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Machine tools — Numerical compensation of geometric errors

Machines-outils — Compensation numérique des erreurs géométriques

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Foreword

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

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

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

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

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

Introduction

This Technical Report provides information associated with numerical compensation of geometric errors of machine tools.

Numerical compensation of geometric errors has the potential to

- increase the accuracy of parts produced on machine tools,
- reduce the costs for production of machine tools and assembly, and
- reduce the maintenance cost during the life cycle of the machine tool by adding or replacing mechanical re-fitting.

The information provided in this Technical Report might be useful to the machine tool manufacturer/supplier, the user, the metrology service provider, and the metrology instrument manufacturer.

Valuable general information on numerical compensation of geometric errors may be gathered in Schwenke, et al[12].

Machine tools — Numerical compensation of geometric errors

1 Scope

This Technical Report provides information for the understanding and the application of numerical compensation of geometric errors for numerically controlled machine tools including:

- terminology associated with numerical compensation;
- representation of error functions output from different measuring methods;
- identification and classification of compensation methods as currently applied by different CNCs;
- information for the understanding and application of different numerical compensations.

This Technical Report does not provide a detailed description of geometric errors measurement techniques that are specified in ISO 230 (all parts) and in machine tool specific performance evaluation standards and it is not meant to provide comprehensive theoretical and practical background on the existing technologies.

This Technical Report focuses on geometric errors of machine tools operating under no-load or quasi-static conditions. Errors resulting from the application of dynamic forces as well as other errors that might affect the finished part quality (e.g. tool wear) are not considered in this Technical Report.

Deformations due to changing static load by moving axes are considered in 7.4.2.

2 Normative references

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

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

ISO 841:2001, *Industrial automation systems and integration — Numerical control of machines — Coordinate system and motion nomenclature*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 841:2001, ISO 230-1:2012 and the following apply.

3.1
machine tool coordinate system
machine tool reference coordinate system
right-hand rectangular system with the three principal axes labelled X, Y, and Z, with rotary axes about each of these axes labelled A, B, and C, respectively

[SOURCE: ISO 841:2001, 4.1, modified]

Note 1 to entry: ISO 230-1:2012, Annex A provides useful information on machine tool coordinate system and position and orientation errors.

3.2
functional point

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

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

3.3
functional orientation

relative orientation between the component of the machine tool that carries the cutting tool and the component of the machine tool that carries the workpiece

3.4
motion uncompensated for geometric errors

linear or angular motion of machine tool axes resulting from commanded motion and the error motions caused by component imperfections, components alignment errors, and/or positioning system errors

3.5
motion compensated for geometric errors

linear or angular motion of machine tool axes resulting from the commanded motion and the application of (numerical) compensation of error motions

Note 1 to entry: Compensation might apply to all geometric errors or to just some geometric errors. It is recommended that the type of compensation (see.8.2) is specified.

Note 2 to entry: Residual errors may still exist after motion compensated for geometric errors. See 3.19.

3.6
structural loop

assembly of components, which maintains the relative position between two specified objects

[SOURCE: ISO 230-7:—, 3.1.13]

Note 1 to entry: A typical pair of specified objects (for a milling machine) is a cutting tool and a workpiece, in which case the structural loop would include the spindle, bearings and spindle housing, the machine head stock, the machine slideways and machine frame, and the fixtures for holding the tool and workpiece. For large machines, the foundation can also be part of the structural loop

Note 2 to entry: When geometric error measurements are being performed, the structural loop also includes the measuring instrument components, including the reference artefacts (if any).

3.7
volumetric error model

geometric model that describes the errors of the machine tool functional point and functional orientation within the machine tool working volume caused by individual error motions as well as position and orientation errors of machine tool axes, including axis positions and other structural loop variables like tool length and tool offset

Note 1 to entry: Volumetric error model may be a kinematic error model or a spatial error grid.

Note 2 to entry: Other models describing the errors due to machine tool thermal effects and structural stiffness as well as dynamic models can be combined with the volumetric error model.

3.8
volumetric compensation of functional point only

numerical compensation for the errors in the position of the functional point within the machine tool working volume based on the volumetric error model, not including the compensation for the errors in the functional orientation

Note 1 to entry: Errors in the functional orientation are compensated at the functional point. For cutting tools with spherical tips, the “volumetric compensation of the functional point only” represents a full compensation, as orientation errors of a spherical tip do not affect the geometry of machined workpieces.

3.9
volumetric compensation of functional point and of functional orientation
numerical compensation for the errors in the position of the functional point and the functional orientation within the machine tool working volume based on the volumetric error model

3.10
kinematic error model
mathematical model that describes the structural loop of a machine tool as a kinematic chain and describes the errors that are included/considered

Note 1 to entry: The complexity of the kinematic error model and the number of parameters may vary.

3.11
rigid body kinematic error model
kinematic error model based on the assumption that the errors of one axis, observed at a specific functional point, are independent from the position of other axes and are not influenced by mechanical loads like tool mass and/or workpiece mass

Note 1 to entry: Rigid body model may include effects of errors due to elastic deformation of components (called quasi-rigid body behaviour); for example, see 7.4.2.

3.12
rigid body kinematic compensation
compensation for the errors based on the rigid body kinematic error model

Note 1 to entry: It is recommended to provide a statement that describes what errors are included in the applied rigid body kinematic error model.

3.13
error table
error file
discrete numerical representation of geometric error parameters of each linear or rotary axis, as well as position and orientation errors of its reference line, for a given set of linear or angular command positions for each axis

Note 1 to entry: For linear axes, error tables typically describe translational error motions (i.e. positioning and straightness error motions) as well as angular error motions (i.e. roll, pitch, and yaw).

Note 2 to entry: For rotary axes, error tables may include translational error motions (axial and radial error motions) and angular error motions (tilt error motion and angular positioning error motions).

Note 3 to entry: Position and orientation errors between axes reference lines (i.e. zero position errors and squareness errors) can be included in error tables.

3.14
compensation table
compensation file
discrete numerical representation of the compensation values of the geometric error parameters of each linear or rotary axis, as well as position and orientation errors of its reference line, for a given set of linear or angular command positions for each axis

Note 1 to entry: Compensation tables are error tables with reversed sign.

3.15
spatial error grid
multi-dimensional error table that contains the numerical representation of translational errors, and/or functional orientation errors, at the given sampled set of the position of the linear and rotary axes concerned

Note 1 to entry: While error tables represent the geometric errors of each axis, the spatial error grid represents the superposition of the effects of geometric errors of multiple axes at each sampling (grid) point.

Note 2 to entry: 9.3 provides information on the representation of errors in spatial error grids and spatial compensation grids.

3.16
spatial compensation grid

multi-dimensional compensation table that contains the numerical representation of the compensation values of the translational errors, and/or the compensation values of functional orientation errors, at the given sampled set of the position of the linear and rotary axes concerned

Note 1 to entry: Spatial compensation grids are spatial error grids with reversed sign.

3.17
sampling point

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

3.18
interpolated error value

error value at points not equal to the sampling points resulting from the interpolation of numerical representation of error(s) at neighbouring sampling points

3.19
residual machine tool geometric error

error in the position of the functional point and the functional orientation after the application of numerical compensation of machine tool geometric errors

Note 1 to entry: Residual machine tool geometric errors can be defined for X, Y, Z directions and for A, B, C orientations.

3.20
least increment step

smallest increment to which the machine tool axis can position in a specified period of time

Note 1 to entry: See 8.5

4 Potential benefits and limits of numerical compensation

The potential benefits of the implementation of compensation are the following.

a) Compensation reduces the effect of geometric errors of the machine tool on the manufactured part and therefore leads to higher quality of manufactured workpieces.

b) By re-verification and subsequent adaptation of compensation, the machine tool accuracy is maintained during its life cycle. Geometric changes from aging, wear, collisions, repositioning of the machine tool, changes of the thermal environment, or stabilization of the foundation are partly or fully compensated.

c) When part measurements are performed on the machine tool, compensation can reduce the measurement uncertainty. However, the metrological traceability of such measurements has to be ensured (see ISO 10360- series).

d) By relaxing the geometric requirements for guideways, positioning systems, and/or physical alignment of machine tool components, it may reduce the overall cost of the machine tool production.

On the other hand, the limits of numerical compensation are the following.

a) Long term stability of the machine tool will not be improved.

b) Thermo-elastic deformations may remain an important source of geometric changes.

c) Repeatability of the motion remains the limit for the achievable accuracy.

d) If model based compensations are used, it has to be ensured that the used machine tool model is consistent with the real machine tool behaviour.

e) An active compensation may drive additional axes during the cutting that would be static in an uncompensated machine tool. This may introduce additional errors, especially if the axes have significant reversal error, limited least increment step, or positioning accuracy characteristics that vary with the direction of motion.

f) The compensation for the errors in the functional orientation (FOR, L-VOL+, R-VOL+, see 8.2) ideally requires three orthogonal rotational axes, which only very few machine tools offer. On a typical five axis machine tool, certain axis orientations exist where one rotary axis is nominally parallel with the spindle axis. Those rotary axis orientations are referred to as kinematic poles. In the vicinity of these kinematic poles, the required motions to compensate for the errors in the functional orientation may not be directly available to the CNC and therefore may result in highly accelerated motions of other axes. This could put high demands on the dynamic stiffness and the control of the machine and may result in, for example, poor surface quality on the workpiece. These motions may also increase the power consumption of the drive systems and increase the thermo-elastic deformation of the machine tool structure. Therefore, compensation for the errors in the functional orientation should be handled with great care and only be used when the vicinity to these kinematic poles can be avoided by the programmed tool path or by other means.

g) The geometrical requirements for the machine tool components and assembly may also be important for the stiffness, the repeatability, and the durability of the machine tool. For example, relaxed tolerances in the guideways may decrease stiffness, repeatability, and/or misalignment of the spindle may increase tool wear. Therefore, lowering such geometrical requirements through error compensation may result in higher life cycle costs of machine tools.

