THE DEVELOPMENT OF THE NC METHOD OF ELIMINATING MACHINING POINT ERRORS CAUSED BY MACHINING CENTERS

FIRST REPORT (Theory)

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1. INTRODUCTION

Rectilinear motions of the tables, columns, and heads of three-dimensional machines such as machining centers cause position errors, angle errors, and squareness errors between the axes of machining motion. It has been pointed out that these geometrical errors are complexly integrated to cause machining point errors. There has been no proposal for a method of eliminating the machining point errors. This report specifies a method of computing the actual position of a tool using a new geometrical error model based on the detected data of errors and the coordinates of the interferometers fixed to the machining center, and a method of feeding back the actual position of the tool to the feeding motors of X, Y and Z axes to eliminate the machining point errors.

2. WIRE FRAME REPRESENTATION OF THE MACHINING CENTER

Figure 1 shows the structure of the test machine, a vertical machining center with a moving column. (①～⑤ represent the machine components; bed ①, table (X-axis) ②, column (Y-axis) ③, head (Z-axis) ④, tool ⑤) Line 120, which is discretionarily positioned on the bed, represents a virtual line parallel to the moving direction of the table. Point 121 is a virtual point that moves together with the table along Line 120, and is arbitrarily determined in the X direction of the table. Likewise, Lines 130 and 140 are virtual lines, and Points 131 and 141 are virtual points. Generally, movement of a rigid body consists of parallel

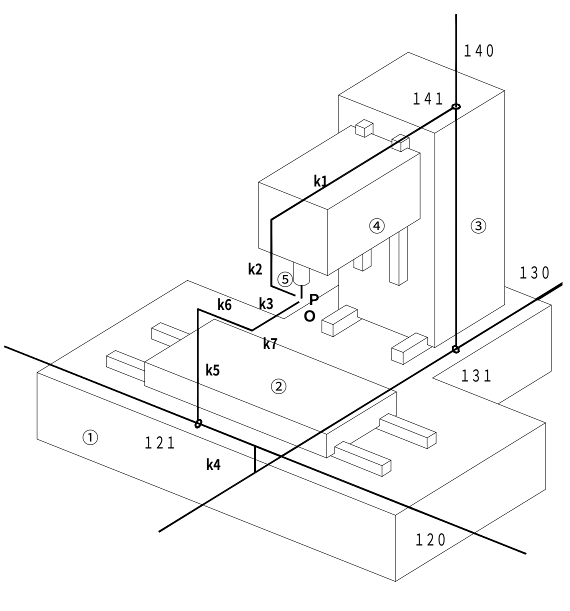

Fig 1. Arrangement of Virtual Lines and Points

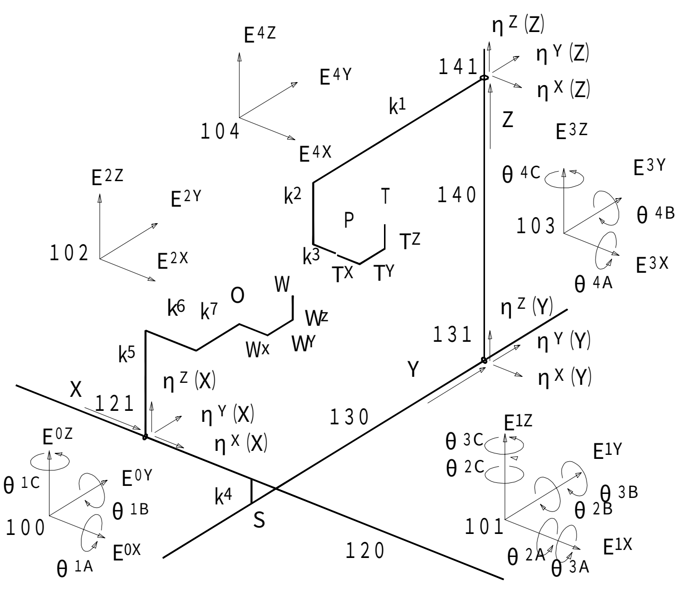

Fig 2. Model of the Machining Center with Error Vectors

motions and turning motions, and the travel can be separated into the turning motion centering on a discretionarily selected point on the body and the parallel motion of the center. Points 121, 131 and 141 in Figure 1 are selected as the centers of angle errors of the table, column and head respectively. Therefore, only the position errors in parallel motion occur at each virtual point.

