

## Study on Post-processing and Nonlinear Error Compensation Technology for Dual 5-axis Linkage NC Machining Center

Yuhou Wu<sup>1,2, a</sup>, Dehong Zhao<sup>12, b</sup>, Li Ning<sup>2, c</sup> and Sun Jing<sup>2, d</sup>

<sup>1</sup>*School of Mechanical Engineering, Dalian University of Technology, Dalian, China*

<sup>2</sup>*College of Traffic & Mechanical Engineering, Shenyang Jianzhu University, Shenyang, China*

<sup>a</sup> *yuhwu@sjzu.edu.cn*, <sup>b</sup> *85755340@qq.com*, <sup>c</sup> *214760977@qq.com*, <sup>d</sup> *85844493@qq.com*,

### Abstract

*For the vertical and horizontal dual 5-axis system of a new turning-milling compound machining center, the dedicated post processor for 5-axis is developed by C++ programming language, B-axis pendulum angle error measurement technology and nonlinear error compensation algorithm are studied; and also analyzed and verified in actual processing; Researches show that: the dual 5-axis post processor works correctly and efficiently, better processing accuracy than 0.05mm can be obtained by nonlinear interpolation compensation for B-axis pendulum angle for 3 times, which meets the demand of crafts machining.*

**Keywords:** *Dual 5-axis linkage, post processor, B-axis pendulum angle error, nonlinear error compensation*

### 1. Introduction

Post-processing is the tie to computer-aided manufacturing (CAM) and digital processing, it is an indispensable part of the digital manufacturing process [1]; Tool paths generated by the automated programming can't be identified by NC machine tools. The message of the tool center coordinates and tool axis vector in the cutter location file need to be converted by post-processing algorithms and programs which are suitable for a particular machine, make it be able to generate the NC program which can be recognized by specific machine [2]; addition to the cutter location file specific tool center coordinates and tool axis vector conversion, excellent post-processing procedures should also get the most of the functional advantages of the processing equipment, reduce field operating time and improve processing quality and efficiency, and so on. For example: the spatial location and the error compensation, tool length compensation, the movement smooth performance and reliability as well as processing different sources cutter location file, and other functions [3].

For a kind of independent research and development HTM50200 special-shaped stone multi-function turning-milling NC machining center, dedicated post-processing algorithm and its programs are studied in this paper, and this dedicated post-processing is utilized to processing the cutter location file of three-dimensional sculpture, make a simulation and processing of its processing results. The correctness and feasibility of the post-processing algorithms and programs is verified by the contrast, detection and analysis of the theoretical model and the actual model, and the machining accuracy is improved by the nonlinear interpolation compensation for B-axis pendulum angle [4].

### 2. HTM50200 Structure Profile

HTM50200 special-shaped stone turning-milling NC machining center with movable gantry structure, as shown in Figure 1; eight-axis dual five-linkage machining capability, can achieve processing of complex special-shaped stone products; According to the number of linkage axis, machining center can be divided into four modules, including: 3-axis machining module,

4-axis machining module (the vertical 4-axis and the horizontal 4-axis), five-axis machining module (the vertical 5-axis and the horizontal 5-axis) and turning module, of which: turning module is different from metal turning. Metal turning is through the work-piece rotate at a certain speed, and the tool is fixed in the tool holder. The two coordinates with interpolated motion through the tool holder in the plane of the external contour of the work-piece, eventually machine out the contour of the work-piece. While in axisymmetric body turning of special-shaped stone, the tool use diamond saw blades rotating around the tool axis, because there is a difference between stone cutting process and metal cutting process, moreover, during two coordinates interpolated motion for the external contour of the special-shaped stone axisymmetric body in XOZ plane, the tool and the work-piece respectively, relatively rotate at a certain speed(in which: the rotational speed of the work-piece/spindle speed $<1$ , and due to the type of stone material, the speed ratio of the work-piece and tool are not the same) so as to achieve the stone parts processing. The composition of the various functional modules shown in Figure 2, main post structure parameters of machining center are shown in Table 1.

