Kinematics Test and Evaluation of Tool Axis Direction Error for Five-axis Machine Tools

L Zhong1, F Ren2, L Guo2, Q Bi1 and Y Wang1

1 State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China
2 Shanghai Aerospace Equipments Manufacture, Shanghai, 200245, PR China

zhonglei@sjtu.edu.cn

Abstract. This paper presents a kinematics detection and evaluation method for tool axis direction error of five-axis machine tools. By measuring the trajectory errors of two tool center positions corresponding to two different tool lengths, the tool axis direction error can be obtained by combining the two measurements. Compared with the evaluation method in ISO10791.6.2014 which can only evaluate the tool center position errors corresponding to a single tool length, the proposed method can infer the processing accuracy corresponding to different tool lengths and to evaluate the comprehensive accuracy of five-axis flank milling. The proposed method is verified through simulations and experiments on a five-axis gantry machine tool.

1. Introduction

Five-axis machine tool is an effective tool for processing complex feature parts. Its dynamic accuracy determines the quality and machining efficiency of the workpiece. Kinematics test is an effective method which can evaluate the dynamic performance of five-axis machine tools. Many scholars have designed a variety of test paths to test the performance of five-axis machine tools by using a variety of test instruments, such as double ball bar (DBB) [1], R-test [2], laser tracking interferometer [3] and so on. Masaomi et al. [1] designed circular trajectory measurement methods using DBB to evaluate the accuracy of the rotary axes. The authors also present the evaluation method of spherical deviation error by using DBB [4] and the S trajectory deviation test method by using R-test [5]. Ibaraki et al. [6] constructed an error map of rotary axes by R-test. In ISO10791-6:2014 [7], four kinematics test methods for dynamic accuracy evaluation of five-axis machine tools with three typical structures are defined. Among them, AK3 is a non-cutting method equivalent to cone-frustum milling by using DBB and AK4 checks the deviations of the tool center point trajectory, which is ideally a fixed point in the workpiece coordinate system (WCS).

The above-mentioned kinematics test method can effectively detect the dynamic error of the tool center point (TCP), but it cannot evaluate the dynamic error of the tool axis direction (TAD). The envelope surface formed by tool movement in five-axis machining process determines the dimensional accuracy of the parts. The position of the tool is determined by both the tool center point and the tool axis direction. When different tool lengths or five-axis flank milling are used, it is impossible to evaluate the machining accuracy according to the TCP error of a point. In this paper, a kinematics testing and evaluation method for tool axis direction error of five-axis machine tools is presented. By measuring and synthetically analyzing the trajectory errors of two tool center positions corresponding...
to two different tool lengths, the TAD error and TCP error can be obtained by combining the two measurements. With the data of tool axis direction error, the performance of five-axis machine tools can be evaluated more comprehensively.

2. Evaluation Method of Tool Axis Direction Error

The principle of comprehensive evaluation index of TCP and TAD error proposed in this paper is as shown in figure 1(a). \( P_0 \) is the initial tool center point and \( P_t \) is the point on the tool axis. The distance between them is \( L \) and the length of the tool is \( D \). The machine tool makes the tool reach theoretical position \( P_n \) and \( P_{tn} \) according to the test path. In fact, because of machine tool error, the actual reaching position of tool center point is \( P_r \), and the point on tool axis reaches \( P_{tr} \). The distance \( e_p \) between \( P_n \) and \( P_r \) is the TCP error \( E_{TCP} \), which is the evaluation index of the TCP error of five-axis machine tool stipulated in ISO10791.6-2014. \( e_t \) is the distance between \( P_{tn} \) and \( P_{tr} \). \( e_t \) and \( e_p \) is different due to the TAD error. So the tool axis direction error \( E_{TAD} \) can be defined as the ratio of the \( (e_t - e_p) \) to \( L \). Therefore, the evaluation index of tool tip and tool axis direction error can be determined by equation (1) and equation (2).

\[
E_{TCP} = \max \left( \frac{e_p}{L} \right)
\]

\[
E_{TAD} = \max \left( \frac{e_t - e_p}{L} \right)
\]

