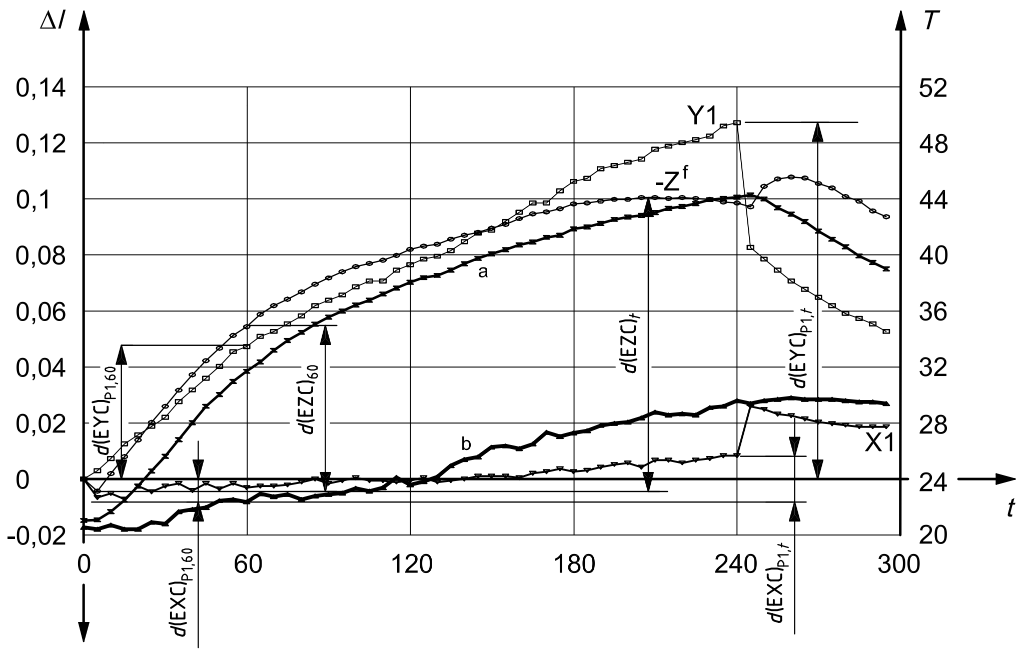
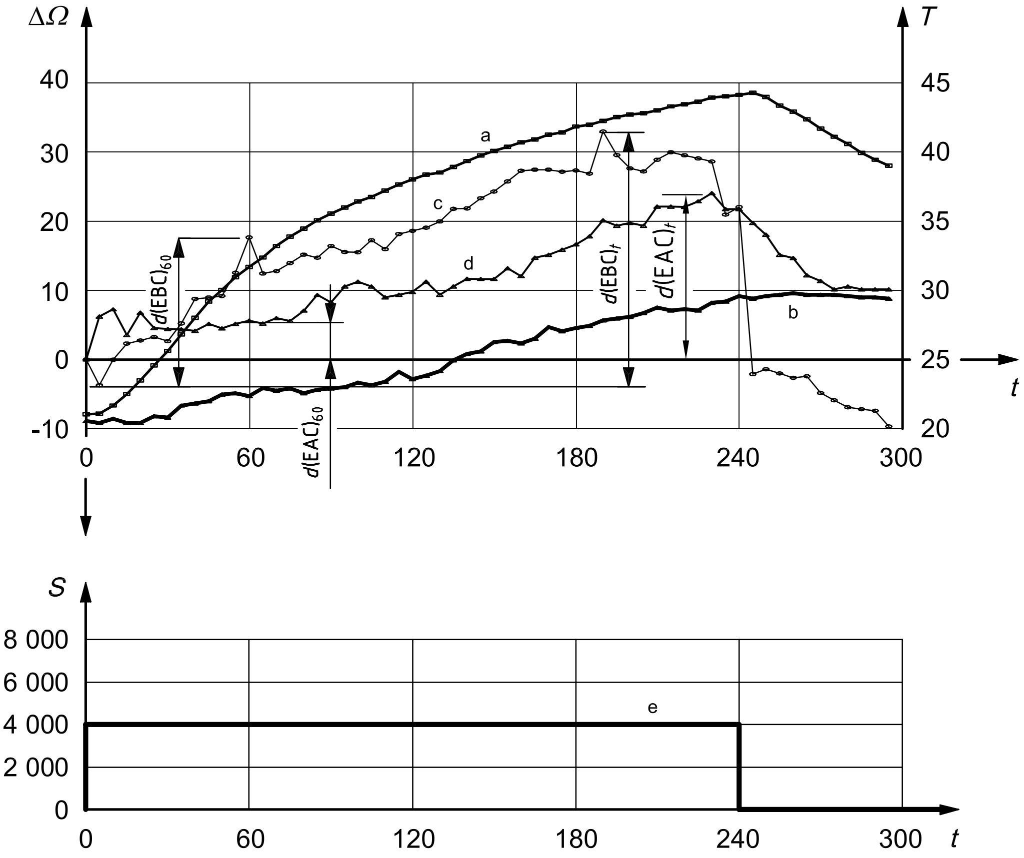


Figure 7 — Thermal linear and angular distortions caused by rotating spindle of machining centre versus time and temperature



	X1	Y1	Z	A	B
	mm	mm	mm	″	″
During first 60 min	0,008	0,048	−0,061	6	22
During spindle running period, *t* (240 min)	0,020	0,124	−0,108	24	38
Distance, *l*	150 mm				

Key

$\Delta\Omega$ angular distortion, arcseconds (″)

Δl linear distortion, mm

T temperature, °C

S spindle speed, r/min

t time, min

a Machine structure temperature.

b Ambient temperature.

c Rotation about Y (BOC).

d Rotation about X (AOC).

e Maximum spindle speed = 6 000 min^{-1}.

f Negative Z data is shown for absolute clarity.

Figure 7 *(continued)*

6.4 Presentation of results

The range of displacements along each machine axis within the first 60 min, [$d(XOC)_{P1,60}$, $d(YOC)_{P1,60}$, $d(ZOC)_{60}$, $d(AOC)_{60}$, $d(BOC)_{60}$], and during the total spindle running period, [$d(XOC)_{P1,t}$, $d(YOC)_{P1,t}$, $d(ZOC)_t$, $d(EAC)_t$, $d(EBC)_t$], 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 facing 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 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 set-up (coordinates of position L1, see Figure 1);

b) distance between spindle face and L1;

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 upon;

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.

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

	X1	Y1	Z	A	B
During first 60 min	$d(XOC)_{P1,60}$	$d(YOC)_{P1,60}$	$d(ZOC)_{60}$	$d(AOC)_{60}$	$d(BOC)_{60}$
During spindle running period, t	$d(XOC)_{P1,t}$	$d(YOC)_{P1,t}$	$d(ZOC)_t$	$d(AOC)_t$	$d(BOC)_t$
Distance, l					

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

A machine component could maintain its shape while warming up only if the thermal expansion were to 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 structure in the presence of local heat sources, such as electric motors, friction in ballscrew bearings and nuts, and hydraulics.

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

Measurements described in this clause reveal the extent of the 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 will only be 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) could change with temperature. In these cases, the bi-directional measurements should be taken if possible.

7.2.2 Set-up of instruments

Three examples of typical measurement set-ups are given 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 traverse stroke (see Figure 8).

The linear displacement sensors shall be set to measure the change 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 tool and the work sides of the machine), are calculated. These calculations are made using the following formulae (and with the set-up and nomenclature shown in Figure 8).The equations are set up such that the sign convention of motion in the opposite direction of the arrows causes positive readouts.

$$d(\mathrm{EXX})_{\mathrm{P1},\,t} = (\mathrm{P}_{\mathrm{X11}})_t - (\mathrm{P}_{\mathrm{X11}})_{t0}$$

$$d(\mathrm{EXX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{X21}})_t - (\mathrm{P}_{\mathrm{X21}})_{t0}]$$

$$d(\mathrm{EYX})_{\mathrm{P1},\,t} = (\mathrm{P}_{\mathrm{Y11}})_t - (\mathrm{P}_{\mathrm{Y11}})_{t0}$$

$$d(\mathrm{EYX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{Y21}})_t - (\mathrm{P}_{\mathrm{Y21}})_{t0}]$$

$$d(\mathrm{EZX})_{\mathrm{P1},\,t} = -\,[(\mathrm{P}_{\mathrm{Z1}})_t - (\mathrm{P}_{\mathrm{Z1}})_{t0}]$$

$$d(\mathrm{EZX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{Z2}})_t - (\mathrm{P}_{\mathrm{Z2}})_{t0}]$$

$$d(\mathrm{EAX})_{\mathrm{P1},\,t} = [(\mathrm{P}_{\mathrm{Y11}} - \mathrm{P}_{\mathrm{Y12}})_t - (\mathrm{P}_{\mathrm{Y11}} - \mathrm{P}_{\mathrm{Y12}})_{t0}] / l$$

$$d(\mathrm{EAX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{Y21}} - \mathrm{P}_{\mathrm{Y22}})_t - (\mathrm{P}_{\mathrm{Y21}} - \mathrm{P}_{\mathrm{Y22}})_{t0}] / l$$

$$d(\mathrm{EBX})_{\mathrm{P1},\,t} = [(\mathrm{P}_{\mathrm{X12}} - \mathrm{P}_{\mathrm{X11}})_t - (\mathrm{P}_{\mathrm{X12}} - \mathrm{P}_{\mathrm{X11}})_{t0}] / l$$

$$d(\mathrm{EBX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{X22}} - \mathrm{P}_{\mathrm{X21}})_t - (\mathrm{P}_{\mathrm{X22}} - \mathrm{P}_{\mathrm{X21}})_{t0}] / l$$

where

l is the distance between the two displacement sensors measuring in the same direction;

t_0 is the beginning of the axis cycling period;

t is the end of the axis cycling period;

$\mathrm{P}_{\mathrm{X21}}$ is the reading of the first displacement sensor in the direction of the X axis located at position P2.

