Development of real-time prediction module for precision and error of CNC system finishing

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Abstract. High speed and high precision are the important trends in the development of CNC machine tools. In order to improve the machining accuracy of CNC machine tools, the errors of CNC machine tools must be reduced as much as possible. Generally speaking, the errors of CNC machine tools include spatial errors, thermal errors, cutting force errors, tool wear errors, etc., in which spatial errors account for a large part of CNC machine tool errors, so reasonable control of reducing spatial errors is of great significance to improve the accuracy of CNC machine tools. Methods commonly used to reduce spatial errors include error prevention methods and error compensation methods. Error prevention is a method to eliminate and reduce error sources through design, manufacturing, assembly, etc. Although this method can reduce the original error, it is limited by improving manufacturing and assembly accuracy to reduce errors, and it is economically expensive. The error compensation method is to artificially create a new error to offset the current original error to achieve the purpose of improving machining accuracy. This method is easy to implement and has low cost. Therefore, the error compensation method is the most economical and effective method to improve the accuracy of the machine tool.

1. Introduction
In this study, the error compensation method is used to compensate the spatial error to improve the machining accuracy of the CNC machine tool. For machine tools, spatial errors include linear displacement errors, straightness errors, perpendicular errors, pitch angle errors, and rotation angle errors. This research is mainly aimed at the VMC860 three-axis vertical machining center. For this machining center, there are six sources of error for each linear axis, plus 3 verticality errors, there are 21 spatial errors in total [1], as shown in Figure 1 as shown.

![Figure 1. Schematic diagram of three-axis machine tool spatial error](image-url)
In order to realize the spatial error compensation of the three-axis vertical machining center, this study first used a laser interferometer to accurately measure 21 spatial errors of the three-axis vertical machining center and establish a spatial error model. Then, I compile a three-axis vertical machining center spatial error compensation algorithm, and import the algorithm into the CNC system. Finally, I imported the spatial error model into the numerical control system to achieve real-time compensation for 21 spatial errors during the machining process. [5].

2. Introduction to research methods

In this study, Renishaw's XM-60 laser interferometer was used to measure the six-axis XYZ motion error. The Renishaw XM-60 laser interferometer uses the change of the laser pulse frequency when the laser transmitter and receiver move relatively to measure displacement, and calculates the bed space error by the difference between the actual displacement and the ideal displacement[6].

![Figure 2. Schematic diagram of delayed stall](image)

When measuring the spatial error with Renishaw's XM-60 laser interferometer, as shown in Figure 2, there is a position sensitive detector (PSD) at the laser receiver end. According to the comparison with the reference position, the deviation of the laser beam from the starting position can be obtained Distance, that is, a straightness error is detected. At the same time, the yaw angle error between the laser head and the receiver can be calculated according to ①② the deviation position of the laser beam, the pitch angle error is calculated according to ②③ the deviation position of the laser beam, and the roll angle error is calculated through ①②③.

2.1. Spatial error modeling method

The Renishaw laser interferometer can measure one positioning, two straightness and three angular errors[7]. However, in the process of spatial error compensation of a three-axis vertical machining center, the compensator often implements the error through the movement of the feed axis [8]. Compensation, because of this, the angle error must be converted into positioning error or straightness error along the axial direction. In the three-axis vertical machining center space error measurement, due to the difference between the measurement point and the tool tip position, the angle error will cause the measurement point to not truly reflect the actual operation error of the tool tip. In order to make the error compensation more accurate, a single-axis comprehensive spatial error model of a three-axis vertical machining center can be established, which is specifically expressed as the following formula [2]:

\[
\begin{align*}
E_x(x) &= \delta_x(x) - Y_{tw} \varepsilon_y(x) + Z_{tw} \varepsilon_z(x) \\
E_y(x) &= \delta_y(x) + X_{tw} \varepsilon_x(x) - Z_{tw} \varepsilon_z(x) \\
E_z(x) &= \delta_z(x) - X_{tw} \varepsilon_x(x) + Y_{tw} \varepsilon_y(x) \\
E_x(y) &= \delta_x(y) - Y_{tw} \varepsilon_y(y) + Z_{tw} \varepsilon_z(y) \\
E_y(y) &= \delta_y(y) + X_{tw} \varepsilon_x(y) - Z_{tw} \varepsilon_z(y) \\
E_z(y) &= \delta_z(y) - X_{tw} \varepsilon_x(y) + Y_{tw} \varepsilon_y(y)
\end{align*}
\]
\[
\begin{align*}
E_x(z) &= \delta_x(z) - Y_{tt}\varepsilon_x(z) + Z_{tt}\varepsilon_y(z) \\
E_y(z) &= \delta_y(z) + X_{tt}\varepsilon_z(z) - Z_{tt}\varepsilon_x(z) \\
E_z(z) &= \delta_z(z) - X_{tt}\varepsilon_y(z) + Y_{tt}\varepsilon_x(z)
\end{align*}
\] (3)

Where \(\delta_x(x)\) is the X-axis motion positioning error, \(\delta_y(x)\) is the linearity error in the Y-axis direction when the X-axis is moving, \(\delta_z(x)\) is the linearity error in the Z-axis direction when the X-axis is moving, \(\varepsilon_x(x)\) is the angular error around the X axis when the X axis moves, \(\varepsilon_y(x)\) is the angular error around the Y axis when the X axis moves, and \(\varepsilon_z(x)\) is the angular error about the Z axis when the X axis moves, \(\delta_y(y)\) is the positioning error of the Y-axis movement, \(\delta_x(y)\) is the straightness error in the X-axis direction when the Y-axis movement, \(\delta_x(z)\) is the straightness error in the Z-axis direction when the Y-axis movement, \(\varepsilon_x(y)\) is the Y-axis movement Angle error around the X axis, \(\varepsilon_y(y)\) is the angle error around the Y axis when the Y axis moves, \(\varepsilon_z(y)\) is the angle error around the Z axis when the Y axis moves, and \(\delta_x(z)\) is the positioning error for the Z axis movement, \(\delta_y(z)\) is the straightness error in the Y axis direction when the Z axis moves, and \(\varepsilon_x(z)\) is the angular error around the X axis when the Z axis moves, \(\varepsilon_y(z)\) is the angular error around the Y axis when the Z axis moves, \(\varepsilon_z(z)\) is the angular error around the Z axis when the Z axis moves, \(X_{tt}\) is the tool tip and measuring point along the X axis during XY axis measurement, \(Y_{tt}\) is the distance between the tool tip and the measuring point along the Y axis during XY axis measurement, \(Z_{tt}\) is the distance between the tool tip and the measuring point along the Z axis during XY axis measurement, \(X_{tw}\) is the tool tip and measuring point along the X axis during Z axis measurement The distance in the axis direction, \(Y_{te}\) is the distance between the tool tip and the measuring point along the Y axis during Z-axis measurement, and \(Z_{te}\) is the distance between the tool tip and the measuring point along the Z-axis during Z-axis measurement. Based on the above model, the angle error can be converted into positioning error or straightness error along the axial direction and then compensated.

2.2. Spatial error compensation method

![Flow chart of space error compensation method](image)

The process of machine tool spatial error compensation is shown in Figure 3. First, the Renishaw laser interferometer is used to measure the XYZ single-axis spatial error, then the polynomial fitting is used, and then the interpolation method is used to intensive the single-axis spatial error, and then the intensive single-axis error Substitute the machine tool space error model to form a three-dimensional space error model, then import the three-dimensional space error model into the space error compensation algorithm to calculate the error compensation control parameters of the space points, and finally import the control parameters into the CNC system to realize the various position points during the movement of the CNC machine tool Spatial error compensation[4].