3. Measuring method of tool axis direction error

This section uses the AK3 and AK4 test paths in ISO standards to detect the TCP and TAD error. As shown in figure 2, the proposed method is to measure AK3 motion twice with a DBB. The same measuring NC code is used for the two measurements, but different tool lengths \( D_1 \) and \( D_2 \) are used for two actual measurements, and different tool lengths \( D_1 \) and \( D_2 \) are set in the CNC system. Because of the different tool lengths, the positions of the three linear axes corresponding to the two measurements are different, but the motion of the two rotary axes is the same.
As shown in figure 1(b), in the second measurement with tool length D2, because the processing program is unchanged, that is, the theoretical trajectory of $P_t$ point is the same as that of $P_0$ point, the $P_t$ point in the direction of the original tool axis is moved to $P_0$ point through the interpolation motion of the three axes of X′Y′Z′. Assuming that the additional errors caused by the change of linear axes travel are ignored, the errors measured twice can be considered to be unchanged. When the machine tool moves to $P_t\text{fr}$ point, the actual position is still $P_t\text{tr}$. The linear axis interpolates in the direction of the theoretical tool axis and moves the $P_t\text{tr}$ point to $P_t\text{fr}$ point. From the geometric relationship in figure 1(b), it can be seen that the TCP $P_t\text{fr}$ error obtained by the second measurement is equal to the point $P_t\text{tr}$ error in the direction of the tool axis. Therefore, the TAD error can be calculated approximately by the equation (3).

$E_{TAD}\approx \max \left( \frac{|p_{t\text{fr}} - p_{t\text{tr}}|}{L} \right)$

(3)

Because the DBB can only measure one-dimensional distance information, it is impossible to calculate directly by equation (3), but the actual distance $R_t$ and $R_{tr}$ can be measured by the DBB. So equation (4) and equation (5) can be used to calculate the TCP and TAD error.

$E_{TCP-\text{AK3}} = \max \left( |R_{t\text{fr}} - R_{t\text{tr}}| \right)$

(4)

$E_{TAD-\text{AK3}} = \max \left( \left| (R_{t\text{tr}} - R_{t\text{fr}}) - (R_{tr} - R_{fr}) \right| \right)$

(5)

It is worth mentioning that, because the tool length $L$ is generally less than 100 mm, the additional machine tool error caused by the change of linear axis 200 mm stroke is generally less than 0.004 mm, which can be neglected compared with the roundness 0.08 mm required by the ISO10791.7.2014 [8] for the milling of cone frustum.

As mentioned in [4], R-test can measure the TCP error in three directions at one time, so it is more convenient to use R-test to perform AK4 measurement. Its basic principle and error calculation method are described in detail in [4]. The AK4 measurement method of TAD error is similar to AK3. Two AK4 measurements are made by R-test. The TAD and TCP error can be obtained by equation (1) and (2).

4. Simulation Analysis of Tool Axis Direction Error

The machine tool structure adopted in the simulation and experiment in this paper is a five-axis machine tool with two rotary axes in the spindle head and the kinematics model is described in [4]. The flowchart of simulation strategy is shown in Figure 3. The tool location coordinates $(x, y, z, i, j, k)$ of the test path in the WCS are post-processed to obtain the axis motion $(X, Y, Z, A, C)$ in the machine tool coordinate system. The second-order dynamic control model is used to simulate the control of the servo system on each axis. $\omega_n = 100$Hz is the natural frequency and $\zeta = 0.7$ is the damping ratio. The proportional gain of the position control loop is $K$. After the servo system simulation, the actual positions of each axis $(X', Y', Z', A', C')$ are obtained, and then the position values are transformed into actual tool locations in WCS by the forward kinematic model of the machine tool with the volumetric errors. After processing, the actual tool position is changed from $P(x, y, z)$ to $P'(x', y', z')$, as well as the tool axis directions $U(x, y, z)$ to $U'(x', y', z')$. Finally, the simulation results of AK 3 and AK4 are obtained by using the calculation method described in Section 3.