The understanding of the benefits and limits of numerical compensations will help the manufacturers and the users to make best benefit of its implementation.

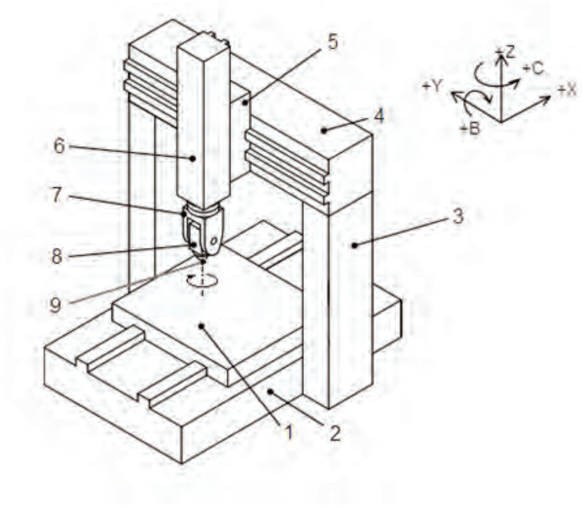
5 Kinematic representation of machine tool structure

5.1 Machine tool configuration and designation

The geometric representation of the machine tool provides a general overview of the machine tool structure and the identification of its axes of motion (see Figure 1).

The configuration of the machine tool is identified by sequentially listing the components that compose the machine tool structural loop between the workpiece and the cutting tool.

As an example, the structural code of the machine tool shown in Figure 1 can be described as [w X' b Y Z C B (C) t] by connecting the motion axes from the workpiece side to the tool side. In this description, the workpiece side and the tool side are distinguished by naming the workpiece by “w”, the tool by “t”, and the bed by “b”; (C) stands for the spindle axis without numerical control for angular positioning. (See ISO 10791-6).



Key

1	table (X’-axis)
2	bed
3	column
4	cross beam
5	ram saddle (Y-axis)
6	ram (Z-axis)
7	yoke (C-axis)
8	swivel spindle head (B-axis)
9	spindle (C)

Figure 1 — Example of geometrical representation of a vertical five-axis machining centre [w X’ b Y Z C B (C) t]

5.2 Kinematic representation of the machine tool

The kinematic representation of the machine tool structural loop describes the motion of (rigid) components and the joints that link them and specifically, for each individual moving component, defines the following:

- order in the kinematic sequence;
- the axes travel;
- the zero position (homing) of individual axes;
- the (nominal) position of the rotary axes average line.

The machine tool kinematic representation is typically defined in CNC-specific files that are configured by the machine tool manufacturer.

6 Geometric errors of the machine tool

6.1 Sources of geometric errors

Geometric errors of machine tools mainly derive from the following:

- component imperfections;
- alignment errors;
- elastic deformations of components;
- thermo-mechanical errors;
- loads and load variations;
- interpolation errors;
- motion control and control software;

— errors in compensation.

6.2 Geometric errors of axes of linear motion

Ideal axes of linear motion provide for nominal straight-line motion. Their position along such nominal straight lines is typically numerically controlled.

NOTE The linear axis to be compensated is not necessarily numerically controlled. A bridge-type machine tool with moveable cross-rail may numerically compensate geometric errors of the cross-rail movement, R, even if the cross-rail movement R is not numerically controlled.

A rigid object in a three-dimensional space has six degrees of freedom: three translations along the axes of an orthogonal coordinate system and three rotations around these axes. Straight-line motion allows one coordinate to vary while deviations in all other five degrees of freedom are constrained. Real machine tool axes of linear motion are affected by unwanted error motions that result in geometric errors along each one of the six degrees of freedom.

Definitions for geometric errors of axes of linear motion are given in ISO 230-1:2012, 3.4.

Definitions for positioning errors of axes of linear motion are given in ISO 230-2:2014, Clause 3.

Error motions and associated measured deviations are identified by the letter E followed by a subscript where the first letter is the name of the axis corresponding to the direction of the error motion and the second letter is the name of the axis of motion (see Figure 2).

6.3 Geometric errors of axes of rotation

Ideal axes of rotation provide angular motion conforming to the numerically controlled (instantaneous) position.

NOTE 1 The rotary axis to be compensated is not necessarily numerically controlled. A non-continuous rotary table may be numerically compensated even if the positioning of the non-continuous rotary table is not numerically controlled.

Real axes of rotation are affected by translational error motions that can (instantaneously or locally) be represented by their components along the axes of an orthogonal coordinate system and are affected by three angular error motions around these axes (see Figure 3).

ISO 230-7 provides comprehensive information, definitions, and procedures for the assessment of geometrical accuracy of axes of rotation. ISO 230-2 specifies tests for the determination of angular positioning errors.

NOTE 2 Error motions of rotary axes may not repeat each 360°, e.g. due to gears for positioning or due to roller bearings (see ISO 230-7:—, A.7.5)

Key

1	X-axis commanded linear motion
E_{AX}	angular error motion around X-axis (Roll)
E_{BX}	angular error motion around Y-axis (Yaw)
E_{CX}	angular error motion around Z-axis (Pitch)
E_{XX}	linear positioning error motion of X-axis; positioning deviations of X-axis
E_{YX}	straightness error motion in Y-axis direction
E_{ZX}	straightness error motion in Z-axis direction

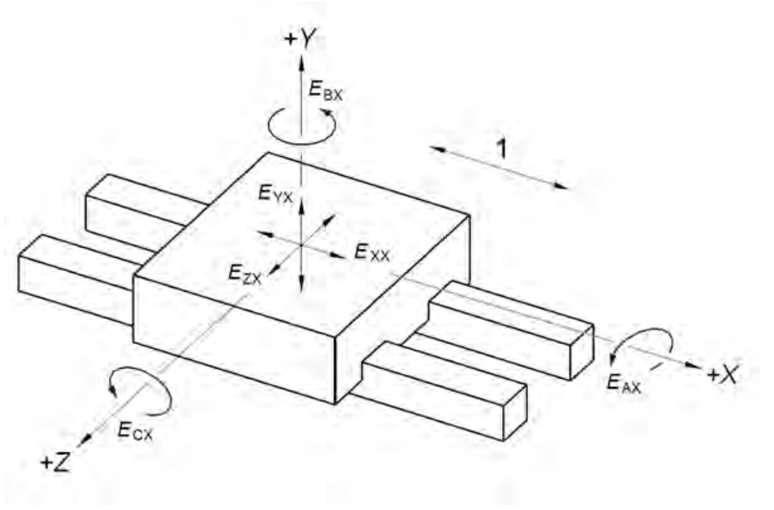
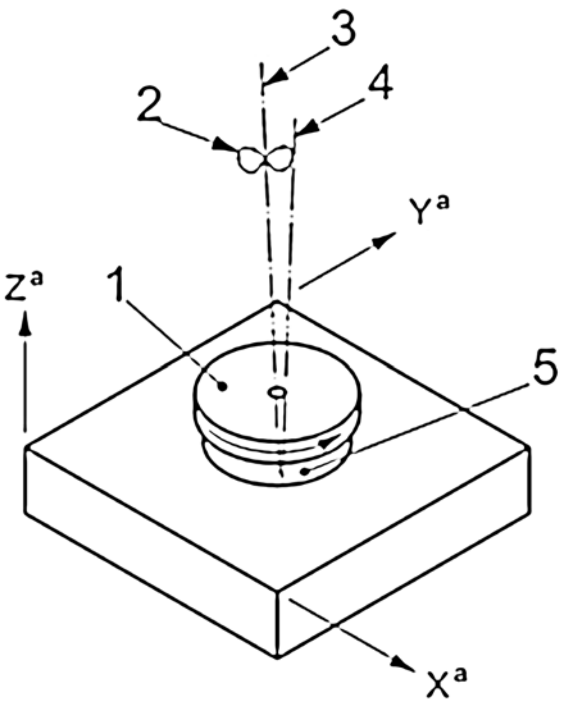


Figure 2 — Angular and linear error motions of a component commanded to move along a (nominal) straight-line trajectory parallel to the X-axis (Adaptation of ISO 230-1:2012, Figure 3)



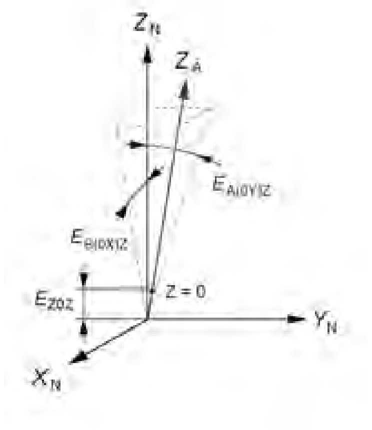
Key

C	C-axis commanded rotation
E_{XC}	radial error motion of C in X direction
E_{YC}	radial error motion of C in Y direction
E_{ZC}	axial error motion of C
E_{AC}	tilt error motion of C around X-axis
E_{BC}	tilt error motion of C around Y-axis
E_{CC}	angular positioning error motion of C; measured angular positioning deviations of C-axis
a	Reference axis

Figure 3 — Error motions of a C-axis of rotation (ISO 230-1:2012, Figure 12)

6.4 Position and orientation errors between axes of motion

Axes of linear motion may be represented by their reference straight lines that are characterized by two orientations (angles) in a three-dimensional coordinate system. For a numerically controlled linear positioning axis, the error of zero position of the axis (e.g. E_{Z0Z}) is also included in the total number of error terms representing the axis as shown in Figure 4.