NOTE 1 $d(\mathrm{ECX})_{\mathrm{P1}}$ and $d(\mathrm{ECX})_{\mathrm{P2}}$ cannot be calculated using the measurement set-up of Figure 8.

NOTE 2 The sign convention in the above equations is such that motion of the spindle relative to the workpiece in the positive direction gives a positive reading by the linear displacement sensor.

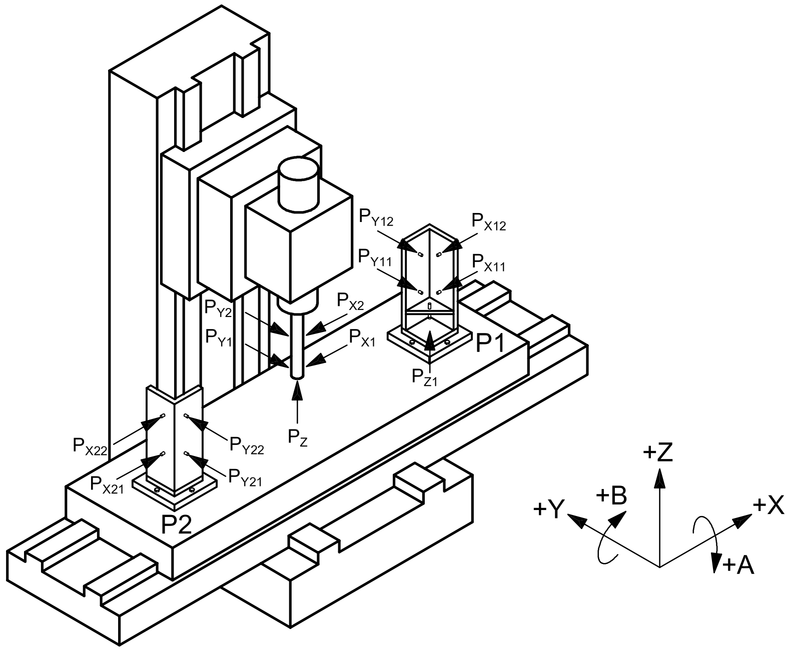


Figure 8 — Typical set-up for measurement of thermal distortions due to moving X axis table of machining centre

The second example consists of one fixture with seven displacement sensors, and two target blocks. It is shown in Figure 9. In such a set-up, a sensor fixture is mounted on the spindle. Two target blocks are mounted at each end of the travel. This set-up 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 the following formulae (using the set-up and nomenclature shown in Figure 9).

$$d(\mathrm{EXX})_{\mathrm{P1},\,t} = (\mathrm{P}_{\mathrm{X1}})_t - (\mathrm{P}_{\mathrm{X1}})_{t0}$$

$$d(\mathrm{EXX})_{\mathrm{P2},\,t} = -\,[(\mathrm{P}_{\mathrm{X2}})_t - (\mathrm{P}_{\mathrm{X2}})_{t0}]$$

$$d(\mathrm{EYX})_{\mathrm{P1},\,t} = (\mathrm{P}_{\mathrm{Y11}})_t - (\mathrm{P}_{\mathrm{Y11}})_{t0}$$

$$d(\mathrm{EYX})_{\mathrm{P2},\,t} = (\mathrm{P}_{\mathrm{Y21}})_t - (\mathrm{P}_{\mathrm{Y21}})_{t0}$$

$$d(\mathrm{EZX})_{\mathrm{P1},\,t} = -[(\mathrm{P}_{\mathrm{Z13}})_t - (\mathrm{P}_{\mathrm{Z13}})_{t0}]$$

$$d(\mathrm{EZX})_{\mathrm{P2},\,t} = -[(\mathrm{P}_{\mathrm{Z23}})_t - (\mathrm{P}_{\mathrm{Z23}})_{t0}]$$

$$d(\mathrm{EAX})_{\mathrm{P1},\,t} = \{[(\mathrm{P}_{\mathrm{Z11}} + \mathrm{P}_{\mathrm{Z12}})/2 - \mathrm{P}_{\mathrm{Z13}}]_t - [(\mathrm{P}_{\mathrm{Z11}} + \mathrm{P}_{\mathrm{Z12}})/2 - \mathrm{P}_{\mathrm{Z13}}]_{t0}\} / l$$

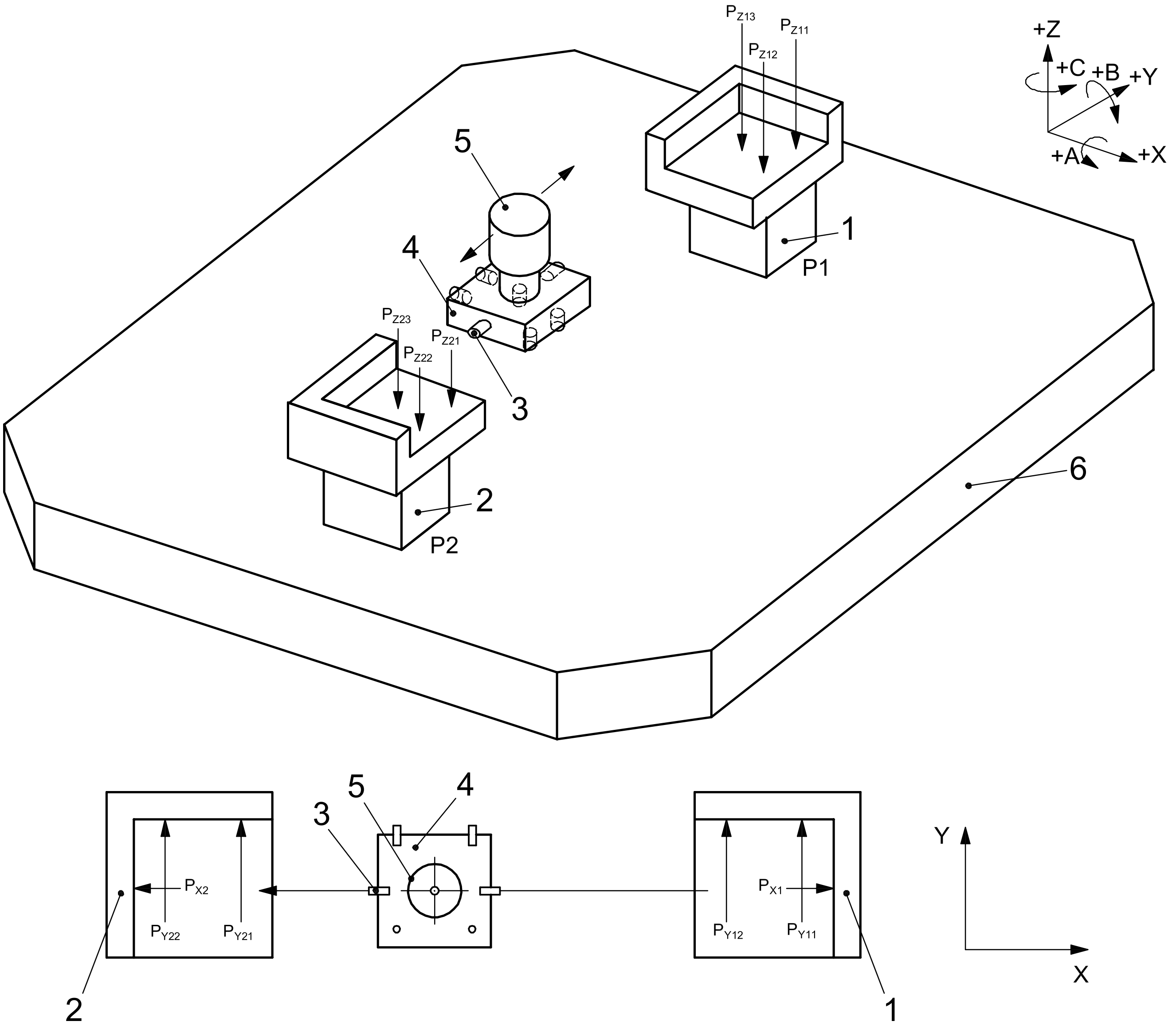
$$d(\mathrm{EAX})_{\mathrm{P2},\,t} = \{[(\mathrm{P}_{\mathrm{Z21}} + \mathrm{P}_{\mathrm{Z22}})/2 - \mathrm{P}_{\mathrm{Z23}}]_t - [(\mathrm{P}_{\mathrm{Z21}} + \mathrm{P}_{\mathrm{Z22}})/2 - \mathrm{P}_{\mathrm{Z23}}]_{t0}\} / l$$

$$d(\mathrm{EBX})_{\mathrm{P1},\,t} = [(\mathrm{P}_{\mathrm{Z11}} - \mathrm{P}_{\mathrm{Z12}})_t - (\mathrm{P}_{\mathrm{Z11}} - \mathrm{P}_{\mathrm{Z12}})_{t0}] / l$$

$$d(\mathrm{EBX})_{\mathrm{P2},\,t} = [(\mathrm{P}_{\mathrm{Z21}} - \mathrm{P}_{\mathrm{Z22}})_t - (\mathrm{P}_{\mathrm{z21}} - \mathrm{P}_{\mathrm{Z22}})_{t0}] / l$$

$$d(\mathrm{ECX})_{\mathrm{P1},\,t} = [(\mathrm{P}_{\mathrm{Y11}} - \mathrm{P}_{\mathrm{Y12}})_t - (\mathrm{P}_{\mathrm{Y11}} - \mathrm{P}_{\mathrm{Y12}})_{t0}] / l$$

$$d(\mathrm{ECX})_{\mathrm{P2},\,t} = [(\mathrm{P}_{\mathrm{Y21}} - \mathrm{P}_{\mathrm{Y22}})_t - (\mathrm{P}_{\mathrm{Y21}} - \mathrm{P}_{\mathrm{Y22}})_{t0}] / l$$