![Figure 3. Flowchart of simulation strategy](image)
4.1. Influence of geometric errors
Geometric accuracy is the basis of dynamic motion accuracy of five-axis machine tools. The 8 PIGEs associated with rotary axes are set either 0.01mm for linear errors or 0.01° for angular errors. The tool length is set to 100mm. Then a simulated contour error trajectory in the WCS can be obtained as shown in Figure4(a), the red lines are the tool axes with errors, and the blue lines are the theoretical tool axes. For easy observation, the deviation is enlarged by 100 times. The TAD and TCP errors results are shown in Table 1. Figure4 (b) show the error maps of the tool center point and the point on tool axis, which are shown in red and blue respectively. It can be seen that in AK3 and AK4 tests, the two points on tool axis have different error trajectories, which is mainly caused by the TAD error.

4.2. Influence of proportional gain mismatch
The proportional gain K of A axis is set to 35 (1/s), and the other axis is 40(1/s), respectively. This can be used to simulate the error caused by the slow servo response of A axis. From Table 1 and Figure 4 (c), it can be seen that the servo mismatch of rotary axis will also produce a large TAD error. In addition, because the motion range and acceleration and deceleration requirements of AK4 test are larger than those of AK3 test, the TAD error in AK4 test caused by slow servo response of A axis is larger.

4.3. Influence of positioning error
It is assumed that the positioning error of A axis has a positive linear trend with a slope of 0.001°, i.e. the positioning error is 0.09° in the range of 90°. From Table 1 and Figure 4(d), it can be seen that the positioning error of A axis will directly produce the equivalent TAD deviation because the swing of A axis directly affects the direction of tool axis.
From the above simulation results, it can be seen that many error factors of rotary axis will lead to the TAD and TCP error. The two-point measurement method can evaluate the TAD error caused by the angular error, so as to better reflect the comprehensive performance of the machine tool.

| Error term     | PIGEs | gain mismatch | positioning error |
|----------------|-------|---------------|-------------------|
|                | AK3 test | AK 4test | AK3 test | AK 4test | AK3 test | AK 4test |
| First TCP error| 55.5 μm  | 46.2 μm   | 40.8 μm  | 94.1 μm  | 61.9 μm  | 157.0 μm |
| Second TCP error| 23.1 μm  | 24.5 μm   | 5.5 μm   | 2.3 μm   | 11.0 μm  | 15.0 μm  |
| TAD error      | 81.9 sec  | 81.9 sec  | 115.0 sec | 195.2sec | 107.7 sec | 323.8 sec |

Figure 4. Influence of different errors on TAD and TCP error in AK3 and AK4 test
5. Experimental study
The proposed method was tested on a five-axis gantry machine tool as shown in Figure 5. The structure of the machine tool is described in Figure 5. AK3 and AK4 tests for the comprehensive TAD and TCP error evaluation are carried out by using the DBB and R-test respectively. The test consists of two parts: one is to test AK3 twice with a double ball bar, the corresponding tool lengths are 190mm and 280mm. The other is to test AK4 twice with R-test. The corresponding tool lengths are 170mm and 260mm, respectively. The test speed is F1000mm/min.

Figure 5. Experimental set up
The measurement results are shown in Table 2 and the error trajectory is shown in Figure 6. It can be seen that the maximum deviation of TAD measured by AK4 is 140 sec, and the deviation of TAD measured by AK3 is 56 sec. Combined with the analysis of rotary axis range corresponding to the two tests, the motion range of C axis of the two tests is the same, but the motion range of A axis in AK3 is [0°, 25°], and that of AK4 is [0°, 90°]. It can be seen that the difference between the two test results is mainly caused by the error of A axis.

Figure 6. Contour error profiles for the AK3 and AK4 test

| Error term     | AK3 test (μm) | AK4 test (μm) |
|----------------|---------------|---------------|
| First TCP error| 109.7         | 312.8         |
| Second TCP error| 89.9         | 251.6         |
| TAD error      | 56.0          | 140.3         |

6. Summary
This paper presents a kinematics test and evaluation method for tool axis direction error of five-axis machine tools. Based on the AK3 and AK4 test standards in ISO10791-6-2014, a testing method and an evaluation index calculation method for tool axis direction are designed. By measuring and
calculating the trajectory errors of two tool center points corresponding to different tool lengths, the TAD error can be obtained by combining the two measurements. It can effectively identify the proportion of errors caused by the deviation of tool axis in the total error of tool tip, and is conducive to faster discovery of machine tool performance problems.

7. References

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