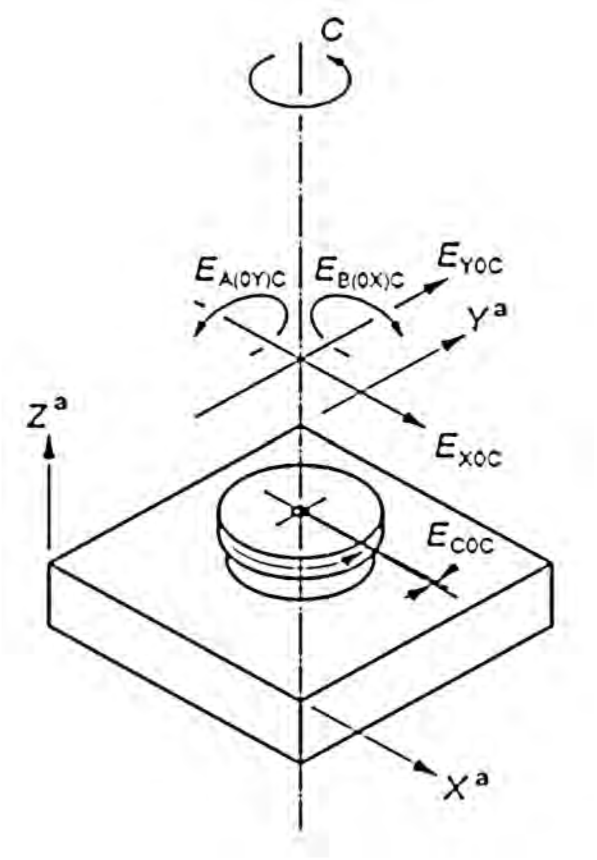
Key

X_N	nominal X-axis
Y_N	nominal Y-axis
Z_N	nominal Z-axis
Z_A	actual reference straight line of the component along Z-direction
E_{Z0Z}	zero position error of Z
$E_{A(0Y)Z}$	squareness error of Z to Y
$E_{B(0X)Z}$	squareness error of Z to X

NOTE In general, errors of the zero positions of linear axes (e.g. E_{Z0Z}) can be set to zero when checking geometric accuracy of a machine tool. Any change of E_{Z0Z} may cause errors in the workpiece.

Figure 4 — Position and orientation errors of a linear axis, Z (Adaption of ISO 230-1:2012, Figure A.1)

Axes of rotation may be represented by their axis average lines that are characterized by four parameters: two position coordinates and two orientations (angles) in the machine tool reference coordinate system (see Figure 5). For a numerically controlled rotary positioning axis, the error of the zero position of the axis (e.g. E_{C0C}) is also included in the total number of error terms.



Key

E_{X0C}	error of the position of C in X-axis direction
E_{Y0C}	error of the position of C in Y-axis direction
$E_{A(0Y)C}$	error of the orientation of C in the A-axis direction; squareness of C to Y
$E_{B(0X)C}$	error of the orientation of C in the B-axis direction; squareness of C to X
E_{C0C}	zero position error of C-axis
a	Reference axis

NOTE – In general, errors of the zero angular positions of rotary axes (e.g. E_{C0C}) can be set to zero when checking geometric accuracy of a machine tool. Any change of E_{C0C} may cause errors in the workpiece.

Figure 5 — Position and orientation errors of C-axis (Adaptation of ISO 230-1:2012, Figure 13)

6.5 Other relationship between axis of motion and axis average lines

The relative position and orientation between axis of motion and axis average lines may be also affected by offset, parallelism error, coaxiality errors, equidistance errors, and errors of intersection. Relevant definitions and methods for their determination are specified in ISO 230-1.

7 Determination of geometric errors

7.1 General

Geometric errors affect the relative motion between the component of the machine tool that carries the cutting tool and the component that carries the workpiece. These errors are defined and measured at the position or trajectory of the functional point.

The functional point is the tool centre point or the point where the cutting tool will contact the workpiece. This single point can move within the machine tool working volume. ISO 230-1 and machine tool specific standards, typically recommend applying test setups to determine errors between a (moving) tool of estimated average length and the hypothetical (straight) line of a (moving) workpiece assumed to be located near the centre travel of the machine tool axes.

7.2 Consideration on determination of geometric errors

When determining geometric errors to be used for numerical compensation, the functional point or trajectory should be carefully chosen keeping in mind the CNC configuration of the machine tool kinematic chain as well as the CNC compensation logic.

The first step for designing the measurement procedure is to choose the machine tool linear axis (or rotary axis) that will be considered as primary axis [thus aligning its reference straight line (or axis average line) to one of the machine tool reference coordinate system axes]. The second step should be to choose the linear (or rotary) axis that will be considered as the secondary axis. The third step should be the selection of the origin of the machine tool coordinate system, in accordance with the CNC kinematic chain configuration. Reference to ISO 230-1:2012, Annex A is recommended.

7.3 Selection of the machine tool coordinate system

The selection of the primary axis of the machine tool coordinate system should consider intended use, the kinematic chain, and the available CNC compensation functions of the machine tool.

ISO 230-1, Annex A provides useful information on machine tool coordinate system and position and orientation errors.

The definition of primary and secondary axis, as well as origin position, may be performed by subsequent transformation of the compensation data, ideally supported by the software that has been used to generate the compensation files.

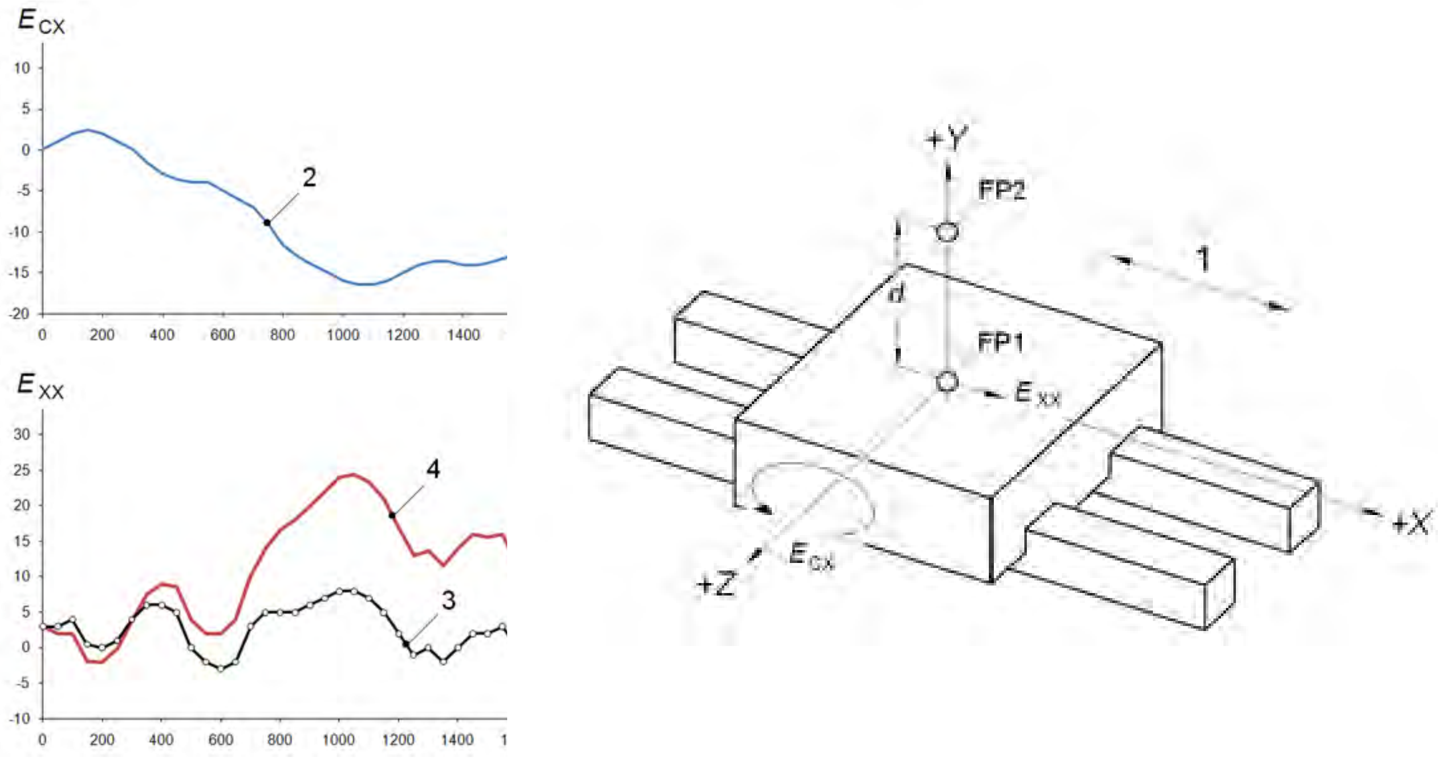
7.4 Superposition of individual errors

7.4.1 Rigid body behaviour

For a rigid body, angular errors of linear motion of machine components are not affected by the relative position of other machine tool components; whereas, the determination of positioning errors, straightness errors, and squareness errors would yield different results depending on the position of the measurement line within the machine tool working volume.

