Modeling of Geometric Error in Linear Guide Way to Improved the vertical three-axis CNC Milling machine's accuracy

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Abstract. The purpose of this study was to improve the accuracy of three-axis CNC Milling Vertical engines with a general approach by using mathematical modeling methods of machine tool geometric errors. The inaccuracy of CNC machines can be caused by geometric errors that are an important factor during the manufacturing process and during the assembly phase, and are factors for being able to build machines with high-accuracy. To improve the accuracy of the three-axis vertical milling machine, by knowing geometric errors and identifying the error position parameters in the machine tool by arranging the mathematical modeling. The geometric error in the machine tool consists of twenty-one error parameters consisting of nine linear error parameters, nine angle error parameters and three perpendicular error parameters. The mathematical modeling approach of geometric error with the calculated alignment error and angle error in the supporting components of the machine motion is linear guide way and linear motion. The purpose of using this mathematical modeling approach is the identification of geometric errors that can be helpful as reference during the design, assembly and maintenance stages to improve the accuracy of CNC machines. Mathematically modeling geometric errors in CNC machine tools can illustrate the relationship between alignment error, position and angle on a linear guide way of three-axis vertical milling machines.

1. Introduction

With the rapid development of manufacturing industry in the business world, machine tool Computer Numerical Control (CNC) is playing a very important role and widely used in large quantities in the field of modern production such as automotive field to the field of aerospace. Meeting the demands required machine tools with precision and high accuracy and high productivity. One of the key performance criteria for modern production is the ability of CNC machines to produce products with very meticulous dimensions with complex shapes [1]. Similarly, the criteria of accuracy and high accuracy must be owned by the performance of machine tools, especially when the design and

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assembly of the machine. There are two ways to improve geometric accuracy in machine tools: (1) design and manufacture of precision machines and (2) fault compensation [2].

A decrease in the quality of production results may be due to a decrease in the performance of CNC machine tools caused by various sources of error factors in machine tools. Some types of error sources that contribute to deviations occur in the construction of machine tools, such as geometric errors, thermal errors and servo errors [3]. Among several deviation factors in machine tools, geometric errors have the greatest effect on accuracy and precision in machine tools [1-3].

In the design of CNC machine tools other than construction must be strong, also must be considered in the straightness profile of linear guide way. Linear guide way is one of the most important components in machine tools because it serves as a place where the work table moves along the path that has been determined in accordance with the motion axis of the machine, especially to do the motion straight.

2. Geometric Error Modeling Methodology

The geometric error component consists of position error, alignment error, angle error, as shown in figure 1. Each one axis with translational movement on the machine tool there are six error parameters ie one position error, two parameters error alignment and three angle error is pitch, yaw, roll.

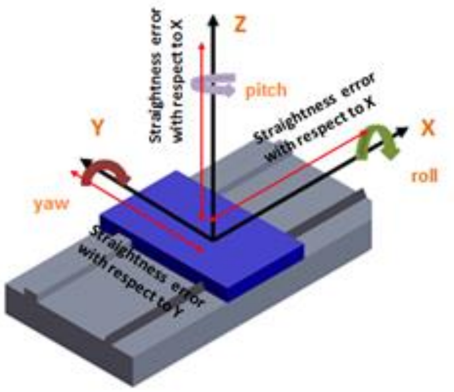

Figure 1. Error parameters of three-axis milling machine.

The source of geometric error will have an effect on the inaccuracy of the parts of the machine so that the position of the cutting tool on the machining process can occur in an undesirable position.

In the three-axis milling machine, there are 21 parameters of geometric errors that come from 3 linear positioning errors, 6 linearity errors, 9 angular errors, and 3 perpendicular errors, as shown in table 1 [4]. Illustration of Figure 1 shows error parameters of three-axis milling machine. Error parameters in figure 1 are elaborated to several geometrical error components for each axis in the three-axis machine. Several geometrical errors are listed in Table 1.

Table 1. Geometrical error components in the three-axis machine

Component errors	**Linear position errors**	**angular errors (roll, pitch, yaw)**
axis-X	$\delta_x(X)$, $\delta_y(X)$, $\delta_z(X)$	$\varepsilon_x(X)$, $\varepsilon_y(X)$, $\varepsilon_z(X)$
axis-Y	$\delta_x(Y)$, $\delta_y(Y)$, $\delta_z(Y)$	$\varepsilon_x(Y)$, $\varepsilon_y(Y)$, $\varepsilon_z(Y)$
axis-Z	$\delta_x(Z)$, $\delta_y(Z)$, $\delta_z(Z)$	$\varepsilon_x(Z)$, $\varepsilon_y(Z)$, $\varepsilon_z(Z)$
Squarness error	φ_{xy}, φ_{yz}, φ_{zx}	

3. Linear Guide Ways

Linear guide way is one of the most important components in machine tools and delivers smooth movement on machine tools, so it can produce high accuracy[5]. The main function of the linear guide way is to ensure that the work table or motion element can move along a predetermined path or in accordance with the axis of the machine tool. In every guide way has two Linear Motion (LM).

