Error Parameters of Milling Machine by Measurement of Machined Parts

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***Abstract*—** Quality of machined parts depends on the accuracy of machine movements in machining processes. In order to improve accuracy of machined parts, all parameters of geometric error of machine movement must be characterized and compensated. A mathematical error-model of 3-axes Vertical Milling Machine Center was derived from a model of imperfect motion of a rigid body. The error-dimensions of the machined part that may affect to each error-parameter were measured by Coordinate Measurement Machine. The errors parameters were then analyzed from those error-dimensions. Then, direct measurement of error parameters were measured by Laser Interferometer System according to the ISO-230 standard. These measured parameters are compared to the analyzed error parameter.

***Keywords*— Geometric error, vertical milling machine, coordinate measurement machine, Laser Interferometer System, machining processes**

I. INTRODUCTION

Precision and accuracy play an important role in industry in order to get acceptable quality of machined parts. Therefore, calibration is necessary for machines or tools. Laser Interferometer System (LIS) is a nanometrological device used to examine and calibrate a machining center. Unfortunately, LIS and calibration process increase overall cost and manufacturing time. This paper proposes a methodology of using Coordinate Measurement Machine (CMM) in ISO-10791 to examine the error parameters of Vertical Milling Machine Center (VMC, Makino S33) comparing the results with those from LIS and mathematical model base on kinematics of VMC in ISO-230.

Error parameters of machine originate from various causes, e.g. geometric errors, thermal errors, force errors and dynamic errors, etc. Geometric errors occur from wear or stress of the assembled parts and the imperfect structures of the machine. Previous study suggested that 70% of geometric errors led to the inaccuracy and imprecision of machined part [1].

Geometric errors have 21 parameters in a 3-axis machine, e.g. scale errors, straightness errors, angular errors and squareness errors. Mathematical model using Homogeneous Transformation Matrix (HTMs) of VMC has been suggested to compute and compensate those errors.[1]. [2] Laser Interferometer Tracking System (LITS) was used to measure translational and also angular errors of a multi-axis machine. It was found that LITS could measure most of geometric error parameters precisely. However, LITS had high cost and was very time consuming to install and align. Generally, when testing the accuracy of machine tools by LIS or other similar devices, technicians often follow ISO-230 (Standard of method for testing the accuracy of machine tools) to examine and collect error parameters. However, due to the number of data and long processing time of ISO-230, ISO-10791(Test condition for machining center) is also used.

II. THEORY

A. Overview of Machine Error Parameters

Geometric error parameters of machine have two main components: linear error parameters and angular error parameters. Linear error parameters comprise of scale error which occurs when the machine moves along the moving axis and two parameters in the direction perpendicular to scale errors called straightness errors. Angular errors occur from rotational movement of the machine called roll, pitch and yaw. Also, squareness errors occur between two faces of a machined part. Fig. 1 demonstrates geometric parameter errors of a three-axis VMC which is moving in X-axis.

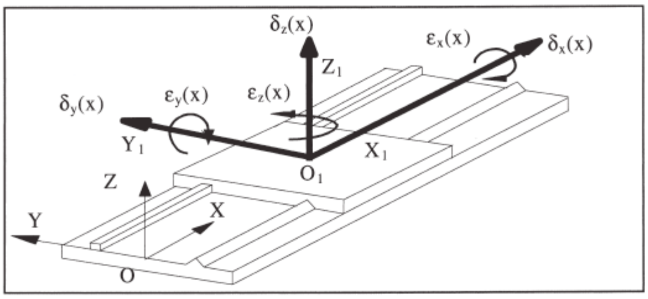

Fig.1 Schematic of geometric parameter errors of 3-axes VMC's X-carriage system

The symbols in Fig.1 are as follows:
O_RXYZ: Reference frame coordinate of the VMC
$O_1X_1Y_1Z_1$: Carriage coordinate system (X-axis)
$\delta_x(x)$: Scale error in X-axis
$\delta_y(x)$: Horizontal straightness error along Y-axis
$\delta_z(x)$: Vertical straightness error along Z-axis
$\varepsilon_x(x)$: Rotational error about X-axis (roll)

$\varepsilon_y(x)$: Rotational error about Y-axis (pitch)
$\varepsilon_z(x)$: Rotational error about Z-axis (yaw)

Subscripted letters represent the axe that the error occurs and letters in parentheses represent the intended motion directions. Table 1 summarizes the number of error parameters of 3-axes VMC including squareness errors.