In the example depicted in Figure 6 (adapted from ISO 230-1:2012, Figure 10), the pitch error motion (E_{CX}) directly affects E_{XX} deviations measured at two lines that have relative offset in the Y-axis direction.

Similarly, the determination of the X-axis reference line slope and the determination of X-axis straightness deviations in the XY plane will be directly affected by the roll error motion (E_{AX}).



Key

1	X-axis motion
2	measured E_{CX} deviations
3	E_{XX} deviations measured at FP1
4	E_{XX} deviations at FP2 (assumed to be affected by 3 and E_{CX} only)
FP1	functional point 1
FP2	functional point 2
d	Y-axis coordinate difference between FP2 and FP1 (1 000 mm, for the depicted diagrams)
E_{CX}	angular error motion (pitch) [µrad]
E_{XX}	positioning error motion [µm]
X	X-axis coordinates [mm]

Figure 6 — Example of E_{CX} effect on E_{XX} (Adaptation of ISO 230-1:2012, Figure 10)

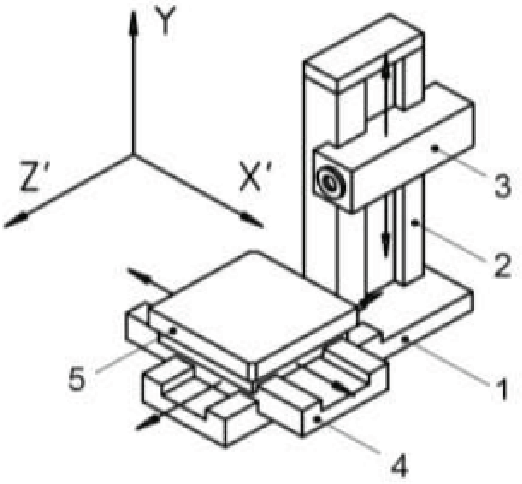
7.4.2 Non-rigid body behaviour

For some machine tool configurations, the rigid body assumption is not necessarily applicable. Certain machine tool types (e.g. machine tools with cross-table configuration) may exhibit non-rigid body behaviour.

For the example depicted in Figure 7, angular error motions of cross tables of large machine tools (Keys 4 and 5) will possibly be affected by the relative position between them, due to finite stiffness of the table saddle and of the bed, the connections between the bed and the foundation and the foundation itself, including its bearing on the sub-soil.

In the example of Figure 7, the Z'-axis pitch and roll error motions may be affected by the X'-axis position.

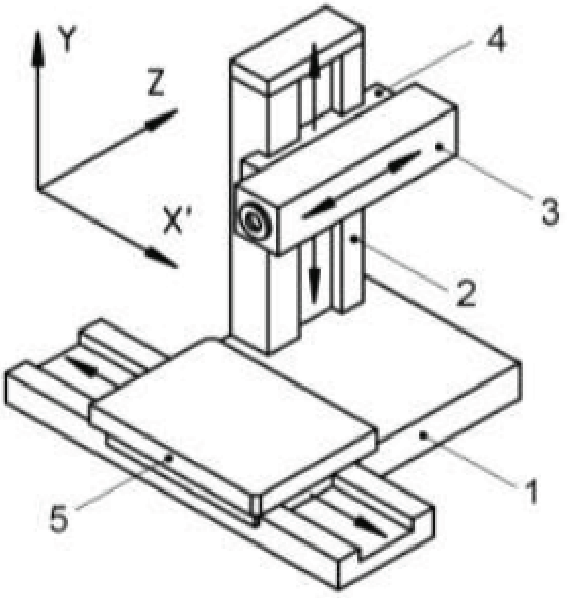
For the example depicted in Figure 8, due to the finite stiffness of the column, its connections to the machine tool bed, the bed itself and its connection to the foundation, the E_{AY} error motion of the spindle-head slide may vary as a function of the position of the Z-axis (ram).



Key

1	bed
2	column
3	spindle head
4	table saddle
5	table

Figure 7 — Example of configuration with possible non-rigid body behaviour of cross table



Key

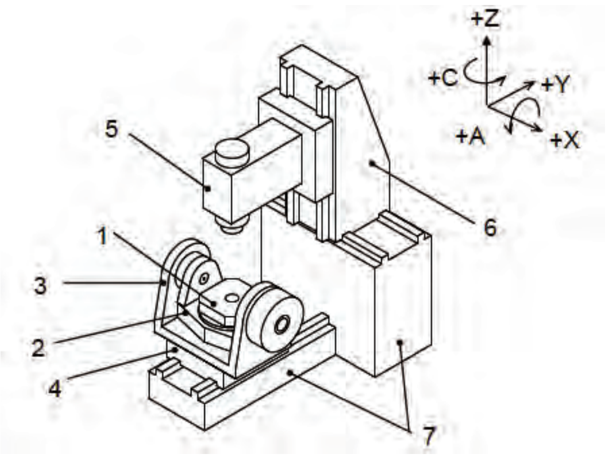
1	bed
2	column
3	spindle head (ram)
4	spindle-head slide
5	table

Figure 8 — Example of possible non-rigid body behaviour of a Y-axis carrying a heavy Z-axis ram

The cross-effect of error motions can be commonly observed also on rotary axes.

For example, in the tilting rotary table configuration depicted in Figure 9, the angular positioning error of a rotary table (C’-axis) may be influenced by the angular position of the tilting cradle A’-axis. Its typical cause is the gravity-induced displacement or deformation of the rotary table. When the table is vertical (A’ = 90° or −90°), the vertical displacement of the table may introduce the measurement error of its angular position by a rotary encoder (when a rotary encoder is attached to the rotating axis), and consequently, cause larger angular positioning error.

The radial error motion or the tilt error motion of the rotary table (C’-axis) may also change with the angular position of the tilting cradle (A’-axis), typically due to the gravity-induced deformation of the bearing of the rotary table.



Key

1	rotary table (C’-axis)
2	tilting cradle (A’-axis)
3	trunnion
4	table saddle (Y’-axis)
5	spindle head (Z-axis)
6	column (X-axis)
7	bed

Figure 9 — Example of a typical vertical five-axis machining centre with a tilting rotary table

In cases where the CNC does not allow for (partial) compensation of non-rigid body geometric errors, careful evaluation should be made to compute, for relevant errors, the single error compensation based on the CNC’s rigid body model that would minimize the residual machine tool geometric errors.

7.5 Direct measurement of geometric errors

Measurement of geometric errors is conducted according to existing test codes, particularly the following.

- For definitions for machine tool geometric errors, see ISO 230-1:2012, Clause 3.
- For geometric accuracy tests for axes of linear motions see ISO 230-1:2012, Clause 8.
- For geometric accuracy of axes of rotation, see ISO 230-7.
- For alignment of axes of motion (parallelism, squareness, coaxiality and intersection), see ISO 230-1:2012, Clause 10.
- For determination of the positioning accuracy and repeatability of numerically controlled axes of linear and rotary motion, see ISO 230-2.

Machine tool specific International Standards typically also specify test methods for the determination of geometric errors. These International Standards typically only specify requirements for the minimum number of sampling points that are deemed to be adequate for the purpose of error assessment.

When measurements are performed for subsequent geometric error compensation, good practice would recommend careful definition of the spatial frequency (steps) to be applied to properly sample the corresponding error function.

Examples of direct measurement of geometric errors are the following:

- determination of positioning error using a laser interferometer;
- determination of straightness error using a reference straightness artefact and a linear displacement sensor.

7.6 Indirect measurement of geometric errors

Indirect measurements include simple measurements like the determination of angular error motion by performing linear positioning error measurements at two (or more) parallel measurement lines, where the distance between measurement lines is known.

Indirect measurement of machine tool geometric errors is considered in ISO 230-1:2012, 11.7 where measurements of multiple distances in the machine tool working volume using 1-D, 2-D, and 3-D reference artefact or distance measuring instruments (multilateration) are described. The distance measuring instrument used for multilateration is, generally, a special laser tracking interferometer that automatically follows the target reflector on the component of the machine tool that carries the cutting tool and records the linear displacements for the programmed set of measurement points along multiple straight lines in the machine tool working volume and, possibly, the spherical angles associated with those lines. Sometimes long-range ball bars are used for the length measurement.

Indirect measurement of machine tool geometric errors also includes

a) circular tests addressed in ISO 230-4,

b) diagonal displacement test addressed in ISO 230-6, and

c) tests performed using 1-D, 2-D, or 3-D artefacts in combination with sensor nests (R-tests) considered in ISO 230-1:2012, 11.3.5.3 and addressed in machine tool specific standards (e.g. ISO 10791-6).

