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Simplifications of the volumetric error model because of the structural loop of machine tools

Majda Paweł[a], Joanna Jastrzębska [a]

[a]*The West Pomeranian University of Technology Szczecin, Piastow 17, 70-310 Szczecin, Poland*

e-mail address: pawel.majda@zut.edu.pl

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ABSTRACT

After many years of intensive work the international experts from ISO TC 39 published the technical report called ISO TR 16907 "Machine tools – numerical compensation of geometric errors". This document defines the terminology, presents benefits and limitations of numerical compensation of machine tools' and measuring machines' errors. It gives machines manufacturers and users vital information about how to use numerical compensation. In the context of those types of compensation defined in ISO TR 16907, this article shows rules of selecting models of Volumetric Error for three-axis machine tools. What is more, this paper presents some principles of reduction of these proposed models because of the functional tasks for machine tools. One of the obtained results is an array of reduced models for three-axis machine tools. This array determines the degree of detail of the model and the experimental research program that needs to be carried out in order to determine the Volumetric Error distribution.

1. INTRODUCTION

Numerical compensation of geometric errors of machines (both: machine tools and coordinate measuring machines) is a standard procedure applied by manufacturers. It is based on independently carrying out errors measurements and introducing them as corrections to the computer numerical control (CNC) system of machine tools. In this way, the positioning accuracy of the actuators of the machine is improved (which is called tuning).

Depending on the type of geometric errors, the ISO TR 16907 [4] report classifies various types of numerical compensation. It gives 15 categories depending on the complexity and types of compensated errors. The most advanced of them take into account the effect of all translation errors and linear and/or rotational axes, including the possibility of compensation of tool orientation throughout the working space of the machine.

This article focuses on the model for volumetric compensation of linear axes for three-axis machine tools. This type of compensation includes the ability to compensate for: positioning errors, straightness, angular errors and the squareness of translational numerically controlled axes. In this approach, the machine tool with the indexed position of the tool head is also classified as three-axis one. Analytical considerations were carried out for the entire population of closed-loop chain of structural elements of three-axis machine tools with a serial kinematic structure.

Manufacturers of CNC control systems for machine tools (e.g. Fanuc, Heidenhain, Sinumerik and others) offer various options for machine error compensation. One can risk saying that the previously mentioned producers provide a full range of possibilities with respect to the types of compensation defined in ISO TR 16907 [4]. Therefore, the purpose of this article is to provide information on the selection of the correct method and/or of the Volumetric Error (VE) model for a three-axis machine tool. This means that the choice is

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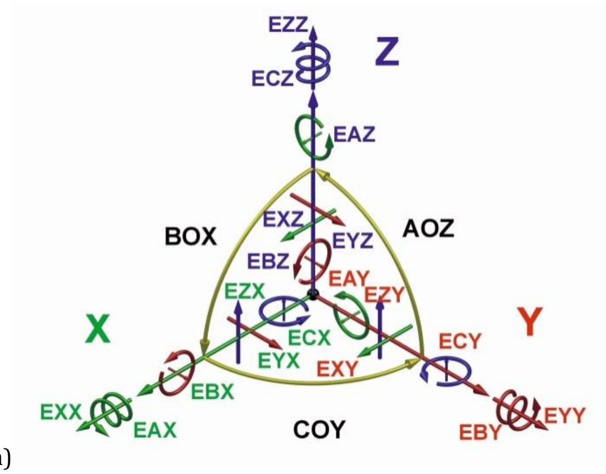
made taking into account the functional features of the machine tool. Achieving that formulated goal should help to support the selection of measuring means as well as determine the scope of necessary to make measurements and buy an adequate error compensation option in the machine tool from the control system manufacturer.

