A measuring and optimizing method of precision consistency for Five-axis Multi-spindle gantry machine

Qin Xiaopin, Zhu Shaowei, Wang Yujie, Gong Qinghong*

Chengdu, Sichuan, 610092, China
Chengdu, Sichuan, 610092, China
Chengdu, Sichuan, 610092, China

* Corresponding author. Tel.: +86-15882278574; E-mail addresses: qinxiaopin@126.com

Abstract

This paper proposes a method for measuring and optimizing the geometric accuracy of the spindle of the large 5-axis multi spindle gantry milling machine, which can ensure the accuracy of the multi spindle and restore the ability of simultaneous processing.

Keywords: multiple-spindle; precision consistency; Five-axis linkage; RTCP

1. Introduction

Large 5-axis multi spindle gantry milling machine, because of its multi spindle can process simultaneously, making a substantial increase in production efficiency, is an important role of the main CNC machining equipment for the efficient production of high value large aircraft structure parts. But with the growth of the service time, mechanical components appeared different degrees of wear. Especially for some super large aircraft structural parts, the machining only uses single spindle, with exacerbating the single spindle wear, resulting in the machining accuracy difference between different spindles is getting bigger and bigger, the multi axis synchronous machining accuracy can not meet the demand of parts processing, thereby greatly reducing the application value of the equipment.

In order to restore the multi spindle processing capacity of the large 5-axis multi spindle gantry milling machine, the machining accuracy of different spindles must be guaranteed, that is, the precision consistency of multi spindle. The machining precision difference of multi spindle is mainly derived from the geometric error of the different spindles. This paper proposes a method for measuring and optimizing the geometric accuracy of the spindle of the large 5-axis multi spindle gantry milling machine, which can ensure the accuracy of the multi spindle and restore the ability of simultaneous processing.

2. Multi spindle precision consistency measuring and optimizing scheme

The Cincinnati 5A3P series of large 5-axis multi spindle gantry milling machine (three spindles along the Y direction parallel) is chosen as the research object of this paper (see Figure 1), to explore the influencing factors of multi spindle precision consistency and error measuring and optimizing method, the whole route as:

Making the three spindles simultaneous cutting NAS 979 square test specimens, NAS 979 5-axis cone test specimens and S-shaped specimens, the difference between the main spindle processing accuracy can be deduced through the accuracy of the test specimens;

According to the structure of the machine, analysis of the mutual position error between the parts and the geometric errors in the process of operation, to find out the influencing factors of processing accuracy of the multi spindle;
In view of the various error factors which lead to the difference of the spindle precision, the corresponding detection and optimizing techniques are studied; Through the optimizing of various error to reduce accuracy differences between multi spindle, in order to meet the requirements of simultaneous processing.

3. Multi spindle accuracy measuring based on standard test specimens

The difference of multi spindle accuracy can be measured by testing the standard test specimens, to check whether the of multiple spindle precision can satisfy the requirement of the parts synchronous machining, and verify the effectiveness of the optimization and adjustment. Commonly used NAS 979 triaxial square test specimens can complete XYZ axis detection of the single axis, two axis linear and circular interpolation, three axis linkage linear interpolation, two axes linkage with unconstant velocity linear interpolation and other various forms. The NAS 979 5-axis cone test specimens and S-shaped specimens, can complete further testing of five axis linkage precision.

![Fig. 1. Cincinnati 5A3P](image)

![Fig. 2. (a) NAS 979 square test specimens; (b) NAS 979 5-axis cone test specimens; (c) S-shaped specimens](image)

Table 1 and figure 3 shows the multi spindle precision measuring result of cutting the NAS 979 triaxial square test specimens and S-shaped specimens. Table 1, in three spindle test specimens, the verticality of A and B axis, B and C axis, the parallelism of B and D axis, and the roundness of cone E have larger differences. Among them, the difference from the parallelism of B and D axis and the roundness of cone E is more than 0.02mm, it is visible that X and Y axis perpendicularity precision is poor. Figure 3, No.2 and No.3 spindle machining S-shaped specimens have accuracy quite, basically meet 0.1mm profile requirements, but No.1 spindle machining S-shaped specimens accuracy is poor (Side A with the profile 0.1851mm. Side B with the profile 0.1972mm), reflecting No.1 spindle AB swing linkage has poor precision. In addition, combined with the S-shaped specimens test procedure and measurement point distribution, the change range of machine tool linkage state and swing angle can be analyzed, which can provide reference for the error optimizing in next step.