TABLE I
TOTAL COMPONENTS OF GEOMETRIC ERROR PAREMETERS OF 3-AXES VMC

	Error Parameters
Scale error	3
Straightness error	6
Angular error	9
Squareness error	3
	Total = 21

B. HTM and Mathematical Model of VMC Makino, S33

A multi-axis machine is assembled by joints and linkages of its carriage system. Coordinates of a cutting point relative to the reference frame of the machine can be computed by rigid body kinematics and modeled by HTM. A HTM is a 4x4 matrix and can be used to represent one coordinate system with respect to another reference coordinate system. When the machining center moves from coordinate (x, y, z) of frame O_R to (x', y', z') of frame O_N in X-carriage system, translation of a, b and c units in X, Y and Z-axis, respectively, occur [3,5]. Scale and straightness errors occur and error matrix of the translation can be expressed as,

$$E_{trans} = \begin{bmatrix} x + a + \delta_x(x) \\ y + b + \delta_y(x) \\ z + c + \delta_z(x) \\ 1 \end{bmatrix} \quad (1)$$

where a, b and c are the offset distances between frame O_R and O_N, respectively.

The rotation, if any, from (x, y, z) coordinate to (x', y', z') can be described in terms of the angles of rotation from (x, y, z) to (x', y', z'). Assuming infinitesimal angles of rotation and denoting the errors by ε_x, ε_y and ε_z, the rotation errors matrix can be written as

$$E_{rot} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y & 0 \\ \varepsilon_z & 1 & -\varepsilon_x & 0 \\ -\varepsilon_y & \varepsilon_x & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Combining both translational errors and rotational errors results in the matrix of total errors

$$E = E_{rot}E_{trans} = \begin{bmatrix} 1 & -\varepsilon_z & \varepsilon_y & x + a + \delta_x \\ \varepsilon_z & 1 & -\varepsilon_x & y + b + \delta_y \\ -\varepsilon_y & \varepsilon_x & 1 & z + c + \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

C. Mathematical Model of Errors for VMC, Makino S33 Machine

To specify nominal position of any point in space, the reference frame must be chosen. The schematic layout is illustrated in Fig.2 of VMC, Makino S33.

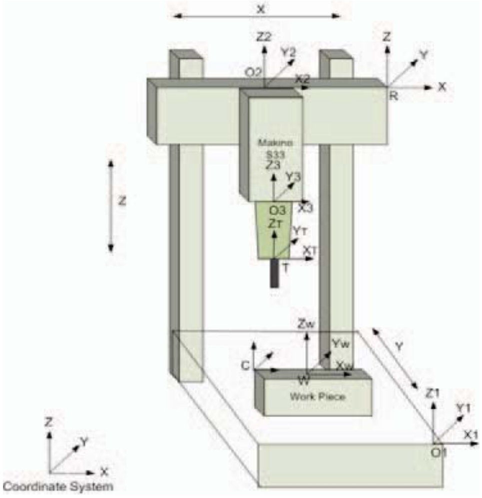

Fig.2 Schematic layout of VMC, Makino S33

At table, if machine has no any geometric errors, the ideal position of frame W (Work Piece frame) with respect to O_1 (table frame) is given by the transformation matrix,

$$^{O_1}T_W = \begin{bmatrix} 1 & 0 & 0 & a_1 \\ 0 & 1 & 0 & b_1 \\ 0 & 0 & 1 & c_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where a_1, b_1 and c_1 are offset distances in X, Y and Z-axis, respectively. However, the position of frame O_1 with respect to the reference frame of machine R frame is given by

$$^{R}T_{O_1} = \begin{bmatrix} 1 & 0 & 0 & a_{R1} \\ 0 & 1 & 0 & b_{R1} \\ 0 & 0 & 1 & c_{R1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

a_{R1}, b_{R2} and c_{R1} are offset distances in X, Y and Z-axis. Thus, ideal position of frame W with respect to the reference frame of the machine is given by the transformation matrix.

$$^{R}T_W = [\,^{R}T_{O_1}\,^{O_1}T_W] = \begin{bmatrix} 1 & 0 & 0 & a_1 + a_{R1} \\ 0 & 1 & 0 & b_1 + b_{R1} \\ 0 & 0 & 1 & c_1 + c_{R1} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

Therefore, if the frame C (Cutting point frame) contains point $\boldsymbol{P_c}$ = (p_x, p_y, p_z), The ideal position of $\boldsymbol{P_c}$ respect to the reference frame of the machine is

$$P_{ideal} = {}^{R}T_W P_c = \begin{pmatrix} a_1 + a_{R1} + p_x \\ b_1 + b_{R1} + p_y \\ c_1 + c_{R1} + p_z \\ 1 \end{pmatrix} \quad (7)$$