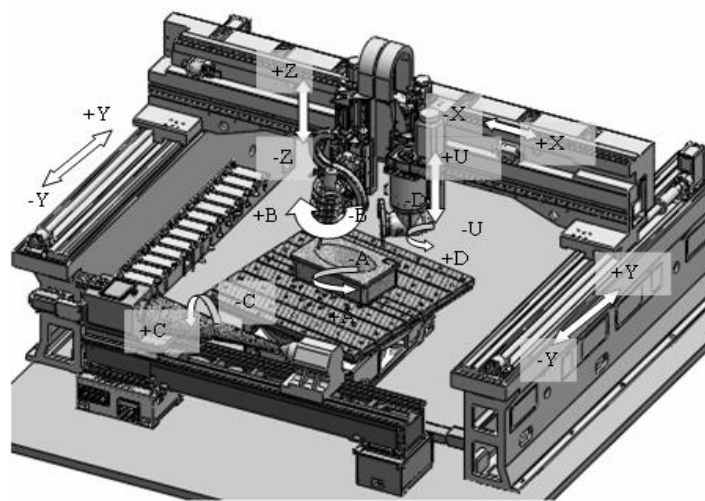


Figure 1. HTM50200 NC MC Construction

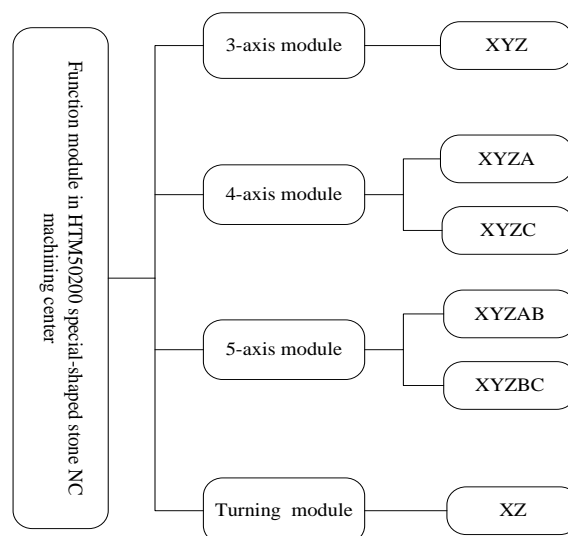


Figure 2. Each Function Module in HTM50200

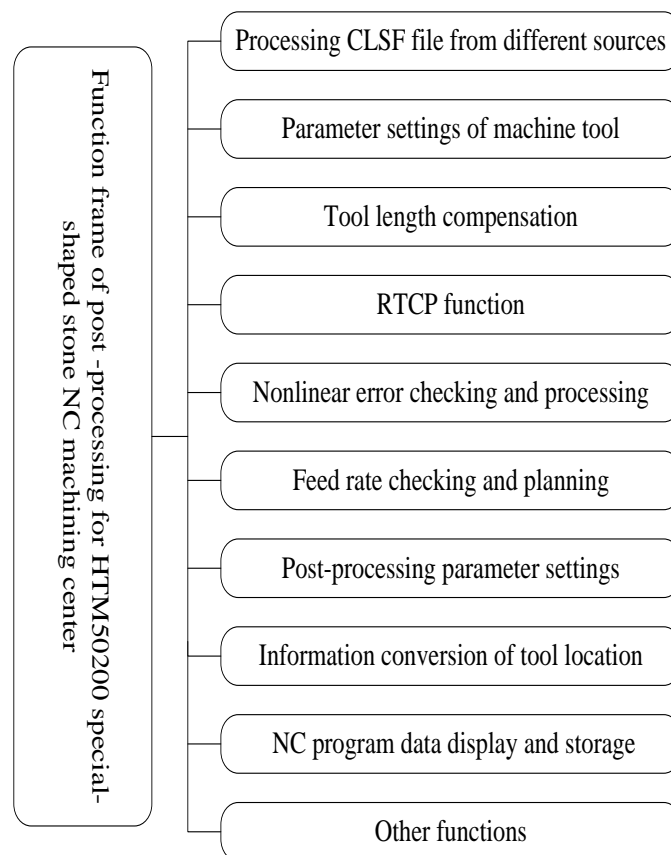
**Table 1. Parameters of HTM50200 MC**

X1-axis stroke	400mm	A-axis stroke	0°~360°
Y-axis stroke	4250mm	A-axis rotation center	(-1500,-1600,-400)
Z-axis stroke	3380mm	B-axis stroke	-15°~90°
C-axis stroke	0°~360°	B-axis rotation center	(0,0,-350)