Key

1 target right

2 target left

3 gap sensor

4 sensor fixture

5 machine spindle

6 machine table

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

For most turning centres, the transducer fixture (with 6 transducers) is mounted to the tool-holding part of the machine and a special artefact, with reference surfaces aligned against those transducers, is mounted on the work-holding spindle as shown in Figure 10. For such a set-up, the thermal distortion can be calculated using the following formulae (using the set-up and nomenclature shown in Figure 10).

$$d(\mathrm{EZZ})_{\mathrm{P1},t} = (P_{\mathrm{Z1}})_t - (P_{\mathrm{Z1}})_{t0}$$

$$d(\mathrm{EZZ})_{\mathrm{P2},t} = -[(P_{\mathrm{Z2}})_t - (P_{\mathrm{Z2}})_{t0}]$$

$$d(\mathrm{EXZ})_{\mathrm{P1},t} = (P_{\mathrm{X11}})_t - (P_{\mathrm{X11}})_{t0}$$

$$d(\mathrm{EXZ})_{\mathrm{P2},t} = -[(P_{\mathrm{X21}})_t - (P_{\mathrm{X21}})_{t0}]$$

$$d(\mathrm{EYZ})_{\mathrm{P1},t} = -[(P_{\mathrm{Y11}})_t - (P_{\mathrm{Y11}})_{t0}]$$

$$d(\mathrm{EYZ})_{\mathrm{P2},t} = -[(P_{\mathrm{Y21}})_t - (P_{\mathrm{Y21}})_{t0}]$$

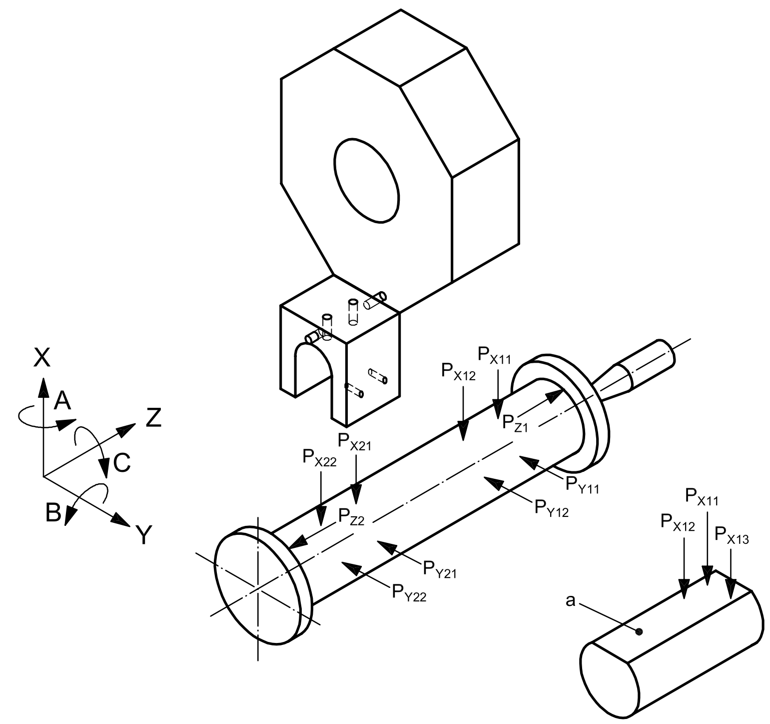
$$d(\mathrm{EAZ})_{\mathrm{P1},t} = [(P_{\mathrm{Y11}} - P_{\mathrm{Y12}})_t - [(P_{\mathrm{Y11}} - P_{\mathrm{Y12}})_{t0}/l$$

$$d(\mathrm{EAZ})_{\mathrm{P2},t} = \{[(P_{\mathrm{Y21}} - P_{\mathrm{Y22}})_t - [(P_{\mathrm{Y21}} - P_{\mathrm{Y22}})_{t0}/l$$

$$d(\mathrm{EBZ})_{\mathrm{P1},t} = [(P_{\mathrm{X12}}) - P_{\mathrm{X11}})_t - (P_{\mathrm{X12}} - P_{\mathrm{X11}})_{t0}]/l$$

$$d(\mathrm{EBZ})_{\mathrm{P2},t} = [(P_{\mathrm{X22}}) - P_{\mathrm{X21}})_t - (P_{\mathrm{X22}} - P_{\mathrm{X21}})_{t0}]/l$$

NOTE d(ECZ) cannot be calculated with the measurement set-up of Figure 10.



[a] Optional flat surface for d(ECZ) calculation.

Figure 10 — Typical set-up for measurement of thermal distortions due to moving Z axis carriage of turning centre

The third example is composed of machine'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 X, Y, and Z positions corresponding to those points all six components of the thermal distortion can be calculated using the following formulae (using the set-up, nomenclature and the machine structure shown in Figure 11).

$$d(\mathrm{EXX})_{\mathrm{P1},t} = (P_{\mathrm{X11}})_t - (P_{\mathrm{X11}})_{t0}$$

$$d(\mathrm{EXX})_{\mathrm{P2},t} = -[(P_{\mathrm{X21}})_t - (P_{\mathrm{X21}})_{t0}]$$

$$d(\mathrm{EYX})_{\mathrm{P1},t} = (P_{\mathrm{Y11}})_t - (P_{\mathrm{Y11}})_{t0}$$

$$d(\mathrm{EYX})_{\mathrm{P2},t} = [(P_{\mathrm{Y21}})_t - (P_{\mathrm{Y21}})_{t0}]$$

$$d(\mathrm{EZX})_{\mathrm{P1},t} = [(P_{\mathrm{Z11}})_t - (P_{\mathrm{Z11}})_{t0}]$$

$$d(\mathrm{EZX})_{\mathrm{P2},t} = [(P_{\mathrm{Z21}})_t - (P_{\mathrm{Z21}})_{t0}]$$

$$d(\mathrm{EAX})_{\mathrm{P1},t} = [(P_{\mathrm{Y11}} - P_{\mathrm{Y12}})_t - (P_{\mathrm{Y11}} - P_{\mathrm{Y12}})_{t0}]/l$$

$$d(\mathrm{EAX})_{\mathrm{P2},t} = [(P_{\mathrm{Y21}} - P_{\mathrm{Y22}})_t - (P_{\mathrm{Y21}} - P_{\mathrm{Y22}})_{t0}]/l$$

$$d(\mathrm{EBX})_{\mathrm{P1},t} = \{[P_{\mathrm{X11}} - (P_{\mathrm{X12}} + P_{\mathrm{X13}})/2]_t - [P_{\mathrm{X11}} - (P_{\mathrm{X12}} + P_{\mathrm{X13}})/2]_{t0}\}/l$$

$$d(\mathrm{EBX})_{\mathrm{P2},t} = -\{[P_{\mathrm{X21}} - (P_{\mathrm{X22}} + P_{\mathrm{X23}})/2]_t - [P_{\mathrm{X21}} - (P_{\mathrm{X22}} + P_{\mathrm{X23}})/2]_{t0}\}/l$$

$$d(\mathrm{ECX})_{\mathrm{P1},t} = [(P_{\mathrm{X12}} - P_{\mathrm{X13}})_t - (P_{\mathrm{X12}} - P_{\mathrm{X13}})_{t0}]/l$$

$$d(\mathrm{ECX})_{\mathrm{P2},t} = [(P_{\mathrm{X22}} - P_{\mathrm{X23}})_t - (P_{\mathrm{X22}} - P_{\mathrm{X23}})_{t0}]/l$$

where

l is the distance between the two probing locations in the same direction;

t_0 is the beginning of the axis cycling period;

t is the end of the axis cycling period.

An angular distortion of a machine component can only be estimated if it causes a difference in the measured drift 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(ECX) calculations, the angular deviations of the Y axis slide (a part of ECY) and Z axis slide (a part of ECZ) are not included in the determination of overall distortions represented by the probing locations shown in Figure 11. Thus, if these probing points are used for the Y axis or Z axis tests, there could be some inconsistency with respect to the other, alternative, measurement set-ups mentioned above.

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

It should be remembered that use of the above-mentioned set-ups requires zeroing of all readings at the start, and thus provides no absolute measurements of deviations, only their drift in time.