<table>
<thead>
<tr>
<th>Test item (mm)</th>
<th>No.1 spindle</th>
<th>No.2 spindle</th>
<th>No.3 spindle</th>
</tr>
</thead>
<tbody>
<tr>
<td>The center point distance of F square and E cone</td>
<td>0.0109</td>
<td>0.0040</td>
<td>0.0093</td>
</tr>
<tr>
<td>The verticality of A and B axis</td>
<td>0.0172</td>
<td>0.0086</td>
<td>0.0029</td>
</tr>
<tr>
<td>The verticality of B and C axis</td>
<td>0.0197</td>
<td>0.0060</td>
<td>0.0103</td>
</tr>
<tr>
<td>The verticality of C and D axis</td>
<td>0.0059</td>
<td>0.0091</td>
<td>0.0074</td>
</tr>
<tr>
<td>The verticality of A and D axis</td>
<td>0.0100</td>
<td>0.0086</td>
<td>0.0061</td>
</tr>
<tr>
<td>The parallelism of A and C axis</td>
<td>0.0083</td>
<td>0.0044</td>
<td>0.0084</td>
</tr>
<tr>
<td>The parallelism of B and D axis</td>
<td>0.0266</td>
<td>0.0153</td>
<td>0.0033</td>
</tr>
<tr>
<td>The roundness of E cone</td>
<td>0.0397</td>
<td>0.0192</td>
<td>0.0163</td>
</tr>
<tr>
<td>The planeness of F plane</td>
<td>0.0234</td>
<td>0.0207</td>
<td>0.0205</td>
</tr>
<tr>
<td>The parallelism of F plane and G plane</td>
<td>0.0274</td>
<td>0.0199</td>
<td>0.0197</td>
</tr>
<tr>
<td>The verticality of F plane and G plane</td>
<td>0.0017</td>
<td>0.0040</td>
<td>0.0046</td>
</tr>
<tr>
<td>The verticality of F plane and G plane</td>
<td>0.0087</td>
<td>0.0078</td>
<td>0.0077</td>
</tr>
</tbody>
</table>

![Fig. 3. The result of cutting S-shaped specimens (a) Side A; (b) Side B](image)

4. Single error measuring and optimizing method

Due to 5A3P series machine X and Z and B axis drive parts wear, electrical drive module abnormal and load uneven, motion process has poor state synchronization, which easily leads to motor load exception, even when serious gantry distorted, machine tool structure damaged.
4.1. Biaxial verticality optimizing

With the X axis as an example, ideally, the synchronization in space performance that perpendicularity error of X axis and Y axis is 0. By square are examined, such as shown in Figure 4, if the verticality error exceeds over 0.02mm/500mm, it needs to be optimized.

\[ \rho_1 = \frac{\| f(x) - g(x) \|}{M} \]

Before compensation

\[ \rho_1 = \frac{\| f(x) - g(x) \|}{M} \]

After compensation

One kind of method is to adjust the offset of the reference point of the numerical control system. As shown in Figure 11, the ideal position point of driving axis of gantry machine is \( f_p(x) \), and the driven axis is \( g_p(x) \). Where \( x \) represents for the pitch point, \( n \) for the total compensation point, \( f_n(x) \), \( g_n(x) \) for the starting point, \( f_f(x) \), \( g_f(x) \) for the final point. \( M \) for the spacing of the driving axis X1 and the driven axis X2, \( f'_p(x) \) for the actual position with no compensation of driving axis, \( g'_p(x) \) for driven axis, \( f''(x) \) for the actual position with pitch compensation of driving axis, \( g''(x) \) for driven axis. The Verticality of X/Y at each point is set as \( \rho_n \), then

\[ \rho_n = \frac{\| f_n(x) - g_n(x) \|}{M} \]

4.2. Biaxial positioning error synchronization compensation

Taking the X axis as an example, the positioning accuracy of X1 and X2 were detected by two laser interferometer at the same time. In accordance with the verticality of standard 0.02mm/500mm, with the span of gantry beam is 5000mm, the positioning error of X1 and X2 should not exceed 0.2mm. In order to ensure axis Verticality and synchronization during the full stroke, the same compensation parameter should be used on two axis, and the compensation value should use arithmetic mean value of two axis positioning error.

Fig. 4. Verticality error examined by square

5. Biaxial driving servo parameters matching

After long-term use of the machine, the electrical and mechanical state will change, so it needs to readjust the servo characteristics of the mechanical state. The servo system includes current loop, speed loop and position loop, and the parameters of each control loop are matched with the machine tool. The optimization process with the order from the inside to the outside, optimizes the parameters of the current loop, and then the speed loop, finally the position loop.