8 Compensation of geometric errors

8.1 General

The main prerequisite for numerical compensation of a machine tool is the quantified knowledge of its errors. This knowledge is generated by measurements of the machine tool error motions. Effective compensation requires repeatability of the machine tool errors and that the errors are time invariant. Depending on the capabilities of the compensation system, the CNC and the machine tool configuration, the compensation algorithm aims to bring the actual machine tool motion as close as possible to the nominal motion by modifying the programmed path in real time; the computational power needed in the CNC depends on the complexity of the compensation algorithm. An active compensation may result in small motions of axes that would not be active in an uncompensated machine tool, e.g. the Z-axis and Y-axis may move during commanded motion nominally along the X-axis to compensate for straightness errors.

8.2 Types of geometrical compensation

8.2.1 General

Different CNCs provide different capabilities of compensation. Compensation capabilities are also depending on the kinematic design of the machine tool, especially on the presence of rotary axes.

This Clause contains a classification of common geometrical compensations. This classification is based on conventional machine tools with two or three linear axes and up to three rotary axes. It provides an overview of different compensation types and their features and contains requirements, considerations for testing, and limits associated with their application.

8.2.2 Compensation for positioning errors of linear axes along specific lines, L-POS

This compensation will only compensate positioning error motions along the specific line. Angular errors (pitch and yaw) impair the positioning error on other lines parallel to this line. It will not reduce straightness error of axes. Furthermore, the effects of angular error motions are not compensated except on those specific lines.

The compensation (and measurement) is typically performed in the centre of travel of the other axes or the most frequently used machine tool volume.

8.2.3 Compensation for straightness errors of linear axes along specific lines, L-STR

This compensation will only compensate straightness error motions along the specific line segments. Angular errors (roll) affect the straightness error on other lines parallel to this line. It will not reduce positioning errors of axes. Furthermore, the effects of angular error motions are not compensated except on those specific lines.

The compensation (and measurement) is typically performed in the centre of travel of the other axes or the most frequently used machine tool volume.

8.2.4 Compensation for squareness error between axes of linear motion at specific lines, L-SQU

This compensation will only compensate squareness errors at the specific lines. Angular errors (roll, pitch, yaw) affect the squareness error at other measurement lines. It will not reduce positioning error of axes.

The compensation (and measurement) is typically performed in the centre of the machine tool volume most frequently used.

A straightness compensation option of a CNC may also be used for the compensation for a squareness error in a specific plane by adding a linear content (slope) to the straightness compensation values, calculated from the non-squareness (e.g. 50 µm/m) multiplied by the travelled distance of the compensated axis (e.g. 0,3 m) from the zero position.

8.2.5 Compensation for the angular error motions of linear axes on 3-D position of functional point in the working volume, L-ANG

The proper application of this compensation will result in homogenous positioning and straightness errors of the functional point in the working volume. It will not affect functional orientation. Machining operations using cutting tools with spherical tips can be compensated entirely. Manufacturing of parts using cutting tools with a large contact area (e.g. fly cutters, large milling tools, drills) will still reveal the effects of angular error motions.

Effective tool length and offset must be specified for machining and testing. Measurement of positioning errors may be performed anywhere in the working volume.

The testing of machine tools applying L-ANG compensation requires special attention (see 11.3).

8.2.6 Physical compensation for errors in functional orientation, FOR

Errors in functional orientation are physically compensated by rotary axes motion. This compensation requires three numerically controlled linear axes and at least two numerically controlled rotary axes that are not parallel to the cutting tool axis of rotation.

NOTE FOR includes compensation of error motions from linear and rotary axes.

Measurement of orientation error may be performed anywhere in the working volume. Direct measurement of relative angular errors between tool and workpiece will show the compensated angular motion.

The application of this compensation is typically implemented in combination with compensation L-ANG and R-ANG. If L-ANG and/or R-ANG are not applied, then unintended X, Y, Z movements introduced by the compensation of functional orientations should be compensated by other means. The application of this compensation will also improve residual errors resulting from large contact areas between tool and workpiece. However, working in the vicinity of kinematic poles (see Clause 4, item f) may result in problematic control behaviour.

8.2.7 Volumetric compensation of linear axes, L-VOL

This compensation includes L-POS, L-STR, L-SQU, and L-ANG compensations. The application of this compensation will result in minimized positioning and straightness errors in the working volume. It will not affect functional orientation. However, when using cutting tools with spherical tips, such functional orientation errors do not affect the quality of the workpiece. The use of tools with large contact area (e.g. fly cutters, large milling tools, drills) will reveal the effect of angular error motions.

Tool length and offset should be input in the CNC for testing. Measurement of positioning errors may be performed anywhere in the working volume. Angular errors of axes and tool are not physically compensated; direct measurement of angular errors will reveal uncompensated angular motion; indirect methods will not reveal uncompensated angular motion.

The testing of machine tools applying L-VOL compensation requires special attention (see 11.3)

8.2.8 Volumetric compensation of linear axes including functional orientation, L-VOL+

This compensation includes L-VOL and FOR compensations and requires three numerically controlled linear axes and at least two numerically controlled rotary axes that are not parallel to the tool axis of rotation.

Tool length and offset should be input in the CNC for testing. Measurement of positioning error may be performed anywhere in the working volume. Angular errors of axes and tool are physically compensated. Direct measurement of relative angular errors between tool and workpiece will show compensated angular motion.

The proper application of this compensation will result in reduced positioning and straightness errors in the entire working volume. Angular error motions of axes and functional orientation errors are compensated. It will also reduce residual errors resulting from large contact area between tool and workpiece. Working in the vicinity of kinematic poles (see Clause 4, item f) may result in problematic control behaviour.

8.2.9 Compensation for positioning errors of rotary axes, R-POS

This compensation will compensate for the angular positioning error of the rotary axis. Determination of angular positioning error performed by indirect methods (e.g. multilateration, R-Test) might be affected by radial and tilt error motions. This compensation will not improve radial, tilt, and face error motions.

8.2.10 Compensation for radial and axial error motion of rotary axes, R-RAX

This compensation will only compensate for the effects of radial error motions at a specific elevation over the table (in case of a rotating table) or at a specific tool length (in case of a rotating tool). Tilt error motions affect the radial error motions in other elevations or other tool length respectively. Tilt error motions affect face error motion even if axial error motion is compensated. The application of R-RAX will not reduce positioning errors of rotary axes.

8.2.11 Compensation for position and orientation errors of rotary axes, R-POR

This compensation will correct for position and orientation errors of rotary axes. Measurement of position and orientation can be affected by positioning error motions and radial error motions of the rotary axes. Typically, an axis average line of the rotation is specified. The measurement of position and orientation errors of rotary axes should be performed after the compensation of the linear axes is applied and activated.

NOTE Position and orientation errors describe the location of the axis average line in the coordinate system of the machine tool (see 6.4). This should not be confused with the angular positioning error of the rotary axis, which is the error function of the CNC axis positioning covered by R-POS.

8.2.12 Compensation for the tilt error motions of rotary axes on 3-D position of functional point in the working volume, R-ANG

The application of this compensation will result in the minimization of the effects of the rotary axis tilt error motions on the position of the functional point in the working volume. It will not affect functional orientation. However, when using cutting tools with spherical tips, such functional orientation errors do not affect the quality of the workpiece. Manufacturing of parts using tools with a large contact area (e.g. fly cutters, large milling tools, drills) will reveal the effects of angular error motion as long as the functional orientation errors are not physically compensated.

The testing of machine tools equipped with R-ANG compensation requires special attention (see 11.3).

8.2.13 Volumetric compensation for rotary axis errors, R-VOL

This compensation requires the CNC to make available volumetric compensation of rotary motion. It includes R-POS, R-RAX, R-POR, and R-ANG.

This compensation will not affect functional orientation. However, when using cutting tools with spherical tips, such functional orientation errors do not affect the quality of the workpiece. The use of large tools with large contact area (e.g. fly cutters, large milling tools, drills) will reveal the effect of the rotational errors.

The testing of machine tools equipped with R-VOL compensation requires special attention (see 11.3).

8.2.14 Volumetric compensation for rotary axis errors including functional orientation, R-VOL+

This compensation requires the CNC to make available volumetric compensation of rotary motion. It includes R-POS, R-RAX, R-POR, R-ANG, and FOR.

Angular errors of axes and tool are physically compensated. It will also minimize residual errors resulting from large contact area. Working in the vicinity of kinematic poles (see Clause 4, item f) may result in problematic control behaviour.

8.2.15 Machine tool-specific geometry compensation for linear axes, L-SPEC

Some machine tool manufacturers might apply specific error compensation strategies for linear axes. Relevant requirements, consideration for testing, and limits should be specified by the machine tool manufacturer.

8.2.16 Machine tool-specific geometry compensation for rotary axes, R-SPEC

Some machine tool manufacturers might apply specific error compensation strategies for rotary axes. Relevant requirements, consideration for testing, and limits should be specified by the machine tool manufacturer.

8.3 Role of temperature

Temperature and temperature variations will affect both the determination of machine tool geometric errors, and the machine tool geometric performances.

Good practice suggests conducting the tests prescribed in ISO 230-3 prior to the execution of machine tool geometric error assessment tests and subsequent validation of numerical compensation of geometric errors. These thermal tests may quantify the machine tool's stability as this constraints the improvement level that can be obtained with geometrical compensation techniques.