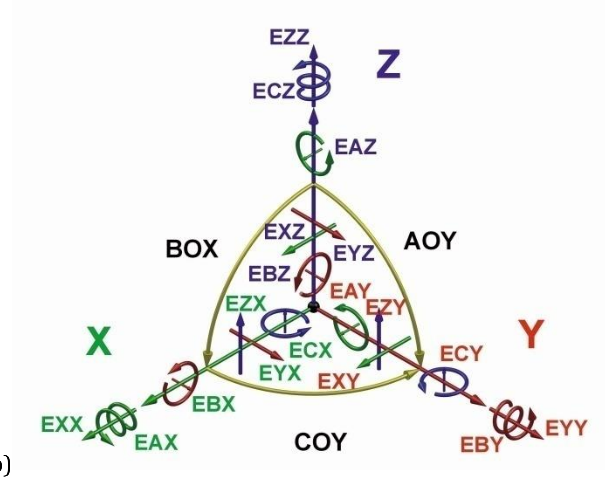
2. SELECTION OF THE REFERENCE SYSTEM FOR THE NUMERICAL MODEL OF GEOMETRIC ERROR COMPENSATION OF THREE-AXIS MACHINE TOOLS

The VE model itself is built on the assumption of the kinematics motion of rigid body. To model the motion of the machine support system including geometric errors homogeneous matrix transformations are usually used [5,6,7,10,11,12]. Firstly, it is crucial to specify a reference system in which the VE distribution is modeled. According to the standard [3], the coordinate system of the machine tool is the right-hand rectangular system. Typically, individual elements of the machine tool structural loop are assigned properly marks of the reference system in directions which they move rectilinearly (*X*, *Y*, *Z*) or rotary (around the following axes - *A*, *B*, *C*). The position and orientation of the machine coordinate system is defined using the reference line of the guide movement axis of the guide connections. This can be done by selecting the main axis of motion so that the reference line is aligned with one axis of the machine coordinate system. In this way, two orientation parameters and an orthogonal plane are specified. Then, the secondary axis is selected so that its reference line is parallel to the next movement axis and defines the third orientation parameter. The parameter is resulted from the projection of the reference line on the previously defined plane. The selection of the main axis, secondary axis and the origin of the machine coordinate system depends on: its construction, the possibility of mechanical adjustment and the possibility of compensating machine tool errors. Normally, the direction and position of the Z axis of machine tools (milling machines and also lathes) coincide with the direction and position of the *C* axis, i.e. the main drive (spindle) [1,2]. It should be noticed that in a three-axis machine tool, it is not possible to numerically compensate for the parallelism of the reference line of axis *C* and *Z*, thus numerical compensation of squareness of the tool axis with respect to the *X* and *Y* axes. This kind of error is very undesirable in the context of drilling deep holes. With the movement of the tool in the Z axis, the diameter of the hole is enlarged. In this situation the Z axis should be considered as the main axis of the coordinate system, because it is obligatory to base it on the *C* spindle axis during assembly. This should ensure minimising the error sources of the machine tool, which cannot be compensated numerically. For the same reason, the orientation of the system should be based on the Z axis in which the VE model will be built. The fulfillment of this criterion means the elimination of numerical error compensation for the squareness of the *X* and *Z* axes and/or the *Y* and *Z* axes during the Z axis movement. These errors compensated during the movement of the *X* or *Y* axes do not impair the accuracy of shaping deep holes.

Further considerations require the adoption of a specific error determination convention. Exemplary designations in accordance with the ISO 230-x series of standards are shown in Fig. 1,



a)



b)

Fig. 1. Sample determination of kinematic errors in the translational axes of machine tools according to ISO 230 with regard to the squareness of the mutual axis a) Z to Y, b) Y to Z

where: *X*, *Y*, *Z* are the axes of the VE model reference system, *EXX*, *EYY*, *EZZ* are positioning errors, *EYX*, *EXY*, *EYZ* are horizontal straightness errors, *EZX*, *EZY*, *EXZ* are vertical straightness errors, *EAX*, *EBY*, *ECZ* are roll errors, *EBX*, *EAY*, *EAZ* are pitch errors, *ECX*, *ECY*, *EBZ* are yaw errors, *COY* is squareness error between *Y* axis to *X* axis, *AOZ* is squareness error between *Z* axis to *Y* axis, *BOX* is squareness error between *X* axis to *Z* axis. Squareness errors between axes are scalars, while the others are the functions of the currently viewed position along the axis.