In a linear guide way there are six parameters of geometric error as shown in the figure 2, and for each linear motion can have six geometic errors, as shown in figure. 3. Geometric error that occurs in one linear guide way will affect the accuracy of machine tools or performance machine tools[6].

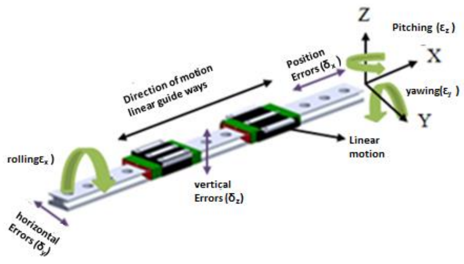

Figure 2. One linear guide way with two linear motion (LM) has six geometric error parameters.

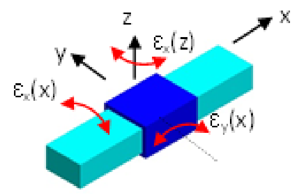

Figure 3. Geometric error in one linear motion at one linear guide way.

3.1. Angular Error Pitching

The angular error in linear guide way is pitch error, yaw and roll. The angle error of pitching in one linear guide way can be modeled as shown in figure 4. Point A 'and B', representing each Linear motion that serves as a place to move and support the machine tool workbench, then the equation angle error as follows:

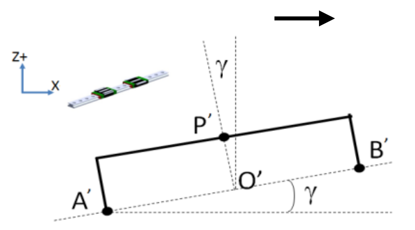

Figure 4. Condition of geometric error occurred in one linear guide way by experiencing angular error (pitching).

$$\gamma = tan^{-1}\left(\frac{(Z_B+\Delta Z_B)-(Z_A+\Delta Z_A)}{(X_B+\Delta X_B)-(X_A+\Delta X_A)}\right) \quad (1)$$

where: z_A , z_B : the linear motion A and B, position of motion A and B moves toward the Z-axis.
x_A, x_B : the linear motion A and B, position of motion A and B moves toward the X-axis.
Δz_A, Δz_B : motion drift position from linear motion A and B toward the Z-axis.
Δx_A , Δx_B : motion drift position from linear motion A and B toward the X-axis.
This one example calculation using mathematical modeling, shown in table 2.

Table 2. Error pitching linear guide way left from Tapping Brother machine.

Z_A(mm)	Z_B(mm)	Y_A(mm)	Y_B(mm)	ΔZ_A(mm)	ΔZ_B(mm)	ΔY_A(mm)	ΔY_B(mm)	pitching(γ^o)
0	0	25	25	-0,0331	-0,0277	0,00	2,60	0,0021

3.2. Position error and Vertical Error

Error position in one linear guide way can be modeled through figure 6 with its mathematic modeling written in equation 2, while the mathematical modeling fot vertical alignment error is given in equation 3.

$$X'_P = \frac{(X_B+\Delta X_B)-(X_A+\Delta X_A)}{2} - h\, sin\gamma \quad (2)$$

where: x_A, x_B : the linear motion A and B, position of motion A and B moves toward the X-axis.
Δx_A , Δx_B : motion drift position from linear motion A and B toward the X-axis.
h : high table from the surface of the machine block to the work table surface.
γ : pitching error

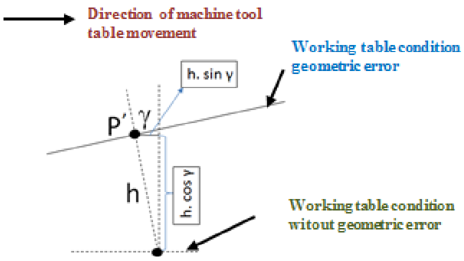

Figure 5. Error position and vertical error in one linear guide way.

Vertical alignment error is a straightness alignment toward the vertical of the linear surface guide ways.

$$Z'_P = \frac{(Z_B+\Delta Z_B+hcos\gamma)-(Z_A+\Delta Z_A+hcos\gamma)}{2} \tag{3}$$

where: z_A , z_B : the linear motion A and B, position of motion A and B moves toward the Z-axis.
Δz_A, Δz_B : motion drift position from linear motion A and B toward the Z-axis.
h : high table from the surface of the machine block to the work table surface.
γ : pitching error
This one example calculation using mathematical modeling, shown in table 3.

Table 3. Error vertical alignment error linear guide way left from Tapping Brother machine.