### 3. The Construction of Post Processor based on UG POSTBUILDER

#### 3.1. Functional Analysis of Dedicated Post-processing

Post-processing functions of the HTM50200 special-shaped stone NC machining center mainly include: (1)processing the CLSF file from different sources [5]; (2)post-processing parameter settings [6]; (3)post-processing algorithms judgment; (4)the tool length compensation [7]; (5)RTCP function [8]; (6)data conversion; (7)nonlinear error checking and processing [9]; (8)feed rate checking and planning [10]; (9)the function of data display and storage [11]; (10)other functions; of which, post-processing judgment function determine which kind of angle programming algorithm to adopt according to the quadrant in which the tool axis vector is located among the tool location information, while post-processing parameter setting initialize origin offset, tool offset and tool wear loss according to the actual situation of the processing center. The frame structure of the dedicated post-processing functions of processing center shown in Figure 3, Post-processing flow is shown in Figure 4.



**Figure 3. Function Frame of HTM50200 Special Post**

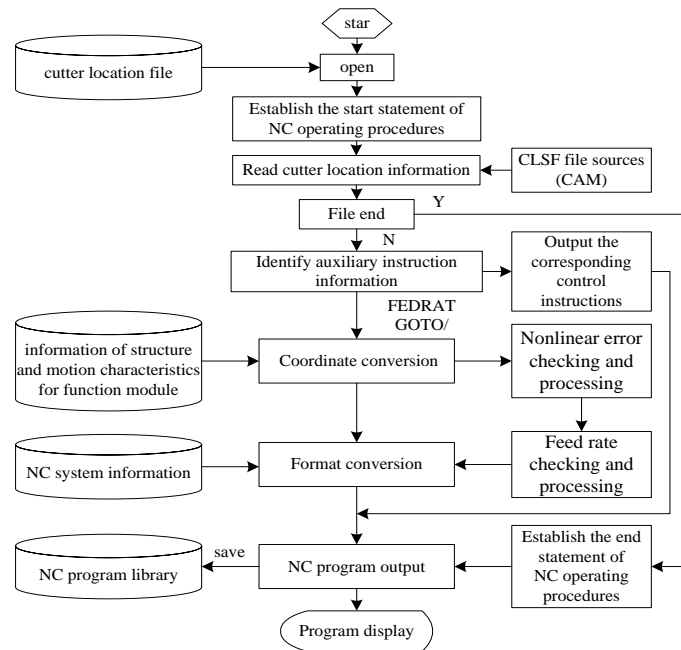


Figure 4. Flow Diagram of HTM50200 Post

### 3.2. Dedicated Post-processing Algorithm

According to the characteristics of the structure and movement of the machining module, work-piece coordinate system, cutting tool and machine tool coordinate system of the parallel axes, supposed that the position coordinate of the origin  $O_w$  in the work-piece coordinate system coordinate is set to the position  $(X_m, Y_m, Z_m)$  in the machine coordinate system, the pendulum length  $L$ , the tool offset  $T_{\text{oset}}$ , any location coordinates  $(X_w, Y_w, Z_w)$  in the work-piece coordinate system, the tool axis vector  $(A_x, B_y, C_z)$ , tip point coordinates in the work-piece coordinate system, after the tool rotation around the tool center point with a angle  $B$ , and after the work-piece rotation around the C-axis with a angle  $C$ , for solving the coordinates  $(X_m, Y_m, Z_m)$  in the machine coordinate system, of which,  $(X_m, Y_m, Z_m)$   $T_{\text{oset}}$  is determined by the actual size.

As shown in Figure 5, five-quadrant system is applied to the condition of angle uncertainty in the path for angle planning, and by means of the program marked to determine exactly which angle value is used as the output rotation angle value in the NC program. In order to introduce angle planning preferably, some of the provisions are made for the specific location of each space region, as shown in Figure 6; Here we assume that the vector direction of the initial tool axis lie in the second quadrant and the initial  $\Delta C < 0$  (the rotation angle algorithm of other cases see appendix), specific angle planning algorithm is as follows:

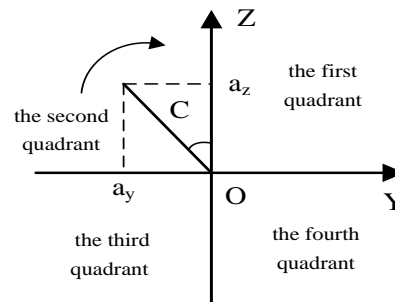
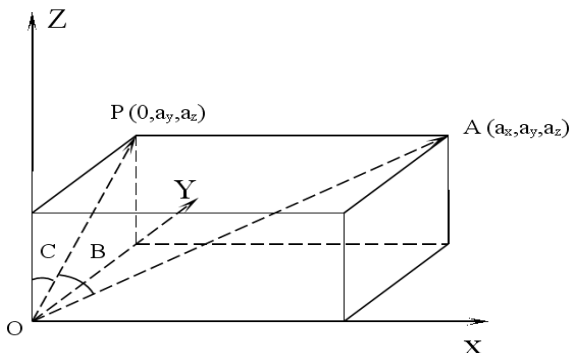


Figure 5. Diagram of Angle Calculation Figure 6. Angle Spatial Position Setting

$$\text{When } a_z = 0, \quad \arctan \left| \frac{a_y}{a_z} \right| = 90^\circ \quad ; \text{ assumed} \quad \theta = \arctan \left| \frac{a_y}{a_z} \right| \quad (1)$$

$$C = \begin{cases} -\arctan \left| \frac{a_y}{a_z} \right| & a_y < 0, a_z \geq 0 \\ \arctan \left| \frac{a_y}{a_z} \right| & a_y \geq 0, a_z > 0 \\ 180^\circ - \arctan \left| \frac{a_y}{a_z} \right| & a_y > 0, a_z \leq 0 \\ 180^\circ + \arctan \left| \frac{a_y}{a_z} \right| & a_y \leq 0, a_z < 0 \\ 360^\circ - \arctan \left| \frac{a_y}{a_z} \right| & a_y < 0, a_z \geq 0 \end{cases} \quad (2)$$

The algorithm implementation process: If the tool axis vector in the second quadrant, and the initial rotation direction of tool path is clockwise (actual rotation direction of horizontal worktable is counterclockwise), *i.e.*,  $\Delta C < 0$ , stipulates the initial tool axis vector which lie in the second quadrant is converted into negative angle coordinate in the machine coordinate system; continue clockwise rotation of the tool path When the path is rotating to the first quadrant, mark it, the principal aim of marking is when the tool axis vector in the first quadrant, if it rotates again to the second quadrant, output negative value, that is: stipulates the output value of angle C is  $-\theta$ , when the tool axis vector in the third quadrant, if it continues to rotate to the second quadrant, provides angle C output positive value  $360^\circ - \theta$ , other conditions and so on.

Angle B is calculated as follows:

$$B = \begin{cases} \arcsin \left| \frac{|a_x|}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \right| & a_x > 0 \\ 0 & a_x = 0 \\ -\arcsin \left| \frac{|a_x|}{\sqrt{a_x^2 + a_y^2 + a_z^2}} \right| & a_x < 0 \end{cases} \quad (3)$$

### 3.3. Linear Coordinate Transformation

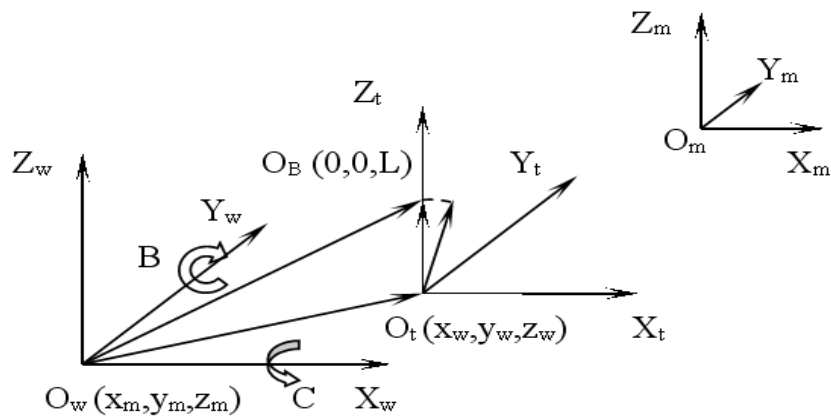


Figure 7. Linear Coordinate Transformation [12]