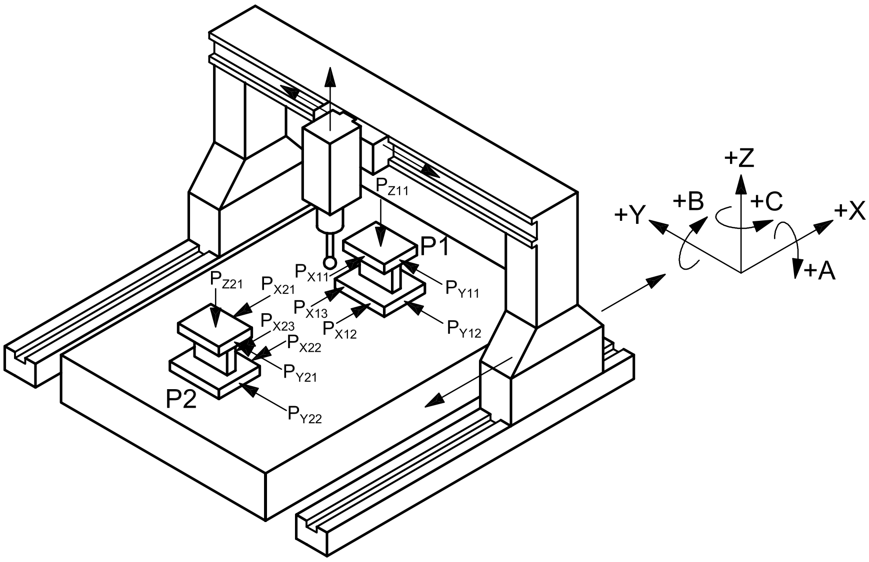


Figure 11 — Typical set-up for measurement of thermal distortion caused by moving X axis bridge of a machining centre using touch-trigger probe

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 that 15 % of the distortion registered over the first hour of the test. In situations where a set pattern of activity (e.g. 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 upon by the supplier/manufacturer and the user. Sufficient time should be allocated after each test to allow for the machine to cool down.

Starting from one of the target positions, target position 1, where the machine will remain at rest long enough (dwell time) to record the readings of the displacement sensors, the machine slide shall be programmed to move to the target position 2, where the second set of readings will be 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 rate*. 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 a different heat input, and can consequently cause different amounts of drift. The dwell time and the traverse rate in these tests can be modified based on agreements reached between the supplier/manufacturer and the user.

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 five bidirectional motions of the machine slide. The exact procedure of the measurements should be reported.

At the end of the axis cycling period, the machine 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

Temperature measurements in some points of the machine can be helpful for the correct interpretation of the results. For example, the temperature growth of the position transducer could be mainly responsible for the linear expansion, whereas the temperature growth of the slide-ways and the consequent gradient inside the fixed part (bed or column) could be mainly responsible for the bending deflections.

The following can be useful positions for the temperature sensors:

- 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 slide-ways, in the ball screw supports, in the ball screw nut);
- an area in the opposite side of the 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 would hide the contribution to the overall drift 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 set up).

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 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 axis under test.

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

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

a) traverse rate;

b) dwell times;

c) start and end point positions;

d) compensation capabilities and facilities;

e) instrument and set-up used;

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

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;

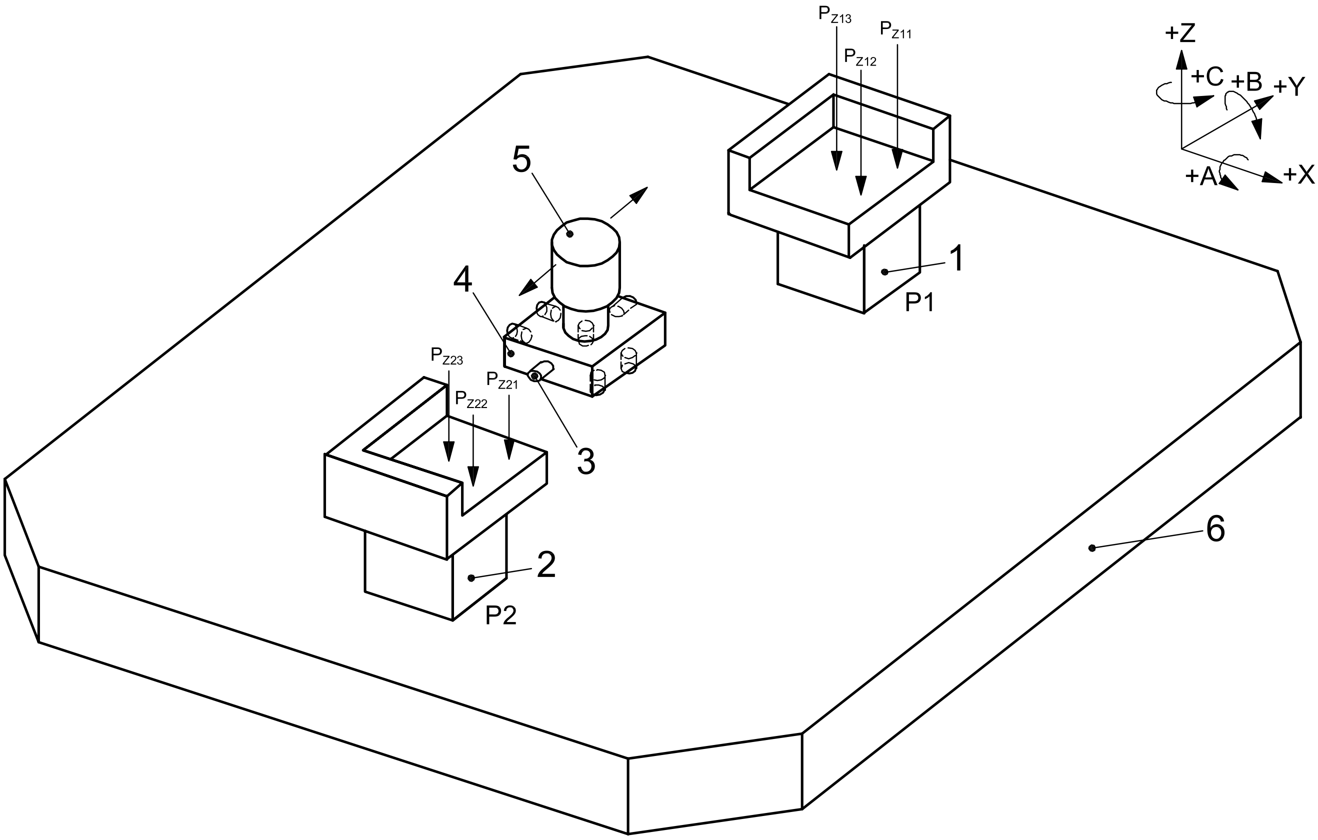
l) positive direction of position drift, if different from the coordinate systems shown in Figures 1, 2, 3, 8 and 9;

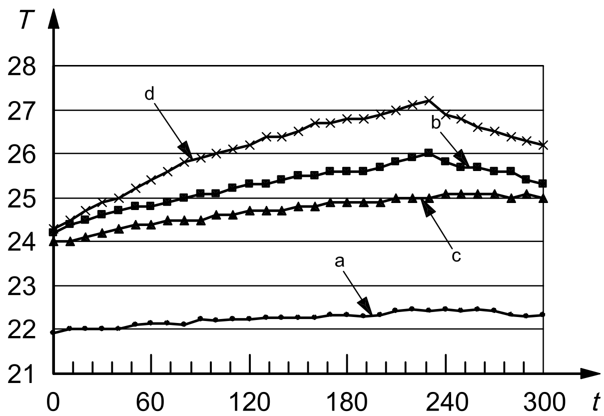
m) if relevant, conditions of any supply systems, e.g. lubrication, hydraulics, air supply, chillers (copy to spindle and ETVE tests).

Date of test:		YY/MM/DD
Machine:		AAA, vertical spindle machining centre/X = 500, Y = 350, Z = 400
Measuring instrument and serial number:		BBB, six probes moved with spindle, two target fixtures
Tested axis and its location:		Y, X = 250, Z = 200
Type of positioning scale:		glass scale
Coefficient of thermal expansion of scale:		$8 \cdot 10^{-10} \cdot °C^{-1}$
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 rate:		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
	T_1:	linear scale
	T_2:	slide

Temperature °C	At start	At end
Machine	24	25
Ambient	21,9	22,3

Figure 12 — Typical presentation of set-up information for tests of thermal distortion caused by moving linear slides

