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Machine tools — Numerical compensation of geometric errors

Machines-outils — Compensation numérique des erreurs géométriques

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

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Foreword

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

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

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.

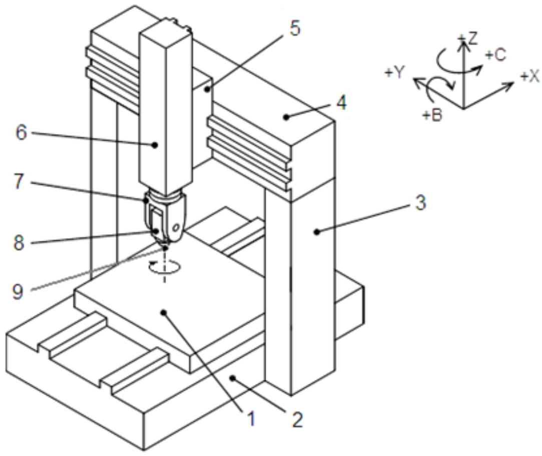
5 Kinematic representation of machine tool structure

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;