Any tool center point coordinates in the workpiece coordinate system, after the motion that the horizontal worktable and the tool rotate around their respective rotation center (table around its axis, the tool around its tool center point), is converted into the coordinates of the machine coordinate system, the conversion process is as follows:

$$\begin{cases} X_m = x_w + (LT_{o.set}) \times \sin(\theta) + x_m \\ Y_m = y_w \times C(\theta) + z_w \times \sin(\theta) + y_m \\ Z_m = y_w \times \sin(\theta) + z_w \times C(\theta) + (LT_{o.set}) \times C(\theta) + z_m \end{cases} \quad (4)$$

Using C++ object-oriented programming techniques for compiling the HTM50200 post-processing, achieves the seamless connection and transformation between the cutter location file written by CAD / CAM software and NC program of HTM50200 special-shaped stone NC machining centers. In addition, the use of object-oriented programming technology is very good for the function perfection of HTM50200 dedicated post-processing, while changing algorithm for the machine with other mechanical structure can be well adapted.

#### 4. The Error Checking of Swing Angle and Nonlinear Compensation for Tool

Ideal tool path in curved surface machining of 5-axis linkage NC is nonlinear continuous curve which is formed by relative motion of the contact point of the tool and the workpiece surface, but cutter location data generated in the pre-processing discrete theoretical tool path into a series of small straight line segments to approximate, in the five-axis simultaneous machining process, due to the influence of the rotational movement, the linear motion synthesis of each coordinate axis may make certain trajectories of straight line segment gravely deviate from the desired trajectory, *i.e.*, the actual tool path is not coincidence with the theoretical, it must be tested and processed.

Located adjacent two cutter location data (Pw1,Uw1) and (Pw2,Uw2),corresponding to each movement of the linkage shaft position (X1,Y1,Z1,B1,C1) and (X2,Y2,Z2,B2,C2), the machine tool by (X1,Y1,Z1,B1,C1) location motion to (X2,Y2,Z2,B2,C2) is accomplished by a the tiny straight segment interpolation, in this straight line segment, the coordinates of an arbitrary position of each movement axis:

$$\begin{cases} X(t) = X^1 + t \times (X^2 - X^1) \\ Y(t) = Y^1 + t \times (Y^2 - Y^1) \\ Z(t) = Z^1 + t \times (Z^2 - Z^1) \\ B(t) = B^1 + t \times (B^2 - B^1) \\ C(t) = C^1 + t \times (C^2 - C^1) \end{cases} \quad (0 \leq t \leq 1) \quad (5)$$

Set the ideal trajectory programming Pw(t), actual tool path PwL(t), the distance from arbitrary point of the curve Pw(t) to straight line PwL(t) is  $\varepsilon(t)$ , there is

$$\varepsilon(t) = \left| P_w(t) - \left\{ P_{w1} + [(P_{w1}(t) - P_{w1}) \times a] \times a \right\} \right| \quad (6)$$

In the above formula:  $a = (P_{w2} - P_{w1}) / |P_{w2} - P_{w1}|$ , after derivation calculus to  $\varepsilon(t)$ , when the derivative is zero, assume that at this time  $t=t_{max}$  and  $\varepsilon(t)$  achieve maximum, the maximum error:

$$\varepsilon_{max} = \left| P_w(t_{max}) - \left\{ P_{w1} + [(P_{w1}(t_{max}) - P_{w1}) \times a] \times a \right\} \right| \quad (7)$$

$\varepsilon_{\max}$  is seen as evaluation indicators, which computing nonlinear error between adjacent cutter locus, because the non-linear error of the midpoint is the maximum, so if the non-linear error exceeds the maximum permissible error, calculation between the adjacent cutter locus according to the following formula:

$$\begin{cases} P_{wm} = (P_{w1} + P_{w2})/2 \\ U_{wm} = (U_{w1} + U_{w2})/2 \end{cases} \quad (8)$$

Insert a new cutter location (Pwm,Uwm), then calculate the position of the linkage shaft insertion point (Xm,Ym,Zm,Bm,Cm), and calculate the nonlinear error between (Pw1,Uw1) and (Pwm,Uwm), (Pwm,Uwm) and (Pw2,Uw2), if still exceeds the allowable error, insert a new cutter location continue to work according to the above principle, until meet the requirements.