Za(mm)	Zb(mm)	Ya(mm)	Yb(mm)	ΔZ_A(mm)	ΔZ_B(mm)	h(mm)	γ	cos γ	Z'_P(mm)
0	0	25	25	-0,0331	-0,0277	30	0,0539	0,9985	0,0027

3.3. *Angular Yawing Error*
The angular error in a linear guide way taking into account the horizontal alignment deviation is called Yawing. Yawing is the rotation that occurs on the vertical axis towards the direction of translation of linear motion guide way. The motion of yawing angle errors can be modeled as shown in fihure 6.

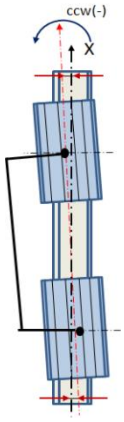

Figure 6. Angular error (yawing) in liner guide way.

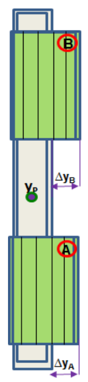

Figure 7. Geometric error linear horizontal error for one linear guide way.

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The yawing angular error equation is as follows:

$$\beta_P = tan^{-1}\frac{(y_B+\Delta y_B)-(y_A+\Delta y_A)}{(x_B+\Delta x_B)-(x_A+\Delta x_A)} \tag{4}$$

where : z_A , z_B : the linear motion A and B, position of motion A and B moves toward the Z-axis.
x_A , x_B : the linear motion A and B, position of motion A and B moves toward the X-axis.
Δz_A , Δz_B : motion drift position from linear motion A and B toward the Z-axis.
Δx_A , Δx_B : motion drift position from linear motion A and B toward the X-axis.
This one example calculation using mathematical modeling, shown in table 4.

Table 4. Error yawing error linear guide way left from Tapping Brother machine

X_A(mm)	X_B(mm)	Y_A(mm)	Y_B(mm)	ΔX_A(mm)	ΔX_B(mm)	ΔY_A(mm)	ΔY_B(mm)	yawing(γ^o)
0	0	25	25	-0,2089	-0,5730	0,0039	0	-0,0108

3.4. *Horizontal Error*

The motion of horizontal errors can be modeled as shown in figure 7. The horizontal errors equation is as follows:

$$Y'_P = \frac{(y_B+\Delta y_B)-(y_A+\Delta y_A)}{2} = \frac{1}{2}[(y_B + \Delta y_B) - (y_A + \Delta y_A)] \tag{5}$$

where: y_A , y_B : the linear motion A and B, position of motion A and B moves toward the Y-axis.
Δy_A , Δy_B : motion drift position from linear motion A and B toward the Y-axis.
This one example calculation using mathematical modeling, shown in table 5.

Table 5. Error horizontal alignment error linear guide way left from Tapping Brother machine.

Ya(mm)	Yb(mm)	X_A(mm)	X_B(mm)	ΔX_A(mm)	ΔX_B(mm)	Y'_P(mm)
25	25	0	0	0,2089	0,5730	0,3641

3.5. *Angular Rolling Error*

The motion of horizontal errors can be modeled as shown in figure 8. Shown in figure 9, the direction of rotation of pitch angle error, yaw and roll.

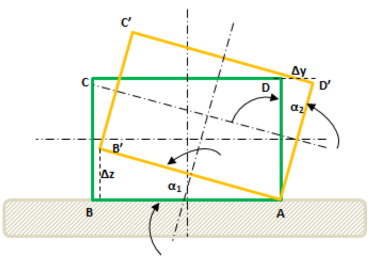

Figure 8. Angular error is a rolling error in linear guide way

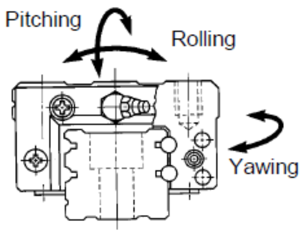

Figure 9. Angular error is a pitching error, yawing error and rolling error in linear guide way.

The rolling errors equation is as follows:

$$\alpha_c = tan^{-1}\frac{1}{2}\frac{\Delta z}{(AB+AD)} \tag{6}$$

where: $\Delta z = \Delta y$: motion drift position from linear motion A and B toward the Z-axi and the Y-axis.
AB and AD: height and width of linear motion.

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4. Conclusion

The conclusion of modeling geometric error is mathematically as follows:

1. Pitching error is affected by the magnitude of vertical alignment error toward the direction of translation movement of the work table and position error.
2. The angular yawing error is affected by horizontal alignment error toward the direction of translation movement of the work table and position error.
3. The vertical alignment error is affected by motion deviations in the direction perpendicular to the direction of translation movement of the work table.
4. Rolling angle error is affected by horizontal alignment error and vertical alignment error on the direction of translational movement of the work table.
5. Furthermore, the development of geometric fault modeling will be done by taking into account geometric error to two linear guide way.

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