Figure 1 is the state when the machine is at the starting position for processing. Point P is the tip of the tool, and Point O is the origin of processing on the table. When starting processing, virtual lines 120, 130, and 140 are in orthogonal positions, respectively. k_1, k_2, and k_3 are the lengths along each coordinate axis from Point 141 to tool tip P. k_4 is the distance between Line 120 and Line 130. k_5, k_6, and k_7 are the lengths along each coordinate axis from Point 121 to origin O.

3. MODELING OF MOTION WITH ERROR VECTORS

Figure 2 represents the wire frame showing the motion from the state in which tool tip P coincides with origin O to the state in which the table, column and head are simultaneously fed along the corresponding axis according to the feed command (X, Y, Z). Point T is the point on the head at a distance of (T_X, T_Y, T_Z) from tool tip P. Point W is the point on the table at a distance of (W_X, W_Y, W_Z) from origin O. Vector 100 ($\boldsymbol{E}_{0X}$, $\boldsymbol{E}_{0Y}$, $\boldsymbol{E}_{0Z}$) is the unit vectors indicating the state of the coordinate of the laser fixed on the machine bed. Vector 101 ($\boldsymbol{E}_{1X}$, $\boldsymbol{E}_{1Y}$, $\boldsymbol{E}_{1Z}$) on the bed, Vector 102 ($\boldsymbol{E}_{2X}$, $\boldsymbol{E}_{2Y}$, $\boldsymbol{E}_{2Z}$) on the table, Vector 103 ($\boldsymbol{E}_{3X}$, $\boldsymbol{E}_{3Y}$, $\boldsymbol{E}_{3Z}$) on the column, and Vector 104 ($\boldsymbol{E}_{4X}$, $\boldsymbol{E}_{4Y}$, $\boldsymbol{E}_{4Z}$) on the head are the unit vectors, indicating the motion of each part respectively. When machining starts with tool point P at origin O, ($\boldsymbol{E}_{1X}$, $\boldsymbol{E}_{1Y}$, $\boldsymbol{E}_{1Z}$), ($\boldsymbol{E}_{2X}$, $\boldsymbol{E}_{2Y}$, $\boldsymbol{E}_{2Z}$), ($\boldsymbol{E}_{3X}$, $\boldsymbol{E}_{3Y}$, $\boldsymbol{E}_{3Z}$) and ($\boldsymbol{E}_{4X}$, $\boldsymbol{E}_{4Y}$, $\boldsymbol{E}_{4Z}$) should coincide and should not have angle errors.

$\eta_F(G)$ indicates positioning errors at Points 121, 131 and 141, where G represents the feeding direction and F represents the direction of the positioning error. θ_{1A}, θ_{1B} and θ_{1C} are the constant angle errors of $\boldsymbol{E}_1$ from $\boldsymbol{E}_0$, indicating the setting error of the laser optical axis on the machine bed. θ_{iA}, θ_{iB}, θ_{iC} (i=2,3, 4)are the angle errors of yaws, pitches and rolls. Vector R_T from Point S to Point T is expressed in Formula (1)

$$R_T=(Y+k_1+k_7)E_{1Y}+\eta_X(Y)E_{1X}+\eta_Y(Y)E_{1Y}+\eta_Z(Y)E_{1Z}+(Z+k_2+k_5+k_4)E_{3Z}$$
$$+\eta_X(Z)E_{3X}+\eta_Y(Z)E_{3Y}+\eta_Z(Z)E_{3Z}+(k_3+T_X)E_{4X}-(k_1-T_Y)E_{4Y}-(k_2-T_Z)E_{4Z} \quad \cdots\cdots(1)$$

Similarly, Vector R_W from Point S to Point W is expressed in Formula (2).