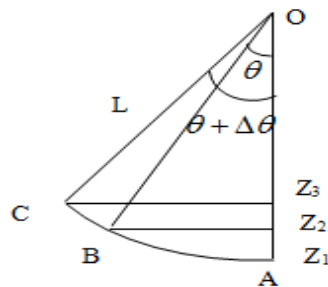


Figure 8. Simplified Model

Inherent error for HTM50200 mechanical structure is the direct cause which lead to pendulum angle error ,worm and gear structural influenced by deformation and friction deformation, simplified model of carving milling head shown in Figure 8:

According to the simplified model, the establishment of the following equation:

$$\begin{cases} h = Z1 - Z2, h' = Z1 - Z3, \Delta \theta = Z2 - Z3 \\ L(1 - \cos(\theta)) = h \\ L(1 - \cos(\theta + \Delta \theta)) = h' \\ L(\cos(\theta) - \cos(\theta + \Delta \theta)) = \Delta Z \\ \cos(\theta + \Delta \theta) = \cos(\theta) - \Delta Z / L \end{cases} \quad (9)$$

Finally get the relationship between swing angular error and error of the tip point on the vertical direction.

$$\Delta \theta = a \cos(\cos(\theta) - \Delta Z / L) - \theta \quad (10)$$

First observed h with the trend of swing angle  $\theta$ , separated the angle range  $0^\circ$ - $40^\circ$  according to the actual processing often application, and separated by a unit angle  $1^\circ$ .

$$dh = L \sin(\theta) d\theta \quad (11)$$

Determine the law of swing angle error varying along with the variation of the pendulum shaft angle. As shown in Figure 9 to Figure 12, respective are quadratic, cubic, quartic and quintic polynomial regression analysis curve;

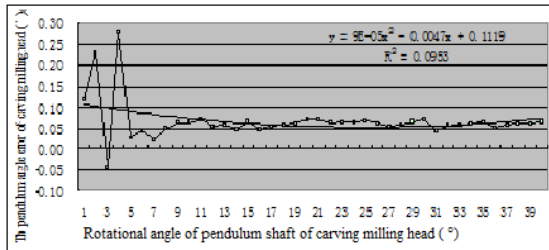


Figure 9. Quadratic Polynomial of Angle Error

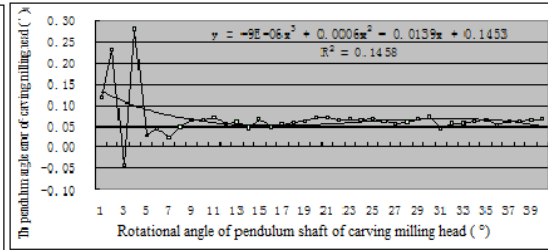


Figure 10. Cubic Polynomial of Angle Error

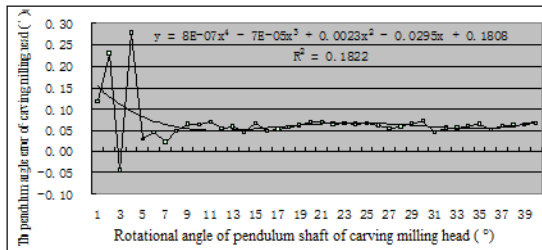


Figure 11. Quartic Polynomial of Angle Error

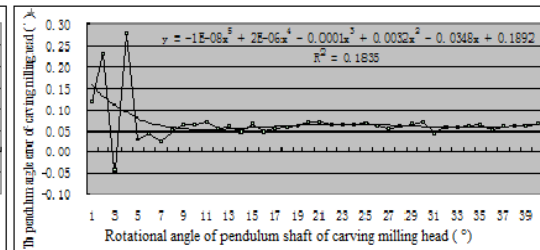


Figure 12. Quintic Polynomial of Angle Error

Pictures From 9 to 12 show that :curve fitting accuracy also increase with the increase of the degree of curves ,the fitting accuracy of quadratic, cubic curve is not as better as quartic and quintic curve, but difference between quartic and quintic curve in the curve fitting accuracy is not great, meanwhile in polynomial regression curve fitting, the swing angle error of carved milling head is relatively large in close to the vertical position. Along with the rising of the swing angle, the error is substantially maintained on the same level and relatively stable, and the angle error curve above benchmark axis about  $+0.05^\circ$ . By a comprehensive analysis of polynomial regression curve fitting for each degree, finally, determine the swing angle error of carving milling head changing with the variation of the angle, its polynomial regression curve is expressed as:

$$y = -8 \times 10^{-7} x^4 - 7 \times 10^{-5} x^3 + 2.3 \times 10^{-3} x^2 - 2.95 \times 10^{-2} x + 0.1808 \quad (12)$$