If compensations for thermally-induced errors are implemented in a machine tool, they should be activated for the measurement of geometric errors. Such compensation can, for example, be a compensation for thermal spindle growth or compensation of thermal scale expansion. Some machine tools may also have more complex thermal compensations.

Valuable information could also be gathered from ISO/TR 16015.[10]

8.4 Role of repeatability

Machine tool repeatability errors over time can have a number of causes including the following:

- reversal error, caused by mechanical play, friction or wear;
- thermo-elastic effects of machine tool components;
- plastic deformation of machine tool components or foundations over time.

Machine tool repeatability limits the part accuracy which can be achieved on a machine tool. During the measurement of geometric errors, the influence of the short-term repeatability can be reduced by averaging over a number of measurements, typically at least over different motion directions to average and/or analyse reversal error.

Reversal errors can potentially be observed in all geometric errors. If backlash compensation is applied (see 9.2.2), great care has to be taken that it is modelled correctly.

8.5 Role of machine tool least increment step

The least increment step of individual machine tool axes determines the minimum amount of compensation that can be applied. The least increment steps contribute to the unsystematic errors that cannot be compensated and potentially contribute to poor workpiece surface finish.

ISO 230-2:2014, Annex E provides considerations on least increment step.

8.6 Role of workpiece mass and tool mass

On some machine tool configurations, workpiece mass and tool mass (e.g. large grinding wheel) can influence the geometric performance of individual linear and rotary axes. Although the geometric accuracy of machine tools is typically determined with the machine tool operating under no-load, good practice would suggest that due consideration be given to the intended use of the machine tool.

9 Representation of geometric errors for compensation

9.1 General

Methods for determining the geometric accuracy of machine tools are described in ISO 230-1:2012. They are used in several machine-tool specific standards where the main objective is the assessment of the magnitude of the errors.

When geometric errors are determined with the specific purpose of applying numerical compensation, additional information is required to correctly input the measured data in the CNC. The detailed conventions for the format must be specified by the machine tool or CNC manufacturer. Special emphasis should be given to the following issues.

a) Use of compensation or error values (sign convention): A physical test using significant values may clarify this in case of doubt.

b) Use of absolute or incremental values: Absolute values are recommended since they are more intuitive to the user as, with incremental values, the error (or compensation) values to be applied at individual sampling points need to be derived from the integration of preceding values.

c) Compliance with the CNC-specific representation of the machine tool kinematic chain: The axis order has to be known and respected for all model-based compensations that involve angular compensations.

d) Compliance to datum and sign conventions: It is recommended to apply conventions of ISO 841 and ISO 230-1:2012.

e) Clarification on whether, for the compensation of angular error motions of rotary axes, the error values (or compensation values) are referred to the machine tool coordinate system or are referred to the axis of rotation itself.

Furthermore, it is good practice to document the following:

- the machine tool conditions prior to measurements (including the description of any warm-up cycles);
- linear or angular position of all linear and rotary axes within the working volume;
- the tool length represented by the instrumentation setup;
- tool offset (if any);
- load conditions (if any);
- feed speeds and accelerations applied during testing of the machine tool;
- ambient temperature conditions;
- thermal conditions of relevant machine tool components;
- active compensations.

9.2 Representation in look-up tables for individual errors

9.2.1 General

Numerical error values (or compensation values) are often input in the CNC in the format of one-dimensional look-up tables. Historically, numerical compensations of positioning errors (L-POS, R-POS) have been the first to be widely applied on numerically controlled machine tools. Straightness compensations (L-STR) came immediately after and are now present on virtually all CNCs available. Modern CNCs have extended these possibilities to cover all kinematic errors.

9.2.2 Common error tables or compensation tables

Common error tables (files) or compensation tables (files) typically contain:

- the identification of the nominal position and of the direction of the motion to be compensated (sometimes identified by CNC-specific G-codes), and
- two columns where the first one represents the axis of motion coordinate value and the second one represents the error to be compensated (or the compensation to be applied) along a specified direction.

Typically, the CNC would apply compensations that result from linear interpolation of discrete error (or compensation) values contained in the error (or compensation) table(s). Some CNCs may apply additional filtering or smoothing to avoid discontinuity in the machine tool velocity.

9.2.3 Compensation of reversal errors

Two different approaches are applied by different CNC manufacturers to express and compensate for a reversal error.

- A single value that is added or subtracted depending on the direction of axis motion.
- Two individual compensation functions depending on the direction of axis motion (in separate tables or columns, see example in Table 1). Sometimes the second table or column represents only the reversal error (or compensation) and is added to the error (or compensation) value for negative motion.

Table 1 — Example of L-POS error table including compensation of reversal error

Sampling positions (mm)	Error values (mm)	
X	$E_{XX}(+)$	$E_{XX}(-)$
0	0	0,000 8
50	0,001 5	0,002 2
100	0,001 9	0,002 5
...	...	...

Compensation for reversal errors can generally be applied to all kinematic errors.

9.2.4 Discussions and suggestions

It is recognized that the approach for the compensation for geometric errors is specific to the CNC manufacturers and that variations to these approaches could generate significant compatibility problems with systems that are already in use in the market.

It is nevertheless considered that, on one hand, when designing and implementing additions and expansions to existing numerical compensation for machine tool geometric errors, CNC manufacturers should give due consideration to the following.

a) Identification of geometric errors as specified in ISO 230-1:2012.

b) Sign convention conforming to ISO 841 and ISO 230-1:2012 prescriptions.

c) Error representation as the difference between measured values and nominal values.

d) Compensation representation as error values with reversed signs.

e) Clarification of geometric error representation/compensation: distinguishing if the CNC requires error values or compensation values.

f) Use of absolute values instead of incremental values.

g) Providing a pre-processor to convert files containing error functions conforming to ISO 841 and ISO 230-1:2012 conventions to the specific format that is interpreted by the CNC.

h) Origin of representation of error or compensation values, especially the axis positions where angular error/compensation values are set to zero.

i) File structure and method employed for compensation of reversal errors.

j) Limitations due to memory constraints to the spatial resolution of the error/compensation tables.

k) Facilities for simple activation/deactivation of individual geometric compensation.

l) Use of higher resolution on rotary axes where large tool or workpiece offsets are present.

On the other hand, measuring instruments and measuring systems manufacturers should consider providing a post processor to convert files formatted according to their standard representation to conform to ISO 841 and ISO 230-1:2012 conventions.

9.3 Representation as a spatial error grid

9.3.1 General

When error tables (or compensation tables) are given as described in 9.2, the CNC calculates an error value (or compensation value) in the functional point position (or orientation) by superposing the effects of individual geometric errors of each axis based on the kinematic model (see Clause 3) programmed in the CNC.

For the spatial error grid, a user is required to input the translational (or orientation) error value (or compensation value) at all the grid points (sampling points) of linear or angular position of each axis. To perform a model-based compensation by using the spatial error grid, a user must have knowledge, and/or software, to calculate the spatial error grid from the machine tool model. It is, on the other hand, possible to apply the spatial error grid to compensate any unmodelled error motion of the machine tool, i.e. even errors that cannot be modelled by the kinematic model assumed in the CNC, if several spatial error grids can be processed correctly.

9.3.2 Common spatial error grid tables and spatial compensation grid tables

It is typical to separate spatial error grids (or spatial compensation grids) for linear axes (e.g. X-, Y-, Z-axes) and rotary axes (e.g. A- and C-axes).

Spatial error grids and spatial compensation grids for linear axes (see example in Table 2) typically contain

— a set of discrete sampling points for each linear axis,

— three-dimensional positioning errors ($E_{\mathrm{X,XYZ}}$, $E_{\mathrm{Y,XYZ}}$, $E_{\mathrm{Z,XYZ}}$ in X-, Y-, and Z-directions), or their compensation values (ΔX, ΔY, and ΔZ to compensate $E_{\mathrm{X,XYZ}}$, $E_{\mathrm{Y,XYZ}}$, and $E_{\mathrm{Z,XYZ}}$), at each sampling point (X,Y,Z) of each axis, and

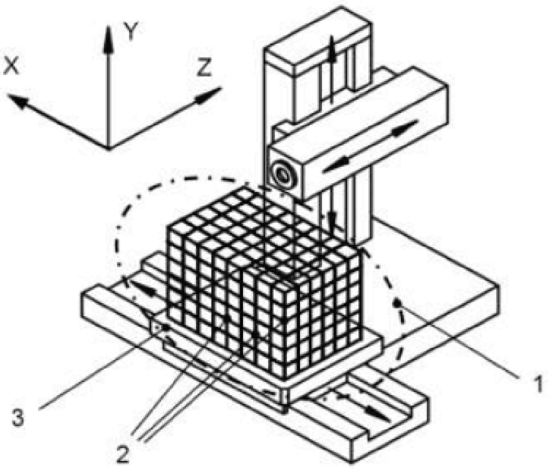
— three-dimensional angular errors ($E_{\mathrm{A,XYZ}}$, $E_{\mathrm{B,XYZ}}$, $E_{\mathrm{C,XYZ}}$ around X-, Y-, and Z-directions), or their compensation values (ΔA, ΔB, and ΔC to compensate $E_{\mathrm{A,XYZ}}$, $E_{\mathrm{B,XYZ}}$, and $E_{\mathrm{C,XYZ}}$), at each sampling point (X,Y,Z) of each axis.