However, the actual position of frame C has geometric error parameters and the transformation matrix turns out to be,

$$^{O_1}T_{W\_actual}=\begin{bmatrix}1 & -\varepsilon_z & \varepsilon_y & a_1+\delta_x\\ \varepsilon_z & 1 & -\varepsilon_x & b_1+\delta_y\\ -\varepsilon_y & \varepsilon_x & 1 & c_1+\delta_z\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (8)$$

Instead of (6), the actual transformation matrix is

$$^{R}T_{W\_actual}=\left[^{R}T_{O_1}\right]\left[^{O_1}T_w\right]$$

$$^{R}T_{W\_actual}=\begin{bmatrix}1 & -\varepsilon_z & \varepsilon_y & a_1+a_{R1}+\delta_x\\ \varepsilon_z & 1 & -\varepsilon_x & b_1+b_{R1}+\delta_y\\ -\varepsilon_y & \varepsilon_x & 1 & c_1+c_{R2}+\delta_z\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (9)$$

The actual position at the table of point $\boldsymbol{P_c}$ with respect to the reference frame of the machine will then be

$$P_{actual}={}^{R}T_{W_{actual}}P_c$$

$$P_{actual}=\begin{bmatrix}a_1+a_{R1}+\delta_x+p_x-\varepsilon_z p_y+\varepsilon_y p_z\\ b_1+b_{R1}+\delta_y+p_y+\varepsilon_z p_x-\varepsilon_x p_z\\ c_1+c_{R1}+\delta_z+p_z-\varepsilon_y p_x+\varepsilon_x p_y\\ 1\end{bmatrix} \quad (10)$$

Consequently, errors positions occurring in the table are

$$\begin{bmatrix}\Delta x\\ \Delta y\\ \Delta z\end{bmatrix}=P_{actual}-P_{ideal}=\begin{bmatrix}\delta_x-\varepsilon_z p_y+\varepsilon_y p_z\\ \delta_y+\varepsilon_z p_x-\varepsilon_x p_z\\ \delta_z-\varepsilon_y p_x+\varepsilon_x p_y\end{bmatrix} \quad (11)$$

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III. EXPERIMENT

A. Standard Part from ISO-10791

As specified in ISO-10791 the side view and top view of a standard part used to test machining center are shown in Fig.3a and Fig.3b.

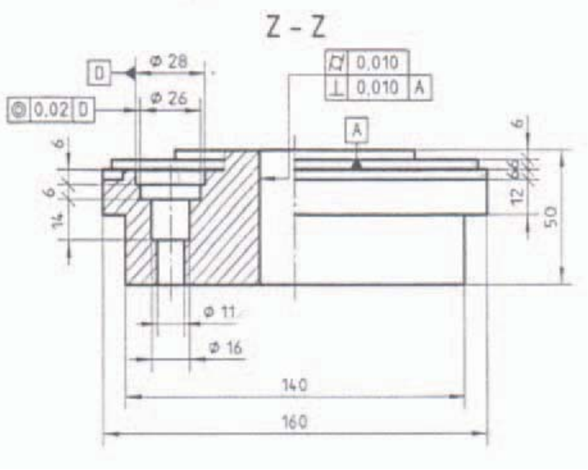

Fig. 3a. Side view of standard part

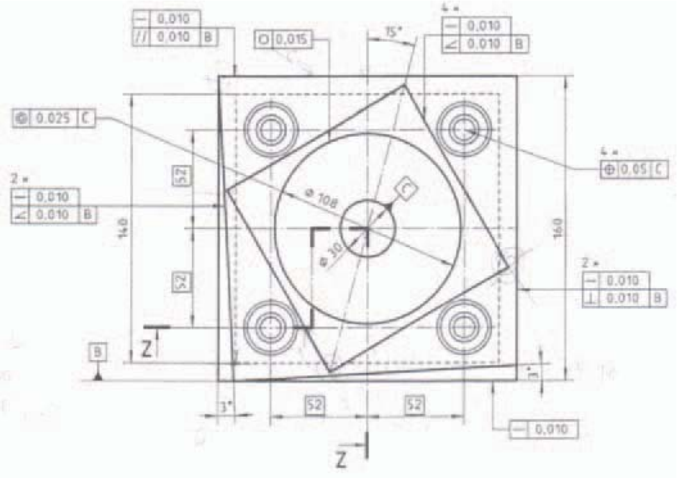

Fig. 3b. Top view of standard part

Examination of G-Code of the standard part in ISO-10791 was carried out by using Virtual CNC (V-CNC) program [4]. Aluminum was chosen as the material to be machined. After machining, the standard part was measured, by CMM and straightness errors were calculated from MATLAB.