It should be noted that the presented case in Fig. 1 b) may ensure the correct selection of the reference system for modeling VE for a three-axis machine tool in view of the issues discussed earlier (i.e. machining holes). The variant shown in Fig. 1 a) could be correctly used to compensate for machine tool errors assuming that the tool will never be used to drill holes (e.g. in specialized machining). However, for typical machine tools this would be unjustified in practical use. If the base axis is assumed so that the remaining axes can be determined according to this orientation, then it is necessary to correctly write squareness errors in the matrices of homogeneous transformations of the VE model. Records for the shown cases in Fig. 1 are presented in Table 1.

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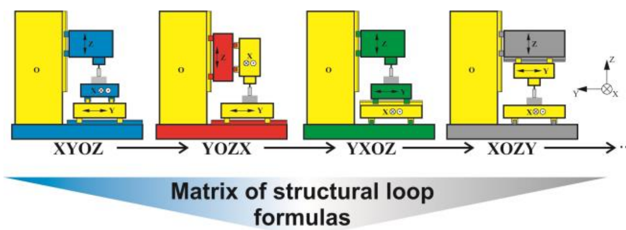
Table 1. Matrices of homogeneous transformations of geometric error models of the X, Y and Z axes

For squareness errors according to Fig. 1a)	For squareness errors according to Fig. 1b)
$E_x = \begin{bmatrix} 1 & -ECX & EBX & EXX \\ ECX & 1 & -EAX & EYX \\ -EBX & EAX & 1 & EZX - BOX * x \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$E_x = \begin{bmatrix} 1 & -ECX & EBX & EXX \\ ECX & 1 & -EAX & EYX \\ -EBX & EAX & 1 & EZX - BOX * x \\ 0 & 0 & 0 & 1 \end{bmatrix}$
$E_y = \begin{bmatrix} 1 & -ECY & EBY & EXY - COY * y \\ ECY & 1 & -EAY & EYY \\ -EBY & EAY & 1 & EZY \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$E_y = \begin{bmatrix} 1 & -ECY & EBY & EXY - COY * y \\ ECY & 1 & -EAY & EYY \\ -EBY & EAY & 1 & EZY - AOY * y \\ 0 & 0 & 0 & 1 \end{bmatrix}$
$E_z = \begin{bmatrix} 1 & -ECZ & EBZ & EXZ \\ ECZ & 1 & -EAZ & EYZ - AOZ * z \\ -EBZ & EAZ & 1 & EZZ \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$E_z = \begin{bmatrix} 1 & -ECZ & EBZ & EXZ \\ ECZ & 1 & -EAZ & EYZ \\ -EBZ & EAZ & 1 & EZZ \\ 0 & 0 & 0 & 1 \end{bmatrix}$
x, $y$andz – current position of the considered axis in the machine coordinate system	

3. THE STRUCTURAL LOOP OF THE MACHINES WITH SERIAL KINEMATICS

The kinematics of machine tools' working process is the result of mutual movements of the machine tool body elements. These movements are directed by the guiding connection. The arrangement of these connections - called the guide system - is the implementation of closed-loop chain of structural elements. Wragow [9] proposed a method to write the types of structural loop by the formula. This method assumes that in the structural formula there is included unambiguous information about the possibility of carrying out movements through separate elements of the machine tool body. Using the classical rule of X, Y, Z axes and rotational axes A, B, C, as well as symbol O as a stationary body, the structural formula is constructed as follows: workpiece → coordinate system axis symbols corresponding to the directions of displacements of subsequent elements together with the body designation a stationary → tool. By transposition (permutations without repetition) of the axis designations (X, Y, Z) with the stationary machine body (O) for a three-axis machine tool, a total of 24 (4!) structural patterns are obtained. So that there are 24 variants of the body system, shown in Fig. 2. In Poland, structural loop study, due to various machine design criteria, was examined by G. Szwengier's team [8].