Current loop. Current controller parameters are determined by the parameters of the motor. Machine tool users don't need too much optimization, only need observe the bandwidth of the motor through Bode diagram.

Velocity loop. The proportional gain and integral time of the speed loop are the most important control parameters, and the optimization principle is to adjust the dynamic characteristics to the maximum under the premise of ensuring the stability of the system. Because of the biaxial driving, the optimizing of the speed loop must be carried out at the same time, and the parameters must be set to the same. If the two drive servo characteristics are not consistent, the better driven state sets parameters based on the the conditions of poor driving state.

Position loop. Based on the optimizing of speed loop, the optimizing of position loop should reach the best match of the characteristics of mechanical system and servo system. The proportional gain \( K_p \) of position loop should be as much as possible, and the associated time constant as less as possible, in order to ensure the fastest response of the system and the minimum follow error. To ensure the system do not generate oscillation, using Ref. frequency response test to ensure that the gain value is not more than 0db.

After completing uniaxial optimization, it needs to use roundness testing on linkage characteristics of two axes linkage, such as a combination of XY, YZ, XA and AB, debugging key system parameters as gain, feedforward, friction coefficient, acceleration and jerk. Test again after the optimizing, until meet the requirements. After roundness test it needs to rerun the Ref. frequency response test to ensure that the gain value is not more than 0db.

After completing uniaxial optimization, it needs to use roundness testing on linkage characteristics of two axes linkage, such as a combination of XY, YZ, XA and AB, debugging key system parameters as gain, feedforward, friction coefficient, acceleration and jerk. Test again after the optimizing, until meet the requirements. After roundness test it needs to rerun the Ref. frequency response test to ensure that the gain value is not more than 0db. If the response and error between two linkage axis is too large, and servo drive characteristics after testing and optimization have no further ascent, then optimize the corresponding uniaxial repeatedly, until it reaches the optimum match of five axis linkage characteristic.

Fig. 5. Verticality error examined by square
Figure 13 shows the Bode diagram of X axis speed loop before servo adjustment and after. Tr1 and Tr3 stands for X1 driving, T2 and Tr4 for X2 driving. After optimizing, the servo characteristic is obviously improved, the motor bandwidth of the X axis is greater, the current response is faster, and the operation is more stable.

6. Rotation center position deviation detection and coordination compensation

The position error of rotation axis can be based on the RTCP function, using the ball and dial gauge. With A axis as an example, execute 5-axis linkage (TRAORI instruction) and at A0B0 position swing A axis respectively to plus or minus 30 degrees, and recording the change quantity of A axis at -30 DEG and 30 DEG position, setting as (x1, Y1 z1) and (X2, Y2, Z2).

If z1=z2 =0, then the original offset values of the machine tool are correct, do not need to be compensated;
If z1=z2 \neq 0, the MD24550[2] (center distance) compensation in original machine compensation offset values is not correct. Add Z1 to the parameter MD24550[2] original numerical, get compensation value and compensate, and remeasure to verify whether the z1=z2=0;
If z1 \neq z2, both the MD24550[1] and MD24550[2] compensation in original machine compensation offset values are incorrect. At first add (z2-z1 )/2 to the parameter MD24550[1] original numerical and then retesting, when appeared new z1= z2 \neq 0, the MD24550[2] compensation in original machine compensation offset values is incorrect. Add the new Z1 to MD24550[2] original numerical, then get new compensation value and compensate, and remeasure to verify whether the z1=z2=0.

For Cincinnati 5A3P, the three A axis components are driven by a motor, and therefore only a set of compensation parameters. The integrated error of three A axes must be considered at the same time when the center position error is compensated. The mean value of the maximum error and the minimum error is taken as the error to compensate, which makes the least difference of the precision between the multi spindles.

7. Implementation effect

After the implementation of the adjustment and optimization, the results of cutting the S-shaped specimens before and after the implementation are shown in table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle</th>
<th>Maximum deviation value</th>
<th>Overproof point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No.1</td>
<td>0.1061</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>No.2</td>
<td>0.0601</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>No.3</td>
<td>-0.0534</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0</td>
<td>0</td>
</tr>
</tbody>
</table>

Visible from the above table, after the implementation of the adjustment, the precision consistency of the multi spindle is greatly improved, and the difference between the multi spindle is significantly reduced. Then put the machine tool into production, the parts which processed by three spindles are proved to satisfy the precision requirement.

Acknowledgements

This paper is supported by National Science and Technology Major Project (No. 2013ZX04001021).

References