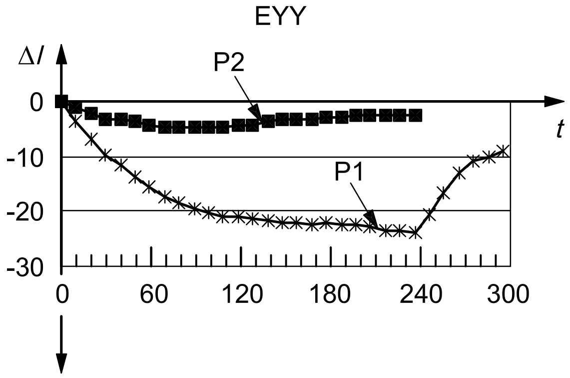


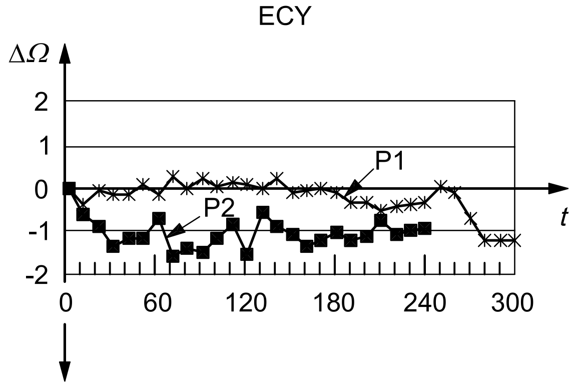


Key

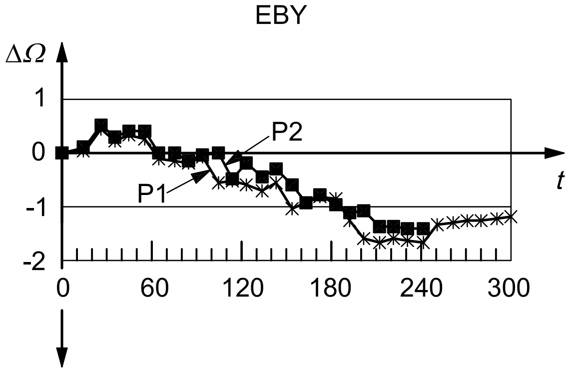
t	time, min	a	Ambient temperature.
T	temperature, °C	b	Y scale temperature.
1	target right	c	Machine temperature.
2	target left	d	Y slide temperature.
3	gap sensor		
4	sensor fixture		
5	machine spindle		
6	machine table		

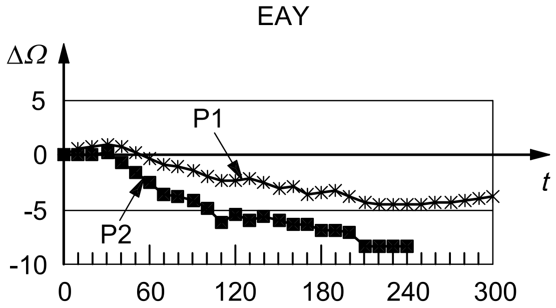
Figure 12 *(continued)*



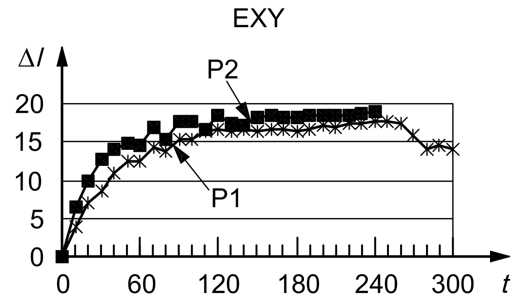


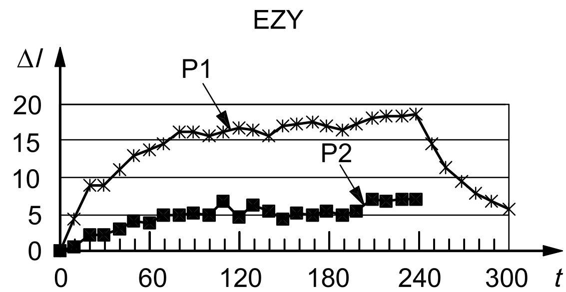
$d(\mathrm{EYY})_{1,\,60} = 16$	$d(\mathrm{EYY})_{1,\,240} = 23$	$d(\mathrm{ECY})_{1,\,60} = 0{,}3$	$d(\mathrm{ECY})_{1,\,240} = 0{,}6$
$d(\mathrm{EYY})_{2,\,60} = 4$	$d(\mathrm{EYY})_{2,\,240} = 4$	$d(\mathrm{ECY})_{2,\,60} = 1{,}3$	$d(\mathrm{ECY})_{2,\,240} = 1{,}5$





$d(\mathrm{EBY})_{1,\,60} = 0{,}5$	$d(\mathrm{EBY})_{1,\,240} = 1{,}6$	$d(\mathrm{EAY})_{1,\,60} = 1{,}9$	$d(\mathrm{EAY})_{1,\,240} = 5$
$d(\mathrm{EBY})_{2,\,60} = 0{,}5$	$d(\mathrm{EBY})_{2,\,240} = 1{,}4$	$d(\mathrm{EAY})_{2,\,60} = 2{,}1$	$d(\mathrm{EAY})_{2,\,240} = 8{,}2$





$d(\mathrm{EXY})_{1,\,60} = 12$	$d(\mathrm{EXY})_{1,\,240} = 16{,}5$	$d(\mathrm{EZY})_{1,\,60} = 15$	$d(\mathrm{EZY})_{1,\,240} = 18$
$d(\mathrm{EXY})_{2,\,60} = 15$	$d(\mathrm{EXY})_{2,\,240} = 17$	$d(\mathrm{EZY})_{2,\,60} = 4$	$d(\mathrm{EZY})_{2,\,240} = 7$

Key

Δl angular distortion, arcseconds (″)

$\Delta\Omega$ linear distortion, µm

t time, min

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

Annex A
(informative)

Linear displacement sensors

A.1 General

There are three categories of linear displacement sensor commonly used to carry out the measurements according to this part of ISO 230:

— mechanical sensors,

— electronic sensors,

— 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

The principal characteristics of these instruments are

a) the curve of errors,

b) the maximum value of 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, and

e) the repeatability when used upside down.

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

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

A.3 Electronic sensors

A.3.1 General

The contact or non-contact type electronic sensor produces a digital or analog output proportional to the amount of movement of its gauge head or target. Three common types are linear variable differential transformers (LVDT), eddy current sensors and capacitance sensors. Electronic sensors should have resolutions of 0,001 mm or better.

A.3.2 Contact type electronic sensors

A.3.2.1 General

Contact type sensors require that sensor styli touch the target surface, displacement of which is 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 should be of sufficient stiffness to prevent unwanted errors. The stylus of the plunger type electronic probe should be perpendicular to the surface to be checked so as to avoid inaccuracies.

A.3.3 Non-contact type electronic sensors

A.3.3.1 Eddy current sensors

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 will create eddy currents in this target.

The electromagnetic field created by the eddy currents in the target opposes the electromagnetic field of the coil in the sensor. This opposing field results in a change of the alternating current resistance in the generating sensor coil. The effect of this is a change in the amplitude, measured in the sensor coil, which is dependent on the distance of this coil to the test object. This measuring principle requires an absolutely stable frequency and amplitude oscillator unit operating at 1 MHz or 2 MHz. The amplitude change in the sensor coil is demodulated and subsequently electronically linearized. Since the output reading does not change proportionally with the input signal (change in distance), the output signal is linearized by means of an appropriate electronic circuit. Another important factor is the temperature dependency of the eddy current principle.

A.3.3.1.1 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

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 will change 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 in this case as a ground electrode. An adjustable compensation voltage is simultaneously generated in the electronic amplifier. After demodulation of both the alternating current voltages, the difference between these two voltage values is amplified and made available as an analogue output signal. This signal is not influenced by, and is completely independent of, the conductivity of the target material.

There is a strictly proportional relationship between the reactance, X_C, and the plate separation without the need for additional linearization. Since the sensor is specially designed as a so-called guard-ring-capacitor, the linearity of the output signal is completely independent of the conductivity of the target and is nearly perfect. Using a special electronic controller, it is also possible to measure against insulator materials, provided the dielectric factor remains constant.

A.3.3.2.1 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 sensor diameter increases proportionally with the measuring distance; 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. The reflection should be diffuse. The reflected laser beam is received via a lens and focused onto an extremely sensitive analogue linear detector or, alternatively, onto a digital CCD array. The position of the focused reflected beam on the detector generates a signal that is related to the distance from the transmitter to the target.

Unfavourable target surfaces, such as highly reflective surfaces, colour differences and colour changes can influence the accuracy of the distance measurement. However, with the aid of modern electronic technology, that is, by means of the automatic light intensity regulator, these influences are minimized or completely compensated.

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 micrometer

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 the machine spindle axis average line drift.

A.4.2.2 Precautions in use

The accuracy and its repeatability depend upon the averaging numbers. If an accuracy better than 1 μm is requested, more than 100 measurements are required. The laser source requires heat-up time, and 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 drift of the sensors. Before using the sensor system for the thermal tests specified in this part of ISO 230, the thermal behaviour of the sensor system itself should be 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 drift relative to steel components that are usually used for machine and measurement fixture construction. The second jig, made of low expansion material, is used to detect the sensor’s absolute drift.

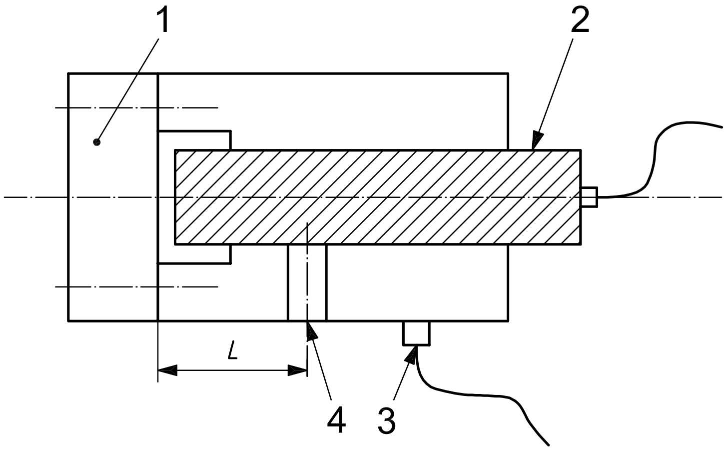
b) Attach the sensor to be tested to the special jig. The distance, L, between the fixing point and the target surface should be the same as in the measurement set up to be used in actual test procedures (see Figure A.1). This distance directly affects the thermal drift of the measurement system.

c) Attach the temperature sensor onto the jig surface so as 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 should be slow, so as to allow all components of the tested system to reach the same temperature. Several temperature-changing cycles shall be performed to identify the sensor’s expansion coefficient, non-linearity and time lag.

f) In some cases, the amplifier unit of the sensors may also have some temperature drift. Therefore, it is useful to check the amplifier’s performance by applying the same test procedure.