Due to the modelling of the VE distribution, it is crucial to consider the overhang of the tool for each structure of three-axis machine tool. The tool overhang can be defined in many ways for example in relation to the point of the tool holder.



ZXYO	ZXOY	ZOXY	OZXY
ZYXO	ZYOX	ZOYX	OZYX
XZYO	XZOY	XOZX	OXZY
YZXO	YZOX	YOZX	OYZX
XYZO	XYOZ	XOYZ	OXYZ
YXZO	YXOZ	YOXZ	OYXZ

Fig. 1. Formulas of structural loop elements of a three-axis machine tool (in these formulas the tool rotation mark around the Z axis, workpiece and tool are omitted)

Fig. 3 presents possible cases where a variant with an indexed swivel head is considered as a general case of a three-axis machine tool. In the further part of the article, it will be shown that the VE model depends on these variants. The selected option determines the appropriate simplifications of the VE model.

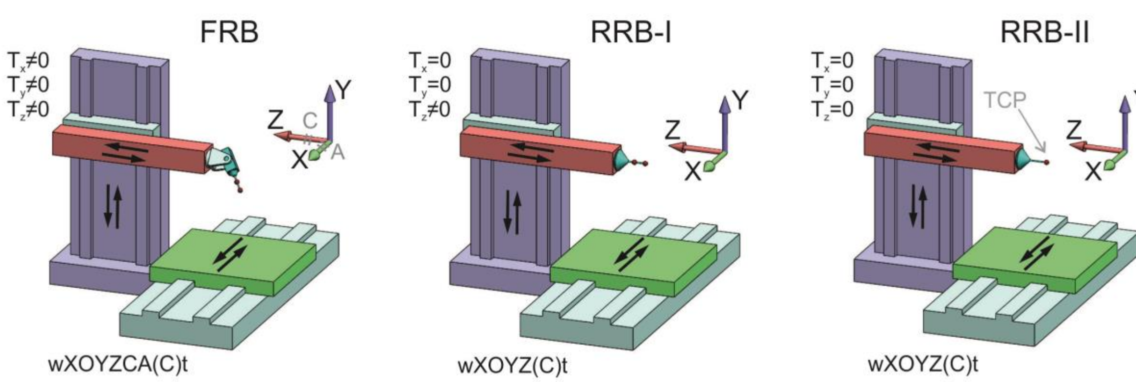


Fig. 2. Three types of the tool overhang and the adequate names of the simplified motion models of the rigid body of a three-axis machine tool: FRB - full rigid body, RRB - reduced rigid body Ti=X,Y,Z - tool overhang in the direction of the X, Y and Z axes

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4. SIMPLIFICATION OF THE VOLUMETRIC ERROR MODEL OF MACHINES

Performing mathematical operations in the convention of modeling the motion of a rigid body with the use of homogeneous matrix transformations, the formulas for the VE components can be obtained for the X, Y and Z axes, respectively. In calculations, the components of errors in the second and higher power are omitted; they are considered to be irrelevant. For example, structural loop with the indexed position of the spindle position is: *wOXYZCA(C)t* that is for the FRB model (fig. 3) in the reference system according to Figure 1b, the designs look as follows:

$$VE_x = EXX + EXY + EXZ + T_z * (EBX + EBY + EBZ) + \\ - T_y(ECX - ECY - ECZ) - ECX * y + + EBX * z + \\ + EBY * z - COY * y \quad (1)$$

$$VE_y = EYX + EYY + EYZ - T_z * (EAX - EAY - EAZ) + \\ + T_x(ECX + ECY + ECZ) - EAX * z - EAY * z \quad (2)$$

$$VE_z = EZX + EZY + EZZ + T_y * (EAX + EAY + EAZ) - \\ - T_x(EBX - EBY - EBZ) + EAX * y + - BOX * x + \\ - AOY * y \quad (3)$$