For example, if a set of N_{x} positions of X-axis, a set of N_{y} positions of Y-axis, and a set of N_{z} positions of Z-axis, are given, the three-dimensional positioning error (or compensation) will be specified at total of $N_{\mathrm{x}} \cdot N_{\mathrm{y}} \cdot N_{\mathrm{z}}$ grid points.

Table 2 — Example of spatial compensation grid for linear axes

#	Sampling points			Compensation values					
	X (mm)	Y (mm)	Z (mm)	ΔX (mm)	ΔY (mm)	ΔZ (mm)	ΔA (°)	ΔB (°)	ΔC (°)
1	0	0	0	0	0	0	0	0	0
2	50	0	0	0,001	0,001	0	0,001	0,002	0
3	100	0	0	0,002	−0,002	−0,001	−0,003	−0,003	−0,002
...	...	...	...	...	...	...	...	...	...

Figure 10 illustrates an example of spatial error grid for linear axes. At each sampling (grid) point, translational and orientation errors are given.



Key

1	spatial error grid
2	sampling points
3	work table

Figure 10 — Example of a spatial error grid for linear axes

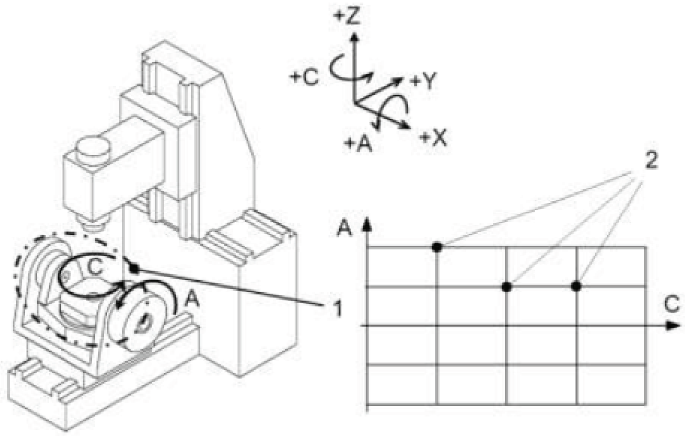
Spatial error grids and spatial compensation grids for rotary axes (see example in Table 3) typically contain

- a set of discrete sampling positions for each rotary axis,
- three-dimensional linear errors ($E_{X,AC}$, $E_{Y,AC}$, $E_{Z,AC}$ in X-, Y-, and Z-directions), or their compensation values (ΔX, ΔY, and ΔC to compensate $E_{X,AC}$, $E_{Y,AC}$, and $E_{Z,AC}$), at each sampling point (A, C) of each axis, and
- three-dimensional angular errors ($E_{A,AC}$, $E_{B,AC}$, $E_{C,AC}$ around X-, Y-, and Z-directions), or their compensation values (ΔA, ΔB, and ΔC to compensate $E_{A,AC}$, $E_{B,AC}$, and $E_{C,AC}$), at each sampling point (A, C) of each axis.

Table 3 — Example of spatial compensation grid for rotary axes

#	Sampling points		Compensation value					
	A (or B) (°)	C (°)	ΔX (mm)	ΔY (mm)	ΔZ (mm)	ΔA (°)	ΔB (°)	ΔC (°)
1	0	0	0	0	0	0	0	0
2	0	5	0,001	−0,001	0,001	0	0	0,001
3	0	10	0,002	−0,002	0	0,002	−0,001	0,002
...	...	...	...	...	...	...	...	...

Figure 11 (for a vertical five-axis machining centre with a tilting rotary table) and Figure 12 (for a five-axis machining centre with two rotary axes on the spindle head) illustrate examples of spatial error grids for rotary axes. At each sampling point (grid point) of angular positions of the two rotary axes, an error (or a compensation value) for the translation and orientation of the rotary table (in Figure 11) or the tool (in Figure 12) is given.



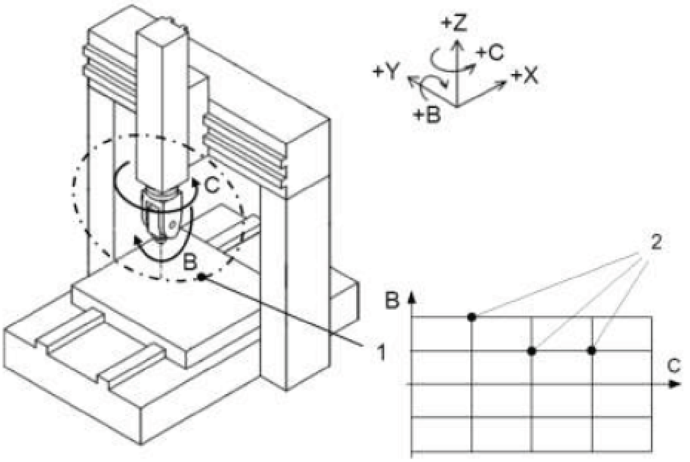
Key

1	spatial error grid
2	sampling points

NOTE 1 For the machine tool shown in Figure 11 angular positioning E_{CC}, radial error motion E_{YC} and tilt error motion E_{AC} of C-axis might change with the angular position of A-axis if rigid body behaviour assumption for C-axis is not fulfilled.

NOTE 2 Some CNCs define the angular positioning of a rotary table only within single full rotation (i.e. 0° to 360°). Others define it in the range exceeding the full rotation. In such a case, sampling points for the spatial error grid can be set over the specified angular range of the rotary axis.

Figure 11 — Example of a spatial error grid for rotary axes for a vertical five-axis machining centre with a tilting rotary table



Key

1	spatial error grid
2	sampling points

Figure 12 — Example of a spatial error grid for rotary axes for a five-axis machining centre with two rotary axes on the spindle head

10 Application of numerical compensation for geometric errors

10.1 General

This Clause introduces some important considerations especially for the applications of complex compensations.

NOTE For machine tools with two drives per axis (e.g. gantry machine tools), a relative compensation of both axes may be first performed to minimize physical angular deviations and optimize the control behaviour.

10.2 Alignment of the compensated motion to the machine tool structure

This issue is addressed in ISO 230-1:2012, Annex A.

When compensating a machine tool for straightness, angular errors, or squareness, special care has to be taken to the relation of the motion of the compensated axis to physical axes of the machine tool. For example, in an uncompensated machine tool, the spindle axis (or its zero position in case of a tilting axis) is typically aligned to the Z-axis. This can be a functional requirement, e.g. for the drilling of deep holes. This relation should also hold for the compensated motion of the machine tool. The alignment of the compensated motion to the physical axes of the machine tool is a rotation in two angles (see 7.3) and is ideally supported by the used metrology software.

NOTE Alignment of axis is conducted for axis average lines. Local alignment (of sections of the axis) is affected by rotational errors.

10.3 Direct measurements for the generation of error tables or compensation tables

For the direct measurements of single error components, the sequence of measurements is crucial.

For linear axes, good practice suggests the following sequence:

a) For each individual linear axis:
    1) measurement of and compensation for angular errors;
    2) measurement of and compensation for positioning and straightness errors;
b) Measurement of and compensation for squareness errors between axes of motion.

For rotary axes, good practice suggests the following sequence:

a) For each individual rotary axis:
    1) measurement of and compensation for tilt error motion;
    2) measurement of and compensation for radial and axial error motions;
    3) measurement of and compensation for angular positioning errors;
b) Measurement of and compensation for position and orientation errors of axis average lines.

For tilting rotary tables and universal heads:

a) Measure and compensate the axis nearer to the bed in the kinematic chain i.e. the rotary axis that carries the other rotary axis.
b) Measure and compensate the axis that is farther from the bed in the kinematic chain i.e. that rotary axis that is carried by the other rotary axis.

Examples:

In Figure 11 (tilting rotary table): first compensate A-axis and then C-axis.

In Figure 12 (swivelling head): first compensate C-axis and then B-axis.

Where measurements of the geometric errors of the rotary axes rely on motion of the linear axes, good practice suggests the following sequence: (i) measurement of and compensation for the individual errors of the linear axes (ii) measurement of and compensation for the individual errors of the rotary axes.

10.4 Indirect measurements for the generation of error tables or spatial error grids

For indirect methods, the machine tool is typically measured in an uncompensated state, or with only compensation for positioning errors (L-POS, R-POS) and/or thermal compensations applied.

The functionality of the respective software will ideally analyse the individual error components in a way that their synthesis in the compensation algorithm in the machine tool CNC will describe the machine tool errors, as appropriate, in error tables (or compensation tables) or spatial error grids (or spatial compensation grids).

10.5 Compensation of already compensated machine tools

Generally it is possible to assess and compensate for the geometric errors of a machine tool already compensated. Geometrical compensation can generally be superimposed by appropriate handling in the CNC or by modification of existing error tables (or compensation tables) or spatial error grids (or spatial compensation grids).