Key

1 target (cap)

2 sensor

3 temperature sensor

4 fixing bolts

L Distance between the target and the fixing bolt.

Figure A.1 — Typical set-up for sensor "cap" test

Annex B
(informative)

Guidelines on the required number of linear displacement sensors

B.1 General

This part of ISO 230 specifies the use of five linear displacement sensors for measuring linear thermal distortions along the X, Y, and Z axes, as well as angular thermal distortions around the X and Y axes. Some numerically controlled (NC) machine tools, such as NC lathes and surface grinders, do not require displacement measurements in all three directions. For these, the number of linear displacement sensors required to carry out thermal distortion measurements may be reduced. Table B.1 shows some examples of the required number of linear displacement sensors for various types of machine tool. Table B.1 serves only as an example to clarify the configuration of linear displacement sensors. Similar machine constructions can use similar transducer configurations.

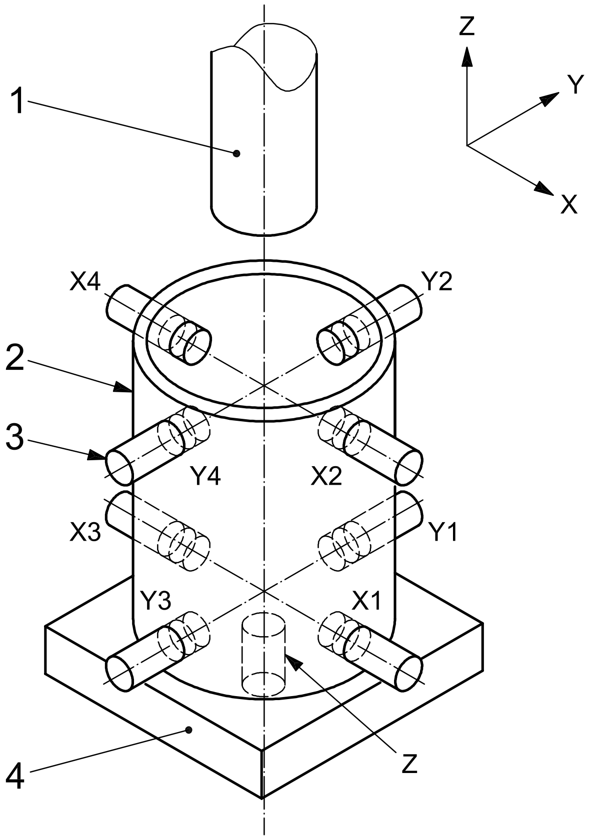
Table B.1 — Examples of numbers of displacement sensors for NC machine tools

Tool	X1	X2	Y1	Y2	Z	Total
Horizontal machine centre	*	*	*	*	*	5
Vertical machine centre	*	*	*	*	*	5
NC lathe	*	*			*	3
Turning centre	*	*	*	*	*	5
Surface grinder			*	*	(*)	2 (3)
Profile surface grinder	*	*	*	*	*	5
Drilling machine	*		*			2
Boring machine	*	*	*	*	(*)	4 (5)
Internal grinder	*	*	*	*	*	5
Cylindrical grinder	*	*			*	3
Jig grinder	*	*	*	*		4

For small sized machines, it can be difficult to set the sensors. In this case, angular deviation measurements may be omitted.

The number of linear displacement sensors may be increased in order to obtain more accurate measurements. To compensate for the thermal expansion of the test mandrel and the transducer holding fixture, nine displacement sensors are used, as shown in Figure B.1.

Some types of linear displacement sensors, such as eddy current sensors or fibre optic sensors, are affected by the material inhomogeneity. In such cases, an angular position detector or rotational trigger with proper data acquisition/analysis software is useful for avoiding this effect. Figure B.2 illustrates an example of rotational trigger attachment to the measurement set-up.



Key

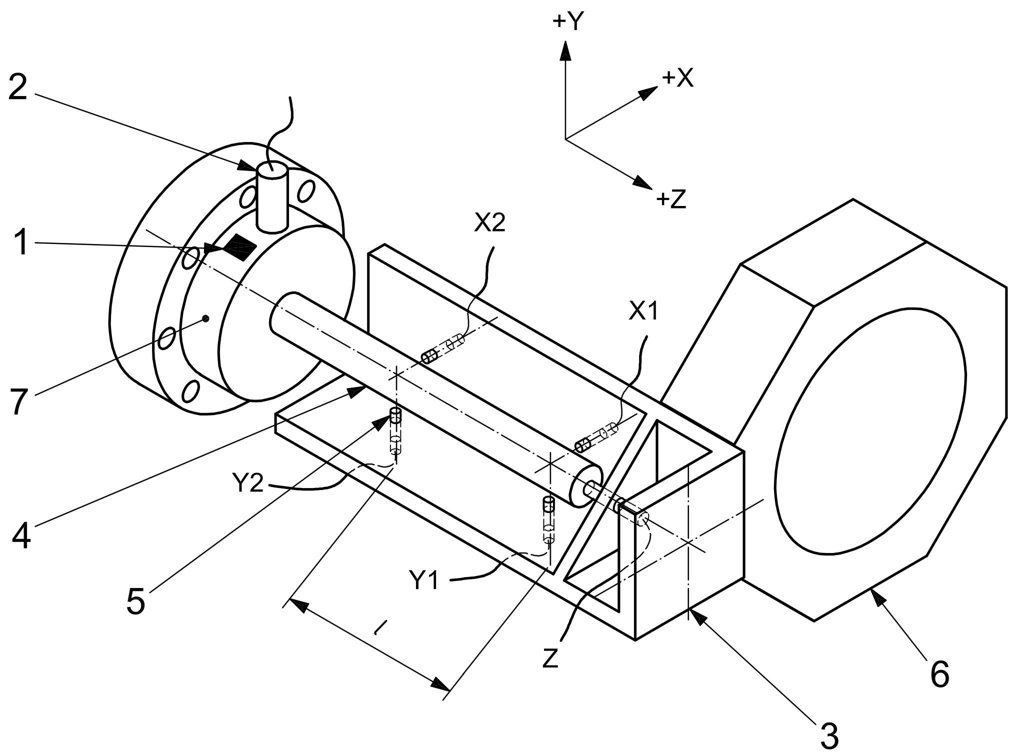
1 test bar

2 main frame

3 linear displacement sensor

4 base

Figure B.1 — Nine-sensor configuration for compensating thermal expansion of mandrel and fixture



Key

1 trigger mark

2 optical sensor

3 fixture

4 test mandrel

5 linear displacement sensor

6 turret

7 chuck

Figure B.2 — Optical trigger for identifying spindle rotation angle

Annex C
(informative)

Guidelines for machine tool thermal environment

C.1 General

Machine tools have many internal heat sources — spindles, spindle motors, drive motors, hydraulic and pneumatic actuators, etc. — that create non-uniform temperature distribution within their structures. Temperature gradients cause structural deformations and therefore affect the performance of the machine. The performance of machine tools is also strongly affected by the thermal characteristics of the environment.

NOTE Some modern machine tools are supplied with their own thermally-controlled enclosures. In these cases, the effect of the environment may not be as significant.

Although the environment can have a beneficial effect on the temperature distribution of the machine structure by removing heat generated by the internal heat sources, it can also cause additional temperature elevations due to convective and radiative heating of the machine structure. In addition, the temperature of the coolant and the utility air can have a significant effect on the overall performance of the machine tool.

Thermal characteristics of the environment in which the machine is expected to operate must be specified by the machine supplier/manufacturer in order to ensure conformity with the specified accuracy. Important parameters defining these thermal characteristics include ambient air velocity, frequency and amplitude of ambient temperature variations, mean ambient temperature and the horizontal and vertical temperature gradients in the environment.

C.2 Flow rate and velocity

The flow rate and velocity of the ambient air are of prime importance in the control of temperature variation and temperature gradients of the machine components. With higher flow rates and velocities, smaller air temperature differences are required to remove heat from the surface of the machine tool components. This means that the components with either internal heat sources (e.g. motors inside machine frames) or receiving heat by radiation (e.g. from electric lights) have temperatures closer to the average ambient air temperature. On the other hand, high air flow rates and velocities have a tendency to cause discomfort to personnel.

C.3 Frequency and amplitude of temperature variations

The dimensional response of an object to ambient temperature variation depends on its size, coefficient of expansion and time constant. The time constant of an object can be estimated from its surface area, film coefficient and thermal capacity. For example, a steel gauge block of 25 mm × 25 mm cross-sectional area and 250 mm length has a time constant of 0,5 h in natural convection. The time constant is the time the gauge block would take to reach 63,2 % of its total change after a step change in the environment temperature. The slowness of response, or thermal inertia, is important to the specification of environments. A high inertia means that high frequency temperature variation in the ambient air is tolerable.