Put  $y = \Delta \theta, x = \theta$  into the above equation, there is

$$\Delta \theta = -8 \times 10^{-7} \theta^4 - 7 \times 10^{-5} \theta^3 + 2.3 \times 10^{-3} \theta^2 - 2.95 \times 10^{-2} \theta + 0.1808 \quad (13)$$

The actual swing angle can be derived according to the following formula

$$\theta_{ac} = \theta_{ro} + \Delta \theta \quad (14)$$

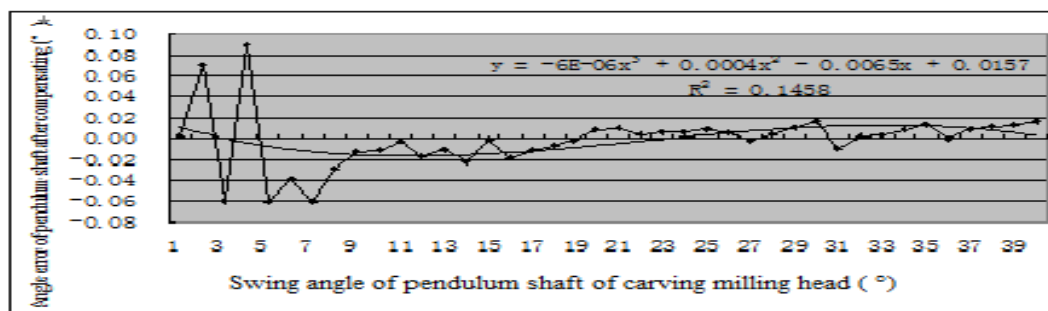


Figure 13. Angle Error Fitted Curve after Compensating



By the formula (10) for the angle error compensation, and measure the vertical error each interval of 1 ° within 0 ° to 40 °, and calculate with the formula (8), obtain the compensated pendulum angle error, as shown in Figure 13, As can be seen from the figure, swing angle error has been greatly improved after compensation, which will also greatly improve the machining quality, reduce impact on the processing quality which affected by the swing angle error.

## 5. Processing Test Study



**Figure 14. Theoretical Model of Maitreya      Figure 15. Maitreya Practical Product**

In order to verify the effectiveness of the compiled the processor and error compensation technique, select the processing of Maitreya Buddha sculpture for example shown in Figure 14. Process include: rough machining, selection of  $\varnothing$  20 mm flat end mill; semi-finishing selection of  $\varnothing$  6mm ball end mill; both of rough machining and semi-finishing adopt 3 +1 axis CNC machining mode; finishing choose  $\varnothing$  3mm ball head grinding wheel, choose horizontal 5-axis linkage machining mode.

The cutter location file (CLSF) is dealt with the above-mentioned dedicated post-processing procedures. Obtain the NC program suitable for HTM50200 CNC machining center. Table 3 as part of the five-axis program, the processing sample is obtained as shown in Figure 15.

**Table 3. CLSF File from CAD/CAM and NC Program Deal with Special Post Processor**

CLSF	post-processing NC program
FEDRAT/300.0000	
GOTO/0.6304,-0.0908,-4.6069,0.3586240,0.0	N0160 X202.536 Y.032 Z-42.057 B21.016
249347,0.9331490	C1.531 F300.
GOTO/0.5762,-0.1639,-4.5338,0.3651502,0.0	N0170 X206.156 Y.062 Z-43.412 B21.417
463164,0.9297957	C2.852
GOTO/0.5240,-0.2371,-4.4607,0.3714898,0.0	N0180 X209.673 Y.089 Z-44.756 B21.808
676745,0.9259673	C4.18

Applying coordinate measuring machine, measured the processed specimens and compared the data with theoretical model. The results are shown in Table 4, The Z-axis error is less than 0.05mm, basically meet the requirements of crafts.