B. Measurement of VMC Makino, S33's Motion

LIS was used to measure scale error, pitch and yaw errors of the Y-axis. The machine was programmed to move within the length of a standard part in the Y-axis after installation and alignment of LIS. Scale error of Y-axis was measured at interval of 10 mm from -100 to 100 mm and in the forward and in backward directions. Similarly, pitch and yaw errors were collected data along the same length. As specified in ISO-230, the machine measured by LIS has to run and collect data at least 5 times in forward and backward directions. Machine errors were computed from the collected data by (11). Since straightness errors in the Y-axis are the deviation of points in the X-axis, using the average values of Δx were compared with measurement from the standard part by CMM.

IV. RESULTS AND DISCUSSION

A CMM (Mitutoyo Crysta Apex Series) was used to measure straightness in the Y-axis of the standard part. The data of points in X and Y-axis were collected and, MATLAB was used to do linear regression and calculate straightness errors. Fig. 4 shows the points in X-axis measured by CMM while the length of measurement is from -80 to 80 mm along Y-axis.

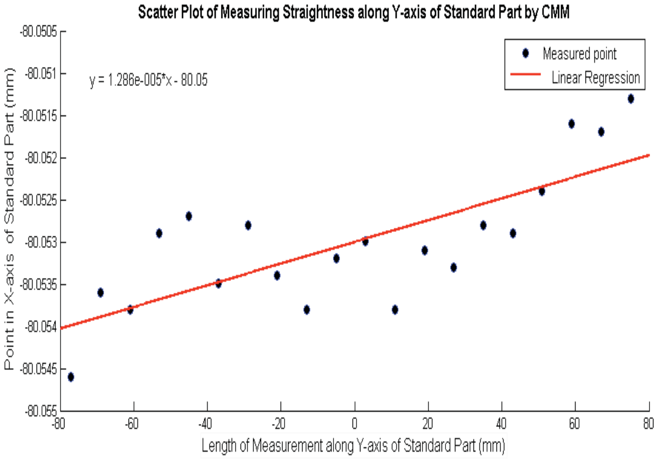

Fig.4 Scatter plot of measuring straightness errors along Y-axis of standard part by CMM

Straightness errors in the Y-axis are simply the deviations of scattered points from the linear regression line.

The straightness errors from CMM measurement of the standard part and from LIS measurement through (11) are shown in Table 2, and plotted in Fig.5.

TABLE II
STRAIGHTNESS ERRORS IN the Y-AXIS FROM the MATHEMATICAL MODEL and CMM

Point of Measurement in Y-axis (mm)	Straightness Error in Y-axis (mm)	
	Mathematical Model	CMM
-80	0.000216	0.0003
-70	0.00196	0
-60	0.0003	0.0007
-50	0.00014	0.0009
-40	0.00136	0
-30	0.00012	0.0005
-20	0.00018	-0.0001
-10	0.0001	-0.0006
0	0	-0.0002
10	-0.0001	-0.0001
20	-0.0001	-0.0009
30	-0.00018	-0.0004
40	-0.00032	-0.0007
50	-0.0003	-0.0002
60	-0.0004	-0.0005
70	-0.00024	-0.0001
80	-0.00038	0.0007

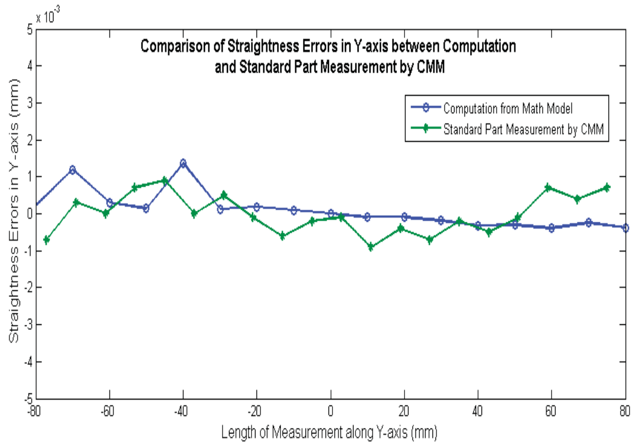

Fig.5 Comparison of straightness errors in Y-axis between mathematical model and standard part measurement by CMM

As seen in Fig.5, straightness errors from the mathematical model were smaller than those measuring by CMM. Nevertheless, both had the same. It was clear that using CMM measuring of a standard part according to ISO-10791 could predict straightness errors of the motion of the machine in the Y-axis.

V. CONCLUSION

Calculation of geometric errors from a mathematical model is known to be impractical for a typical manufacturer for industry. An alternative method that can examine a machine is by measuring a machined part using CMM.

It can be seen in this paper that measurement of a standard part in ISO-10791 can estimate the straightness errors in the Y-axis similar to measuring scale and angular errors by LIS and then calculation by HTM. Using CMM inspection the machine errors can reduce cost and time in maintenance and manufacturing processes.

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