Although different machine components can have different time constants, in general, most machine tools have large thermal time constants. Good results are often achieved in an environment with a frequency of temperature variation (in air) of 15 cycles/h to 30 cycles/h and an amplitude of up to 0,5 °C.

C.4 Mean temperature

Selection of the mean environmental temperature affects the cost of refrigeration and heating equipment, insulation and flow distribution. Operation at a temperature other than the standard reference temperature of 20 °C will cause potential errors in the machine performance measurements as well as in the machined parts. Assessment of the consequences of temperatures other than 20 °C on length measurements can be obtained by calculating the difference between the estimated expansion of the machine length scale and that of the part or the test equipment. However, uncertainties related to temperature measurements and the actual coefficient of thermal expansions of materials involved cause uncertainty in this assessment. Furthermore, this procedure is not always straightforward for cases other than length measurements. For example, consider the case of a cast iron bed of a machine, where the casting may have both thick- and thin-walled sections, the physical composition of the material may not be homogeneous, resulting in a non-uniform coefficient of thermal expansion. The magnitude of such a variation in expansion coefficient may be as much as 5 %. If the non-uniformity is distributed as a vertical gradient, raising and lowering the mean temperature will result in a bending similar to that produced by a vertical temperature gradient. This can only be avoided by strict temperature control at 20 °C, which can be very difficult to realize in a typical machine shop environment.

C.5 Temperature gradients

The existence of gradients implies that different parts of the environment have different mean temperatures and that the consequences of mean temperatures other than 20 °C will be different according to the position in a room. Additional complexity is created when these temperature gradients change in time. Movement of machine components or workpieces from one area to another will result in a change in the geometric deviation pattern.

Machine tools are affected by temperature gradients in a variety of ways. For example, a machine with a high vertical column (Z motion) will have a progressive positional deviation along the Z axis per unit of motion if there is a vertical temperature gradient. In addition, if the vertical slide carries a long cantilever quill, the quill will undergo a transient change of length when raised or lowered. Vertical gradients also cause bending of horizontal slide-ways, resulting in angular and straightness error motions.

Temperature gradients occur because of heat sources that exist within the boundaries of the environment. The main sources of heat are the sun, electrical lighting fixtures, drive motors for the slides and spindles, electrical and electronic equipment, and people. A typical room, with only electrical lighting fixtures present and operating, nominally has a gradient of less than 0,2 °C/m in any direction. However, the same room with equipment installed could have temperature gradients 10 to 20 times higher near the machine surfaces, electrical cabinets, etc. Increasing the flow rate of the cooling medium will decrease the temperature gradients.

Users of machine tools should take the above-mentioned environmental effects into consideration when testing and using the machines. In order to ensure that a machine operates within specified tolerances, a machine tool supplier/manufacturer should provide recommended environmental characteristics in which the machine is expected to perform. An example of such an environmental thermal specification is given in Table C.1.

Table C.1 — Sample environment thermal requirements

Temperature range in which the specified accuracy can be achieved	15 °C to 25 °C
Safe operating temperature range	0 °C to 40 °C
Temperature variation per hour	1 °C
Temperature variation per 24-hour period	5 °C
Temperature variation in machine space	0,5 °C/m
Coolant temperature range	18 °C to 22 °C
Utility air temperature range	18 °C to 25 °C

Annex D
(informative)

Alternative measurement devices and set-ups

D.1 Device for measuring ETVE and thermal distortion of structure caused by rotating spindle

The measurement device consists of a short test mandrel, six non-contact type linear displacement sensors and a fixture for the sensors. The set-up of the measurement device and the location of the sensors are shown in Figure D.1. Three sensors, S_a, S_b and S_c, located in the radial direction are used to detect thermal deviations d(EXC) and d(EYC) in the X and Y directions, respectively. The deviations can be calculated from the outputs of the three sensors without the influence of the thermal and centrifugal expansions of the test mandrel as well as the thermal expansion of the fixture in the radial direction. Thermal deviations d(EXC) and d(EYC) and radial expansion ΔR are expressed by Equation (D.1), where the sign of the sensor signals is positive when the sensors leave from the test mandrel. To remove the influence of the roundness and run-out of the test mandrel before the output signal of the sensor is processed, the use of time averaging or a low-pass filter is recommended.

$$\begin{bmatrix} 0 & 1 & -1 \\ \sin\alpha & \cos\alpha & -1 \\ -\sin\beta & \cos\beta & -1 \end{bmatrix} \begin{pmatrix} d(\text{EXC}) \\ d(\text{EYC}) \\ \Delta R \end{pmatrix} = \begin{pmatrix} S_\text{a} \\ S_\text{b} \\ S_\text{c} \end{pmatrix} \tag{D.1}$$

d(EXC), d(EYC) and ΔR are derived from Equation (D.1) as follows:

$$d(\text{EXC}) = \frac{S_\text{a}(\cos\alpha - \cos\beta) + S_\text{b}(\cos\beta - 1) + S_\text{c}(1 - \cos\alpha)}{(\cos\beta - 1)\sin\alpha + (\cos\alpha - 1)\sin\beta} \tag{D.2}$$

$$d(\text{EYC}) = \frac{-S_\text{a}(\sin\alpha + \sin\beta) + S_\text{b}\sin\beta + S_\text{c}\sin\alpha}{(\cos\beta - 1)\sin\alpha + (\cos\alpha - 1)\sin\beta} \tag{D.3}$$

$$\Delta R = \frac{-S_\text{a}\sin(\alpha + \beta) + S_\text{b}\sin\alpha + S_\text{c}\sin\beta}{(\cos\beta - 1)\sin\alpha + (\cos\alpha - 1)\sin\beta} \tag{D.4}$$

Three sensors, S_d, S_e, and S_f, located against the end surface of the test mandrel, are used to detect linear deviation d(EZC) in the axial direction (Z direction), and angular deviations d(EAC) and d(EBC). If the signs of the output signals of the sensors are the same as the radial direction, linear deviation d(EZC) and angular deviations d(EAC) and d(EBC) around the X and Y axes, respectively, are given by Equation (D.5):

$$\begin{bmatrix} 1 & -R_0 & 0 \\ 1 & -R_0\cos\theta & R_0\sin\theta \\ 1 & -R_0\cos\phi & -R_0\sin\phi \end{bmatrix} \begin{pmatrix} d(\text{EZC}) \\ d(\text{EAC}) \\ d(\text{EBC}) \end{pmatrix} = \begin{pmatrix} S_\text{d} \\ S_\text{e} \\ S_\text{f} \end{pmatrix} \tag{D.5}$$

where, R_0 is the distance between the sensor and the axis of the spindle at the beginning of the measurement.

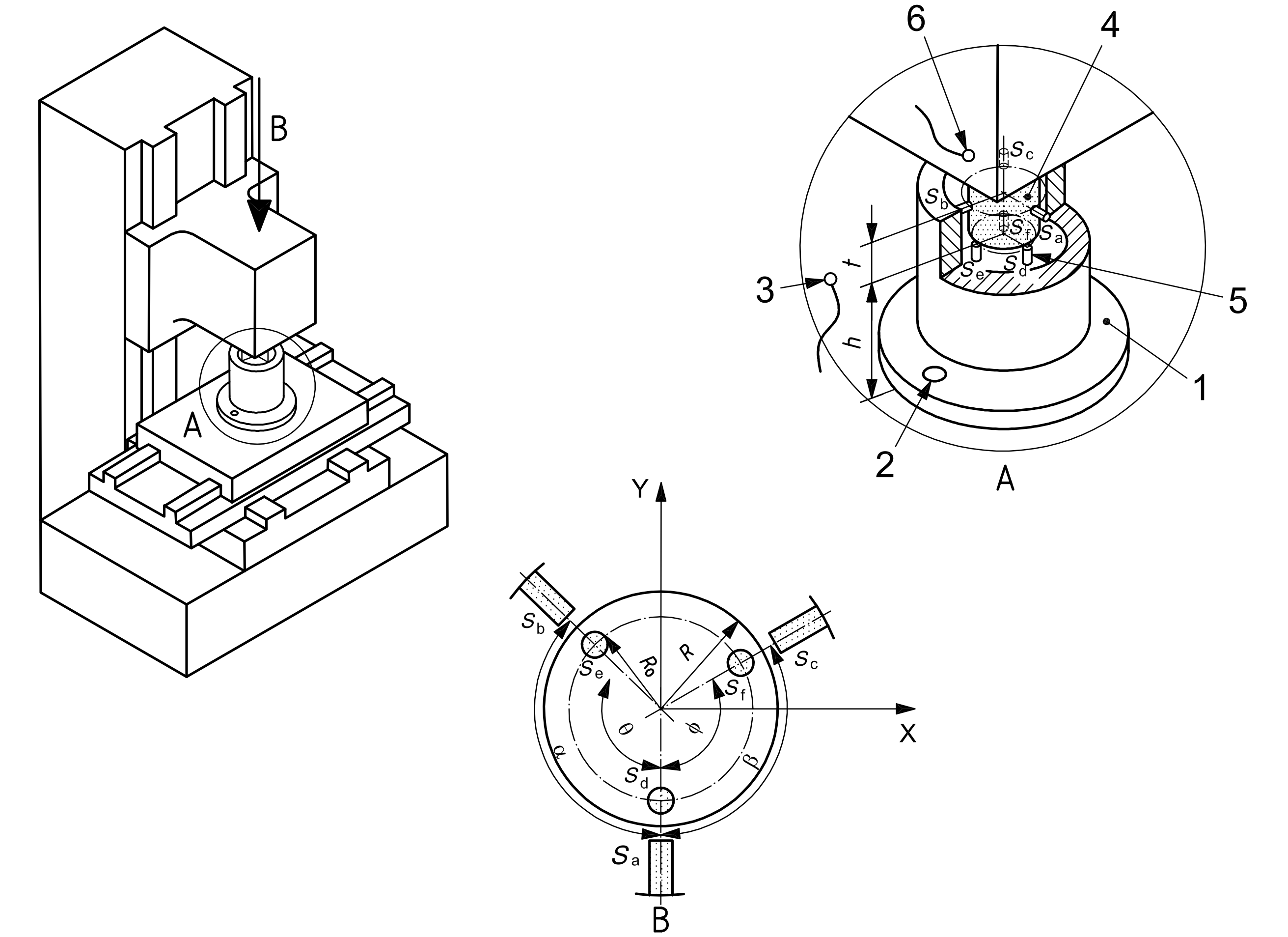
Deviations d(EZC), d(EAC) and d(EBC) are expressed by Equations (D.6), (D.7) and (D.8), respectively:

$$d(\text{EZC}) = \frac{S_\text{d}\sin(\theta + \phi) - S_\text{e}\sin\phi - S_\text{f}\sin\theta}{(\cos\phi - 1)\sin\theta + (\cos\theta - 1)\sin\phi} \tag{D.6}$$

$$d(\text{EAC}) = \frac{S_\text{d}\left(\sin\theta + \sin\phi\right) - S_\text{e}\sin\phi - S_\text{f}\sin\theta}{R_0\left[\left(\cos\phi - 1\right)\sin\theta + \left(\cos\theta - 1\right)\sin\phi\right]} \tag{D.7}$$

$$d(\text{EBC}) = \frac{S_\text{d}\left(\cos\theta - \cos\phi\right) + S_\text{e}\left(\cos\phi - 1\right) + S_\text{f}\left(1 - \cos\theta\right)}{R_0\left[\left(\cos\phi - 1\right)\sin\theta + \left(\cos\theta - 1\right)\sin\phi\right]} \tag{D.8}$$

Angles α, β, θ and ϕ, radii R_0 and R, and heights h and t (see Figure D.1) should be recorded in the data sheet.



Key

1 fixture for sensor

2 fixture bolted to table

3 ambient air temperature sensor

4 test mandrel

5 displacement sensors

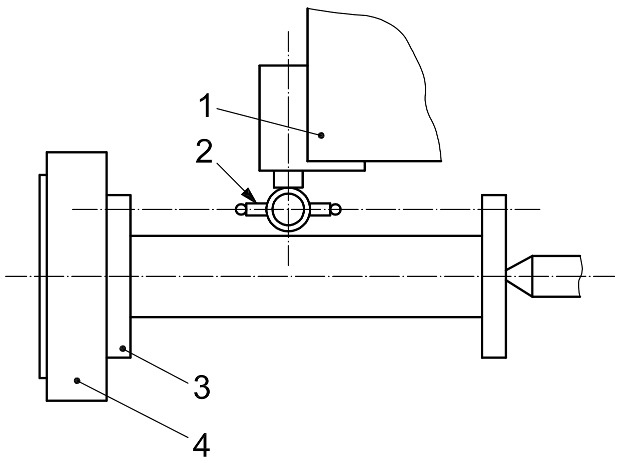
6 spindle bearing temperature sensor

Figure D.1 — Alternative set-up for tests of ETVE and thermal distortion of structure caused by rotating spindle and by moving linear axis on vertical machining centre

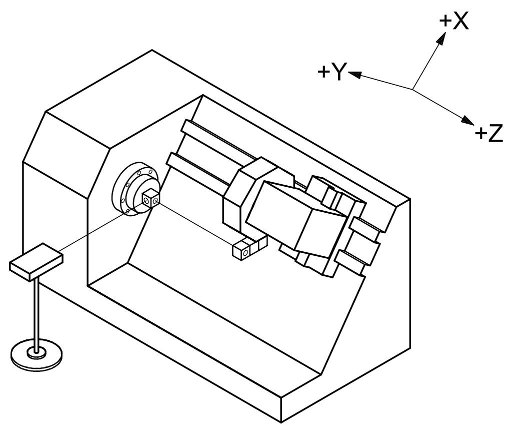
This measurement device can measure the thermal displacement of the spindle axis, without reflecting the influence of the thermal and centrifugal expansions of the test mandrel, as well as the thermal expansion of the fixture for the sensors in the X and Y directions. However, the influence of the thermal expansion of the test mandrel in the Z direction can be reduced by shortening the test mandrel as much as possible, though there still remains slight influence. In addition, it is quite suitable for the high-speed spindle, because the length of the test mandrel can be made short.

D.2 Alternative measurement set-ups for thermal distortion due to linear motion of components

Some machine tools, such as certain turning machines and cylindrical grinding machines, might not need angular measurements for checking the thermal distortion due to moving components. For these, the alternative measurement set-ups shown in Figure D.2, for checking only linear travel elongation, are adequate.



a) Set-up with two dial gauges



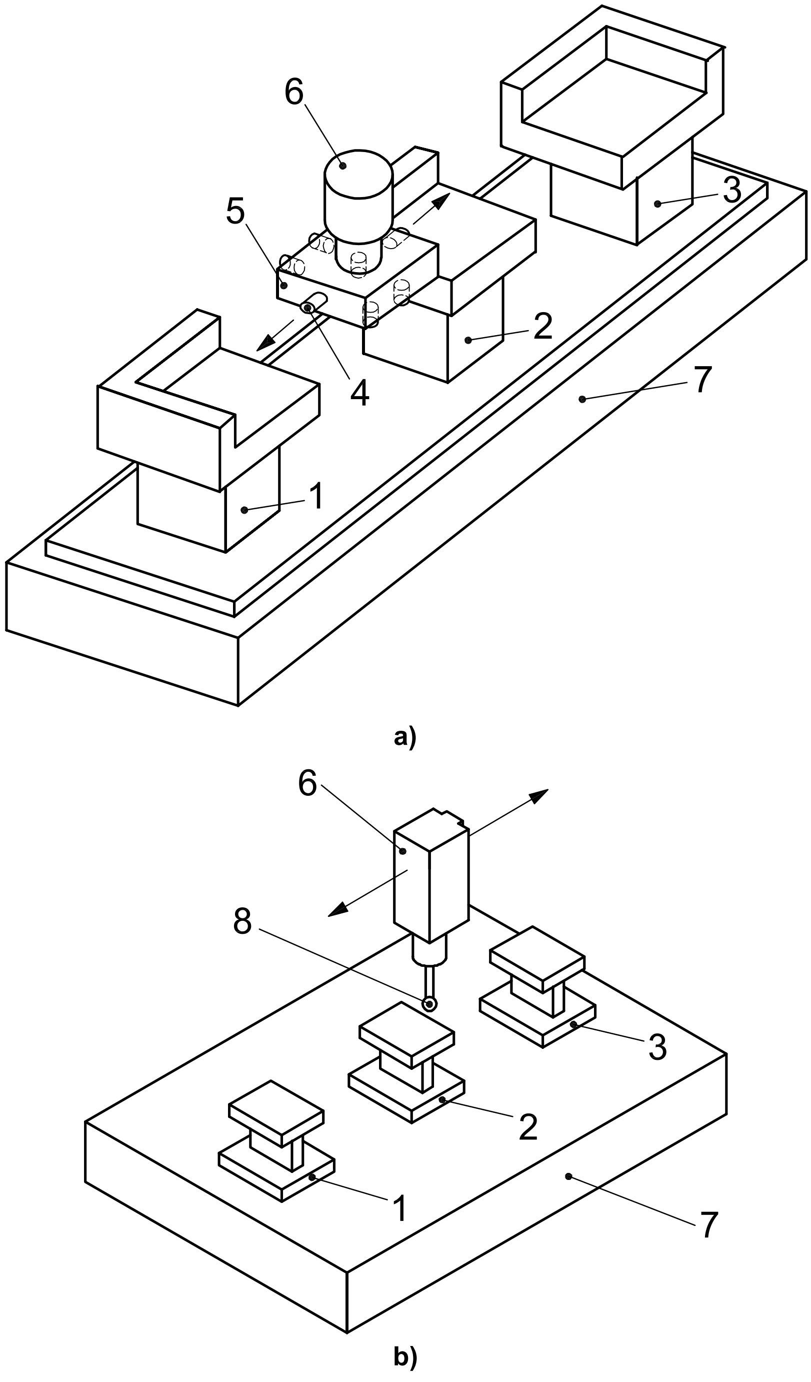
b) Set-up with laser interferometer

Key

1 tool post
2 gauge
3 test artefact
4 chuck

Figure D.2 — Typical set-ups for measuring thermal distortion caused by moving Z axis slide of NC turning machine

For some cases, measurement in the middle of the travel range, in addition to both ends, might reveal interesting thermal behaviour. To obtain data in the middle of the travel range, a centre target block may be mounted as shown in Figure D.3.



Key

1 target left
2 target centre
3 target right
4 gap sensor
5 sensor fixture
6 machine spindle
7 machine table
8 touch trigger probe

Figure D.3 — Alternative set-ups utilizing centre target block

Bibliography

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

ICS 25.080.01

Price based on 44 pages