**Table 4. Analysis of Test Data Between Theoretical and Practical Model (partial)**

No	simulation data/mm	actual data/mm	Z-axis
1	X207.915 Y.032 Z-43.055 B21.016	Z-43.011	0.044
2	X211.633 Y.062 Z-44.448 B21.417	Z-44.422	0.026
3	X215.245 Y.089 Z-45.829 B21.808	Z-45.871	-0.042
4	X218.749 Y.113 Z-47.196 B22.188	Z-47.189	0.007
5	X222.144 Y.135 Z-48.546 B22.557	Z-48.531	0.015
6	X225.428 Y.154 Z-49.875 B22.915	Z-49.902	-0.027
7	X228.599 Y.17 Z-51.18 B23.261	Z-51.214	-0.034
8	X231.655 Y.184 Z-52.46 B23.596	Z-52.419	0.041
9	X234.595 Y.196 Z-53.71 B23.918	Z-53.753	-0.043
10	X237.417 Y.206 Z-54.928 B24.229	Z-54.922	0.006
11	X240.12 Y.213 Z-56.111 B24.527	Z-56.082	0.029
12	X242.703 Y.218 Z-57.257 B24.812	Z-57.275	-0.018

## 6. Conclusion

The analysis of the relationship between the mechanical structure and movement of the various functional modules for HTM50200 NC machining centers, verifies that the post-processing algorithm is correct and efficient. The post-processor can realize the program conversion of 5-axis NC machining. Nonlinear compensation for B-axis pendulum angle improves the running accuracy of the machine dramatically. Test show that the processing accuracy can reach 0.05 mm, which meets the requirements of crafts processing.

## Acknowledgements

This work was financially supported by the Innovation Program of Education Commission supported plan (IRT1160), the Liaoning technology Research plan (2011220012), Shenyang Municipal technology Research plan (F12-036-2-00), the Research Project of Liaoning Department of Education (L2011094) and Shenyang Jianzhu University Key Laboratory Foundation (JX-200906).

## References

- [1] Y. Wu, D. Zhao and X. Mu, "The modular design of turn-milling CNC for special stones", *Telkomnika*, vol. 11, no. 5, (2013), pp. 2845-2852.
- [2] Y. H. Wu, L. X. Zhang, K. Zhang and S. H. Li, "Design on High-Speed Precision Grinder", *13CCAT, Key Engineering Materials*, vol. 304-305, (2006), pp. 492-496.
- [3] X. Mu, K. Zhang, D. Zhao and Y. Wu, "The topological optimization design of cross beams structure of shaped stone turning-milling CNC (HTM50200)", *Advanced Materials Research*, vol. 694 697, (2013), pp. 2725-2728.
- [4] Y. Gao, "Application of UG-based 5-axis linkage numerical control machining technology in blow mold", *Applied Mechanics and Materials*, vol. 220-223, (2012), pp. 355-359.
- [5] Y. Liu, Y. Z. Wang, H. Y. Fu and Q. Liang, "Curve interpolation control strategy for 5-axis linkage computer numerical control machine", *Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS*, vol. 15, no. 4, (2009), pp. 758-761.
- [6] M. K. Shao, Z. Wang, J. Z. Zhi, R. Z. Wu and R. Wang, "Research on post processing of 5-axis linkage machines", *Applied Mechanics and Materials*, vol. 141, no. 1, (2012), pp. 438-441.

- [7] K. Zhang, D. Zhao and Y. Wu, "The Detection and Analysis of Straightness Errors on Pillar and Guide Rail of Alien Stone Turning-milling Compound Machining Center", *Applied Mechanics and Materials*, vol. 9, no. 8, (2011), pp. 80-81.
- [8] L. Feng, D. Zhao and Y. Wu, "Modal Analysis of Special-shaped Stone Multi-function NC Machining Menter", *International Journal of Digital Content Technology and its Applications*, vol. 5, no. 8, (2011), pp. 168-174.
- [9] Y. Hu, B. Li, D. Su and H. Hu, "Dynamic design for a novel parallel kinematic machine with passive linkage", *Key Engineering Materials*, vol. 364-366 II, (2008), pp. 1037-1042.
- [10] Y. Liu, Y. Z. Wang, H. Y. Fu and Z. Y. Han, "Study on cutter radius compensation methods for 5-axis CNC machining", *Materials Science Forum*, vol. 628 629, (2009), pp. 347-352.
- [11] Y. G. Shi, X. Y. Zhao, L. Q. Zeng, H. Y. Wang and D.W. Zhang, "Dynamic characteristic analysis and structural modification of a 5-axis horizontal machining center considering joint surface", *Materials Science Forum*, vol. 697-698, (2012), pp. 513-516.
- [12] Y. Xia, "5-axis virtual machining technology research on integral impeller under PROE and vericut environment", *Advanced Materials Research*, vol. 591-593, (2012), pp. 573-576.

