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Test code for machine tools —

Part 3: Determination of thermal effects

Code d'essai des machines-outils —

Partie 3: Évaluation des effets thermiques

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Foreword

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

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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

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

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

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

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

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

Introduction

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

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

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

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

Test code for machine tools —

Part 3: Determination of thermal effects

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

1 Scope

This document defines four tests:

— an environmental temperature variation error (ETVE) test;

— a test for thermal distortion caused by rotating spindles;

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

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

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

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

2 Normative references

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

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

3 Terms and definitions

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

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

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

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

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

EXAMPLE Linear and rotary encoders are typical machine scales.

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

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

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

where

T is the temperature of the object in °C;

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

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

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

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

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

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

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

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

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

where

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

L is the length of the object;

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

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

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

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

where

L is the length of the object;

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

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

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

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

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

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

$$u_{\mathrm{NDE}} = \sqrt{u_{\mathrm{EM}}^2 + u_{\mathrm{ET}}^2} \quad (4)$$

where

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

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

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

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

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

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

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

$$u_{\mathrm{ETVE}} = \sqrt{\frac{E_{\mathrm{TVE}}^2}{12}} \quad (5)$$

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

3.13
combined standard thermal uncertainty
$\boldsymbol{u_{\mathrm{CT}}}$
combined uncertainty in length measurements caused by an environment with a temperature other than a constant and uniform 20 °C

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

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

$$u_{\mathrm{CT}} = \sqrt{u_{\mathrm{ETVE}}^2 + u_{\mathrm{TM}}^2 + u_{\mathrm{NDE}}^2} \quad (6)$$

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

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

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

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

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

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

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

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

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

4 Preliminary remarks

4.1 Measuring units

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

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

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

4.2 Reference to ISO 230-1

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

4.3 Recommended instrumentation and test equipment

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.4 Machine tool conditions prior to testing

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

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

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

4.5 Testing sequence

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

4.6 Test environment temperature

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

4.7 Uncertainty due to temperature effects

The ETVE test (Clause 5), along with the uncertainty due to environmental temperature variation error, u_{ETVE}, and the tests (Clauses 6 to 8) for thermal distortions $[d(E_{\alpha0\beta})_{xx,t}$, $d(E_{\alpha\ \gamma})_{xx,t}]$, provide the temperature effects that contribute to the uncertainty of performance and/or performance evaluation of machine tools.

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

5 Environmental temperature variation error (ETVE) test

5.1 General

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

It is recommended that the supplier/manufacturer offer guidelines regarding the thermal environment, which can be considered as acceptable for the machine tool to perform with the specified accuracy. Such general guidelines can contain, for example, a specification on the mean room temperature, maximum amplitude and frequency range of deviations from this mean temperature and environmental thermal gradients (see Annex C). It is the user's responsibility to provide an acceptable thermal environment for the operation and the performance testing of the machine tool at the installation site. However, if the user follows the guidelines provided by the machine supplier/manufacturer, the responsibility for machine performance according to the specifications reverts to the machine supplier/manufacturer.

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

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

5.2 Test method

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

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

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

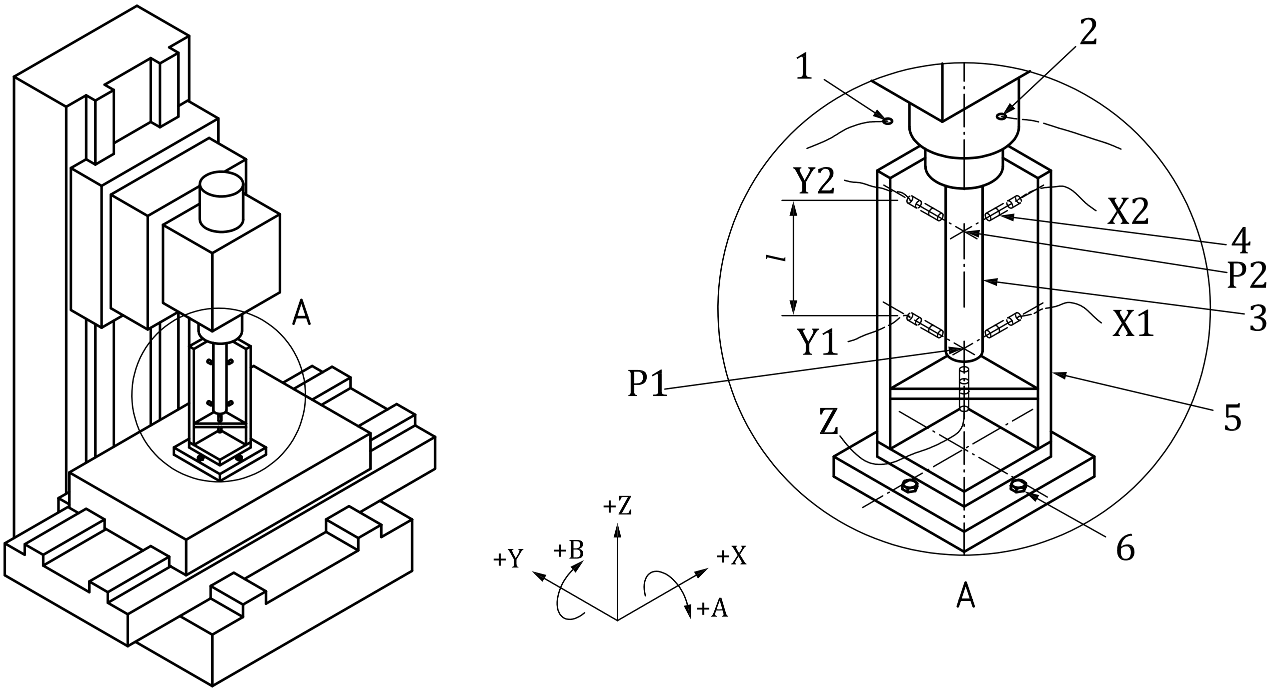
WARNING — Figures 1 to 3 show test mandrels that need end surfaces with proper flatness and squareness to the axis of the mandrel as these deviations influence the measurement uncertainty directly. To minimize such uncertainty, spherical ended mandrel or precision spheres can be used.

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

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

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

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



Key

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

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