$$R_W=(k_3-k_6+X)E_{1X}+k_4E_{1Z}+\eta_X(X)E_{1X}+\eta_Y(X)E_{1Y}+\eta_Z(X)E_{1Z}$$
$$+(k_6+W_X)E_{2X}+(k_7+W_Y)E_{2Y}+(k_5+W_Z)E_{2Z} \quad \cdots\cdots(2)$$

Vector Δ from Point W to Point T is expressed in Formula (3) using the two vectors above. Δ_X, Δ_Y, Δ_Z are the components of E_{0X}, E_{0Y}, and E_{0Z} respectively.

$$\Delta=(\Delta_X E_{0X},\ \Delta_Y E_{0Y},\ \Delta_Z E_{0Z})=R_T-\boldsymbol{R}_W \quad \cdots\cdots(3)$$

Vectors E_1, E_2, E_3 and E_4 are produced using E_0 [1], treating θ_{iD} (D=A, B, C) as the Eulerian angle. When incorporating these Vector into Formula (3) and ignoring $\eta_F(G)\ \theta_{jD}$ as the minimum, Δ_X, Δ_Y, Δ_Z, are calculated. For instance, Δ_X is expressed in Formula (4).

$$\begin{aligned}&\Delta_X(X,\ Y,\ Z,\ W_X,\ W_Y,\ W_Z,\ T_X,\ T_Y,\ T_Z)\\ &=-\eta_X(X)+\eta_X(Y)+\eta_X(Z)-X-W_X+T_X+\{Z+T_Z-W_Z\}\theta_{1B}\\ &\quad-\{Y+T_Y-W_Y\}\theta_{1C}+\{Z+k_4+k_5+T_Z\}\theta_{3B}+\{k_1-T_Y\}\theta_{3C}\\ &\quad+\{T_Z-k_2\}\theta_{4B}+\{k_1-T_Y\}\theta_{4C}+\{k_7+W_Y\}\theta_{2C}-\{k_5+W_Z\}\theta_{2B}\end{aligned} \quad \cdots\cdots(4)$$

X', the actual X-feed of tool tip P in the work coordinate system corresponding to the feed command X, is calculated by substituting zero for W_X, W_Y, W_Z, T_X, T_Y, and T_Z in Formula (4). The unknown numbers $\eta_F(G)$ are calculated in the way described in Section 4.

4. ARRANGEMENT OF THE ERROR DETECTORS ON THE MACHINING CENTER

Figure 3 shows the arrangement of the error detectors. Each detector is arranged separately to clarify its correspondence to the theory. Though the figure looks complicated, the actual constitution is simpler, thanks to multifunctionality and minimization of the detectors. 11, 12, 13, 14, 15, 16 and 17 are laser oscillators. Numbers from 51 to 56 are beam splitters to distribute laser beams. 21a, 24a, 25a, 26a, 31a, 34a, 35a, 36a, 41a, 44a, 45a and 46a are mirrors, and 21b, 24b, 25b, 26b, 31b, 34b, 35b, 36b, 41b, 44b, 45b and 46b are interferometers to detect feeds, pitches, yaws and rolls[2]. For example, 21a is attached to the table, and 21b is attached to the bed for detecting table feed.

61 and 62 are the pentagonal prisms used to reflect incident beams at a right angle. 61 is attached to the bed, and 62 is attached to the column. Beam 91 is the laser beam radiating from laser oscillator 17 and entering pentagonal prism 61. Beam 92 is the laser beam reflected through pentagonal prism 61 and entering pentagonal prism 62. Beam 93 is the laser beam reflected through pentagonal prism 62. Pentagonal prism 62 is attached to column, and it should be adjusted so that laser beams 93 and 91 cross orthogonally when the column starts to move. Vector E_0 indicates the states of 91, 92, 93. Numbers 22, 23, 32, 42 and 43 are the PSDs to detect rectilinear errors of moving lines. The units may be substituted by detectors using laser interference, which are composed of mirrors and interferometers[3].