However, the following points have to be considered.

a) A compensation of type ANG or VOL will compensate for the effect of angular errors on the functional point, but not the physical orientation of the tool. Therefore, direct measurements of angular errors (e.g. by an angular interferometer or an electronic level) will still reveal the physical motion, even if the compensation is applied. In contrast, indirect measurement (e.g. by multilateration or laser interferometer measurements at different lines) will show the effect of the compensation type ANG or VOL, when the measurement is performed at the functional points (or trajectories) specified in the CNC. Therefore, the reference point for the measurement on the tool side must be specified, typically by setting the tool length in the CNC accordingly.

b) Differently from item a), a physical compensation for the error in the functional orientation (FOR) does not necessarily also compensate the effect that the angular errors of the axes have on the 3-D position of the functional point. Direct measurement may indicate the actual functional orientation errors to be zero, although the linear effect of errors might still lead to significant errors in X, Y, and Z at the functional point.

c) When a machine tool with compensation A is measured and the superimposed compensation model B is based on certain assumption (e.g. rigid body behaviour), it has to be ensured, that the machine tool with the compensation A can be described adequately by the compensation model B.

d) The repeatability and reversal error, of straightness measurement for example, could be adversely affected when a nominally stationary axis is applying compensation compared to when it is stationary.

Generally, the superposition of compensation L-POS and/or R-POS with any other compensation is not likely to cause problems.

11 Validation of numerical compensation of geometric errors

11.1 Measurement uncertainty and compensation

Numerical compensation is regarded as a tool to improve machine tool accuracy, similar to a mechanical alignment or scraping. Of course, any metrology applied for performing measurement for compensation will have a measurement uncertainty associated with it. It is not trivial to evaluate the effects of this measurement uncertainty on the accuracy of the compensated machine tool. Some metrology instrument manufacturers offer software to predict achievable machine tool accuracy e.g. by Monte

Carlo simulations. However, the performance of a compensated machine tool should be tested according to the applicable standards (see 11.3).

11.2 Considerations on operation of compensated machine tools

Generally the operation of compensated machine tools is not different from the operation of an uncompensated machine tool when the instructions given by the machine tool manufacturer/supplier or the CNC manufacturer are followed. However, the following points should be considered.

a) An active compensation may execute small motions also on axes that are nominally not programmed to compensate errors of the nominal motion axes. E.g. on a programmed X-axis motion Y- and Z-axis may be moved by the CNC to compensate for straightness errors of the X-axis.

b) Clamping of an axis would prevent it from applying numerical compensation. Clamping of an axis can also alter geometric errors. Effective compensation on machines that operate with axes in both clamped and unclamped states may require special attention.

c) The inherent small motions of all axes may lead to degraded surface finish on the part due to the least increment step and the parameterization of an active friction control. Sometimes the friction compensation of a numerical control has to be optimized for the application of compensations.

d) In case of a compensation of angular errors by linear axes (VOL, ANG), the active tool length has to be known by the CNC. If the tool length specified in the CNC is significantly different from the real tool length, the compensation will not work effectively. However, when applying usual tool setting operations, the tool length should also be set correctly for the compensation. This also applies to many types of compensations for rotary axes (R-POS, R-POR, R-ANG, R-VOL).

e) A physical compensation for the errors in the functional orientation (VOL+, FOR) may result in high axes speeds when working in the vicinity of kinematic poles (see Clause 4, item f). Typically, this condition should be avoided for tasks, where high part accuracy is required. In extreme cases, even a potential safety problem may arise due to unexpected high accelerations of axis motions.

11.3 Consideration for testing compensated machine tools

Generally, the numerical compensation of a machine tool is an intrinsic component of the system and it is activated for testing. By agreement between the machine tool manufacturer/supplier and the user, a subset of tests may also be performed without compensation, but the default case is the activation of all installed compensations.

Testing of machine tools can be done by machining of test pieces (see, for example, ISO 10791-7) or by performing interpolation measurements (see, for example, ISO 10791-6). For the machining of test pieces, the considerations of 11.2 apply.

For geometrical measurements of the motions of compensated machine tools, it is recommended that measurements are carried out using setups (and sampling points) different from the ones used in generating compensation values. Furthermore, special attention has to be given to the following points.

a) Measurement of positioning, straightness or squareness errors between linear axes, location of rotary axes, axial and radial error motions of rotary axes:

If compensation L-ANG, R-ANG, L-VOL, or R-VOL is applied, the effective offset where the measurement is taken must be properly specified on the tool side, e.g. the offset of the used optical reflector or the contact point of the indicator.

b) Measurement of angular errors of linear axes or tilt error motions of rotary axes:

A compensation of type L-ANG, R-ANG, L-VOL or R-VOL will compensate for the effect of rotations on the position of the functional point, but not the functional orientation of the tool. For testing, the following has to be considered.

- Direct measurement of angular errors (e.g. by electronic levels or angular interferometers) will still reveal the physical uncompensated angular motion. The observed errors will be unchanged by the compensations.
- Indirect measurements (e.g. by multilateration, R-test or differential positioning or straightness measurement) will correctly measure the effect of the angular compensation on the functional point. However, it has to be kept in mind, that the functional orientation of the tool is unchanged. For measuring the physical orientation of the tool, direct measurements must be applied. Alternatively indirect measurements may be performed with an offset applied that is not communicated to the CNC: In this case the angular motion of the tool is still detectable by indirect measurements.

c) Circular errors (ball bar test):

If compensation L-ANG, R-ANG, L-VOL, or R-VOL is applied, the tool offset must be properly specified to the spherical joint on the tools side. If such compensations are applied, then changed offsets are required on the tool side or on the workpiece side to detect angular error motions like pitch, yaw, or roll. This method only works if the changed offsets are not communicated to the CNC.

d) Spindle alignment:

The spindle should be aligned to the direction of the compensated Z-axis motion when all rotary axes on the tool side are set to 0°. Spindle alignment is tested typically by an indicator probing along a cylindrical test mandrel mounted on the spindle.

11.4 Traceability of compensation

If traceability of a machine tool is required to perform measurements for part inspection, relevant tests specified in ISO 230-10 as well as applicable tests specified in ISO 10360 (all parts) have to be performed on the compensated machine tool.

12 Documentation on compensation

The availability and extent of the documentation on numerical compensation of the machine tool geometric errors involves the machine tool manufacturer Intellectual Property Rights and the possible partial transfer of such rights to the end user or to third parties (e.g. service providers).

It is strongly suggested that manufacturer/suppliers and users reach clear agreement on this specific subject, with due consideration to the following points:

a) the technology for numerical compensation of geometric errors is, very often, resulting from specific research and development activities of the machine tool manufacturer;

b) the end user might want to have full access to compensations;

c) modification and/or adaptation of numerical compensation data involves responsibility issues and requires adequate knowledge and skill.

Annex A
(informative)

Alphabetic list of abbreviations of compensation types

Acronym	Description	Sub-clause
FOR	Physical compensation for the error in the functional orientation by rotary axes	8.2.6
L-ANG	Compensation for the of angular error motions of linear axes on 3-D position of functional point in the working volume	8.2.5
L-POS	Compensation for positioning errors of linear axes along specific lines	8.2.2
L-SPEC	Machine tool-specific geometry compensation for linear axes	8.2.15
L-SQU	Compensation for squareness error between axes of linear motion at specific lines	8.2.4
L-STR	Compensation for straightness error of linear axes along specific lines	8.2.3
L-VOL	Volumetric compensation of linear axes (incl. L-POS,L-STR, L-SQU, L-ANG)	8.2.7
L-VOL+	Volumetric compensation of linear axes including functional orientation (incl. L-VOL, FOR)	8.2.8
R-ANG	Compensation for the of angular error motions of rotary axes on 3-D position of functional point in the working volume	8.2.12
R-POR	Compensation for the position and orientation errors of rotary axes	8.2.11
R-POS	Compensation for rotary axis angular positioning error	8.2.9
R-RAX	Compensation for radial and axial error motion of rotary axes	8.2.10
R-SPEC	Machine tool-specific geometry compensation for rotary axes	8.2.16
R-VOL	Volumetric compensation for rotary axis errors (includes R-POS, R-RAX, R-POR, R-ANG)	8.2.13
R-VOL+	Volumetric compensation for rotary axes errors including functional orientation (incl. R-VOL, FOR)	8.2.14

Bibliography

[1] ISO 230-2:2014, *Test code for machine tools — Part 2: Determination of accuracy and repeatability of positioning of numerically controlled axes*

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

[3] ISO 230-4, *Test code for machine tools — Part 4: Circular tests for numerically controlled machine tools*

[4] ISO 230-6, *Test code for machine tools — Part 6: Determination of positioning accuracy on body and face diagonals (Diagonal displacement tests)*

[5] ISO 230-7[1], *Test code for machine tools — Part 7: Geometric accuracy of axes of rotation*

[6] ISO 10360-2:2009, *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions*

[7] ISO 10360-3:2000, *Geometrical Product Specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 3: CMMs with the axis of a rotary table as the fourth axis*

[8] ISO 10360-5:2010, *Geometrical product specifications (GPS) — Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 5: CMMs using single and multiple stylus contacting probing systems*

[9] ISO 10791-6, *Test conditions for machining centres — Part 6: Accuracy of speeds and interpolations*

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

[11] ASME B5-54-2005, *Methods for Performance evaluation of Computer Numerically Controlled Machining Centers*

[12] SCHWENKE H., KNAPP W., HAITJEMA H., WECKENMANN A., SCHMITT R., DELBRESSINE F. Geometric error measurement and compensation of machines – An update. CIRP Annals – Manufacturing Technology, **Vol. 57**, 2008, pp. 660–75.

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[1] To be published.

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