3. Analysis of research results

Using Renishaw’s laser interferometer to measure the space error of VMC860 three-axis vertical machining center, the measurement results are as follows.
3.1. X-axis motion error analysis

The measuring range of X-axis motion error is 0-600mm under the user-defined machine coordinate system. As can be seen from Figure 4, the X-axis positioning error of the machine tool increases as the X-axis coordinates continue to increase, and the error varies from 0 to 17μm. The machine tool Y-direction straightness error slowly decreases with increasing X-axis coordinates, and the error continues to fluctuate. The error varies from 0 to 8μm. The machine tool Z-direction straightness error slowly decreases as the X-axis coordinate continues to increase, and the error continues to fluctuate. The error varies from 0 to -2.7μm. The angular error of the machine tool around the X axis increases with increasing X axis coordinates, and the error varies from 0 to 65μm/m. The angular error of the machine tool around the Y-axis increases with the X-axis coordinates increasing, and the error varies from 0 to 30μm/m. The angular error of the machine tool around the Z-axis decreases as the X-axis coordinate increases, and the error varies from 0 to -13 μm/m.

3.2. Spatial error modeling

The angular error is converted into an axial error according to Formula 2-1. The integrated error of X-axis motion after conversion is shown in Figure 5. It can be seen from the figure that after the angular error is converted into an axial error, the X-axis orientation error gradually increases as the X-axis coordinate continues to increase, and the error varies from 0 to 22 μm. The Y-axis straightness error gradually decreases with increasing X-axis coordinates, and has certain fluctuations, and the error
varies from 0 to -15 μm. The Z-axis straightness error changes with the X-axis coordinates increasing with small amplitude fluctuations, and the error varies from 0 to 2 μm.

Figure 5. X-axis motion comprehensive error curve after conversion of angular error to axial error

3.3. Spatial error field distribution
Since the machine tool spindle verticality errors $\alpha_{xy}$, $\alpha_{xz}$, and $\alpha_{yz}$ are errors generated when the spindle is running, they are affected by the spindle running dynamics. Measurement and compensation can be achieved through spindle dynamic modeling and other methods. By appropriately adjusting the machine tool spindle verticality errors to space errors, the impact is small, so it is not considered in this study. The spatial error of feature points in the spatial error field in this study can be expressed as:

$$
\begin{align*}
E_x &= E_x(x) + E_x(y) + E_x(z) \\
E_y &= E_y(x) + E_y(y) + E_y(z) \\
E_z &= E_z(x) + E_z(y) + E_z(z)
\end{align*}
$$

(4)

Figure 6. Spatial error field distribution

Fit the respective motion synthesis errors of the XYZ axis separately, and then substitute it into Formula 4, and then interpolate the model to obtain the distribution of the XYZ spatial error field as shown in Figure 6. It can be seen from the figure that the spatial error continuously changes with the position of XYZ and is consistent with the change trend of the uniaxial error.

3.4. Spatial error compensation
The XYZ space error field distribution after interpolation is imported into the numerical control system, and a compensation algorithm is compiled according to the error model to compensate the machine tool spatial error. Renishaw's laser interferometer measures the diagonal PPP positioning error of the machining space of the VMC860 three-axis vertical machining center to verify the compensation result. The measurement stroke is from (0, 0, 0) to (600, 300, 400). 13 measurement points, the measurement results are shown in Figure 7. It can be seen that the original positioning error of the diagonal of the PPP body of the machine tool increases as the position coordinate increases, and the error range is between 0 and 52 μm. After using the spatial error compensation model proposed in this study to compensate the machine tool, the positioning error of the diagonal of the PPP body of the machine tool is slow as the position coordinates increase, and the error range is between 0 and 10 μm.
Compared with the original error, after adopting the spatial error compensation method of this study to compensate the error of VMC860 three-axis vertical machining center, the maximum error of diagonal positioning of the machine tool PPP body is reduced by about 81%.

Figure 7. Diagonal PPP positioning error compensation before and after comparison

4. Conclusions
In summary, we measured the six-axis XYZ motion error through a laser interferometer, and used the diagonal PPP positioning error compensation algorithm among the linear displacement error, straightness error, verticality error and pitch angle error. In the above process, we can find that by introducing the spatial error model into the CNC system, 21 spatial errors can be compensated simultaneously. By linearly fitting each motion error, we can find that even if the position of the spatial error will continue to change, the trend of the single-axis error will not change.

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