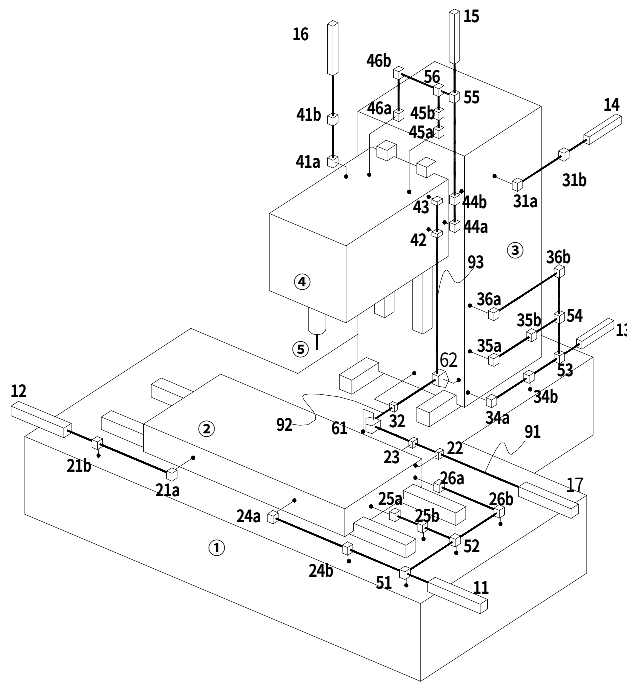

Fig3. Arrangement of the Error Detectors on the Machining Center.

The relation between the detected position errors and the fixed coordinates of the detectors can be calculated as follows. For instance, when $\delta_X(X)$ is defined as the feed error while feeding in the X-direction, and (P_{X2}, P_{Y2}, P_{Z2}) is defined as the fixed coordinate of detecting mirror 21a measured from origin O on the table at the start of processing, detected feed is not influenced by feed in the Y-direction or Z-direction, and it is, therefore, considered that Y=0 and Z=0, even though the machine feeds the head in three axial directions simultaneously. As a result, detected feed can be indicated as Formula (10) and an unknown value $\eta_X(X)$ is calculated from it.

$$X+\delta_X(X)=-\Delta_X(X,\ 0,\ 0,\ P_{X2},\ P_{Y2},\ P_{Z2},\ P_{X2},\ P_{Y2},\ P_{Z2})$$
$$=\eta_X(X)+X-(k_7+P_{Y2})\,\theta_{2C}+(k_5+P_{Z2})\,\theta_{2B} \qquad \cdots\cdots(10)$$

Calculate η_F(G), i.e. the position errors at virtual points 121, 131 and 141, and incorporate them into Δ_X, Δ_Y, Δ_Z. Then, the actual feed (X', Y', Z') is calculated as indicated by formulas (12), (13) and (14), using the quantity of feed command, detected position error δ_F(G), detected angle error θ_{iD}, the coordinates of the position error detectors (P_{Xi}, P_{Yi}, P_{Zi}), (H_{Xi}, H_{Yi}, H_{Zi}), (P_{Xi}, P_{Yi}, P_{Zi}), and the coordinate of pentagonal prism 62 (M_{Xi}, M_{Yi}, M_{Zi}) measured when processing is started.

$$X'=X+\delta_X(X)-\delta_X(Z)-P_{Z2}\,\theta_{2B}+P_{Y2}\,\theta_{2C}+(M_Z-Z)\,\theta_{3B}-H_{Y4}\,\theta_{3C}+H_{Z4}\,\theta_{4B}-H_{Y4}\,\theta_{4C} \qquad \cdots\cdots(12)$$

$$Y'=Y+\delta_Y(Y)-\delta_Y(X)+\delta_Y(Z)+\delta_Z(Y)-H_{Z2}\,\theta_{2A}+H_{X2}\,\theta_{2C}+(P_{Z3}+V_{Z4}-V_{Y3}+M_Y-M_Z)\,\theta_{3A}$$
$$+(V_{X3}-M_X)\,\theta_{3B}-(V_{X4}-M_X+P_{X3})\,\theta_{3C}+V_{Z4}\,\theta_{4A}-V_{X4}\,\theta_{4C} \qquad \cdots\cdots(13)$$

$$Z'=Z+\delta_Z(Z)-\delta_Z(X)+\delta_Z(Y)+V_{Y2}\,\theta_{2A}-V_{X2}\,\theta_{2B}-V_{Y3}\,\theta_{3A}+V_{X3}\,\theta_{3B}-P_{Y4}\,\theta_{4A}+P_{X4}\,\theta_{4B} \qquad \cdots\cdots(14)$$