For the RRB-I model, that is for T_x and T_y = 0, they will be simplified to the form:

$$VE_x = EXX + EXY + EXZ + T_z * (EBX + EBY + EBZ) + \\ - ECX * y + EBX * z + EBY * z - COY * y \quad (4)$$

$$VE_y = EYX + EYY + EYZ - T_z * (EAX - EAY - EAZ) + \\ - EAX * z - EAY * z \quad (5)$$

$$VE_z = EZX + EZY + EZZ + EAX * y - BOX * x - AOY * y \quad (6)$$

and for the RRB-II model, i.e. for T_x, T_y and T_z = 0, they will be simplified as follows:

$$VEx = EXX + EXY + EXZ - ECX * y + EBX * z + EBY * z + \\ - COY * y \quad (7)$$

$$VE_y = EYX + EYY + EYZ - EAX * z - EAY * z \quad (8)$$

$$VE_z = EZX + EZY + EZZ + EAX * y - BOX * x - AOY * y \quad (9)$$

Analysing the formulas 1-9, it can be seen that depending on the considered variant of the tool overhang there are simplifications consisting in the elimination of appropriate angular errors.

Positioning errors, straightness and squareness occur in every type of model, i.e. FRB, RRB-I and RRB-II for each structure. In the FRB model, all geometrical errors are considered. However, in the RRB-II model of the *wOXYZt* structure (see Fig. 3) four angular errors are eliminated: *ECY*, *EAZ*, *EBZ* and *ECZ*. This means that the movement of the central point of the tool (TCP) does not dependent on these errors. Therefore, there is no need to determine these errors in the measurements and to include them in the CNC control system as a compensating correction of the TCP position.

After performing the analogous calculations for the other structural loop, the results were obtained. They made it possible to compare the data presented in Table 2 for the RRB-II model.

Table 2. Angular error table in the RRB-II model for different structural loop

Structurallo op / ERROR	OXYZ	OYXZ	OZXY	OXZY	OYZX	OZYX	XOYZ	YOXZ	ZOXY	XOZY	YOZX	ZOYX	XYOZ	YXOZ	ZXOY	XZOY	YZOX	ZYOX	XYZO	YXZO	ZXYO	XZYO	YZXO	ZYXO
EAX					●	●					●	●					●	●					●	●
EBX			●		●	●			●		●	●					●	●						
ECX		●			●	●		●			●	●					●	●						
EAY			●	●		●			●	●		●			●	●								
EBY			●	●					●	●					●	●					●	●		
ECY	●		●	●			●		●	●					●	●								
EAZ	●	●			●		●	●			●		●	●										
EBZ	●	●		●			●	●		●			●	●										
ECZ	●	●					●	●					●	●					●	●				
●does not appear in the model RRB-II																								

5. CONCLUSIONS

The analytical results of the VE model presented in this article allow formulating a general conclusion for three-axis machine tools: the type of the structural loop of the machine determines the form of VE patterns due to the influence of the tool overhang and angular errors (pitch, yaw, roll). Therefore the influence of the factors considered in this article should always be taken into account. Especially while planning the scope of measurements of geometrical errors of the machine tool and while selecting the option to compensate these errors in the CNC controller. Realising these mentioned aspects, time and money can be saved.

Considering dimensions that were mentioned before, if the structure has the designation of the "O" in the structural formula of stationary body which is at the beginning of the whole structural formula, it means that this type of structural loop is the most resistant to the influence of the tool overhang (even if amplified by angular errors). In these cases, the solution is to reduce the largest number of angular errors (Table 2). This is probably the reason why coordinate measuring machines are designed as gantry structure or other options with a movable table (in one axis) in relation to

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the stationary body. Moreover, it is crucial while selecting the reference system for the VE model to consider the machining tasks that need to be performed by the machine tool. This determines the direction of compensation for errors in the squareness of the numerically controlled axes during the implementation of straight-line movements. Omitting this criterion (in specific cases, e.g. while drilling deep holes) might lead to a deterioration of the accuracy of shaping workpieces even when numerical error compensation of the machine tool is used.

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