5. NUMERICAL CONTROL(NC) SYSTEM

In this method, the data of feed errors and angle errors detected by each interferometer, the data of rectilinear errors detected by each PSD, and the fixed coordinate of each detector are put into the high-speed calculation circuit. In the circuit, (X', Y', Z'), the actual position of tool tip P, is calculated using Formulas (12), (13) and (14). Next, the actual position is fed back to the motor controllers through pulse

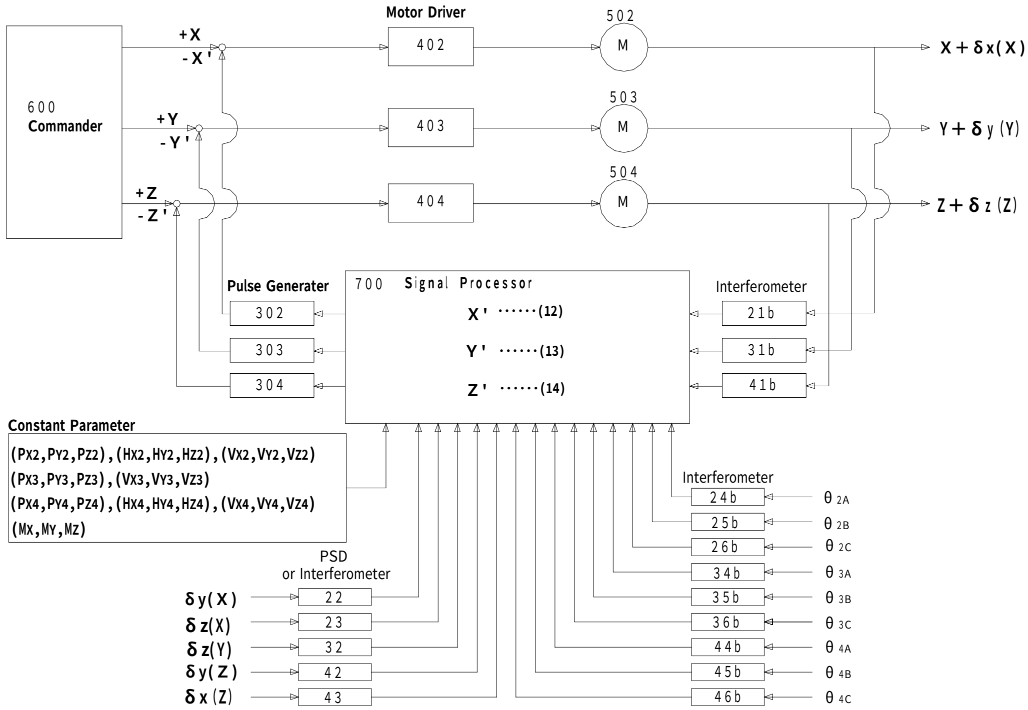

Fig4. Block diagram of the NC system to eliminate machining point error

generator circuit. In this way, the method aims to eliminate the machining points errors in feeding the tools. Rectilinear errors are detected by laser beams fixed on the bed crossing each other at a right angle, therefore, squareness errors between axes are included in rectilinear errors.

6. EFFECTS

The method controls the motion of the tool tip, which moves according to the orthogonal coordinate of the laser fixed on the machining center, and it enables highly precise processing without influence of irregular leads of feed screws, bending or uneven guide rails, or squareness errors between the axes which are caused during machine assembly. Moreover, even in the case of thermal deformation of a machine, rectangularity of the coordinate E_0 can be maintained. As a result, precision of machine operation can be maintained. When the theory is applied to a coordinate measuring machine, precision measurement can be attained while measuring the actual position of a measuring probe.

7. CONCLUSION

(1) The geometrical error vector model showed the relation of the machining point errors to the detected errors and the fixed coordinates of the detectors.

(2) The actual tool feed was calculated from the data of all detected in-process errors using the model above.

(3) Our NC method enabled the elimination of machining point errors by feedback of the actual tool feed to the servomotors of the tool.

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