# A New Direct 9-line Geometric Error Measurement Method for CNC Machine Tools

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## Abstract

The existing line measurement methods are analyzed. In the process of obtaining the existing error parameters, the assumption conditions in the model developing are adopted, which makes the insufficient adaptability of the model and unreliable measurement results. A method for directly obtaining the error values of the machine tools have suggested by using a high-precision laser interferometer. The 9 lines at different places in the working space of the machine tool is proposed. A three-axes CNC vertical machining center was measured, which proved that the measurement process is easy to operate and the operation is relatively simple, which can be applied to actual industrial field measurement. This method is further popularized and can be used to verify other line measurement methods and check the error models, which has great practical application value.

**Keywords:** CNC machine tools; Positioning error; Error measurement; Geometric error.

## 1. Introduction

The unremitting pursuit of manufacturing industry is to improve the machining accuracy of work pieces. High precision CNC machine tools is the only way to achieve this goal. Through the error measurement of CNC machine tools, the characteristics of machine errors and the error sources of machine tools can not only provide the basis for the high-precision manufacturing of important parts of machine tools, but also provide the basic parameters for the compensation of machine tools. After years of research, the measurement technology of geometric error of CNC machine tools has been significantly improved.

As for the measurement method of the geometric errors of the translation axes of CNC machine tools, there have been corresponding measurement standards[1, 2]. It generally divides into direct measurement method and indirect measurement method. The direct measurement method generally adopts laser interferometer, which uses the combination of interferometer and optics to measure the positioning error of translational axes, the combination of interferometer and electronic level meter to measure rolling error of translational axes. Zhang et al. use laser interferometer and Wollaston prism schlieren interferometer to measure straightness errors[3]. Among of these measurements, a variety of instruments have been used together to measure the 6 geometric errors of the translational axes. Using a complete set of laser interferometer can directly measure the 6 geometric errors, which require multiple light adjustment at the same time, which requires high requirements for the operator and is not conducive to wide application in the workshop [4]. The indirect error measurement method generally uses high-precision instruments to measure the positioning error of the integrated motion...
track of the translation axes of the machine tool in the working space, and then uses the mathematical model to calculate the geometric errors. Numerous researchers have developed high-precision measuring instruments for this method. At the same time, many scholars use laser interferometer as a tool to measure the track positioning error, and put forward a variety of indirect measurement methods, some of which have been widely used; especially for the linear measurement and modeling methods of machine tool workspace have been studied in depth.

Professor Zhang[5], who proposed this kind of method earlier, used laser interferometer to measure the positioning errors of 22 lines in the translational axes, and then used error model to calculate 21 errors of three-axes CNC machine tools including straightness errors and rolling error. The algorithm for this method is complex and has strict requirements on the number of measurement points, and it needs to meet the assumption that the sum of all errors is zero. In 2001, based on this, Guiquan Chen et al.[6] proposed 15-line measurement methods, 7 of which are required by ANSI and ASME standards. This method includes the measurement of positioning error of four three-axes linkage track lines. In order to avoid the difficulty of light path adjustment caused by the measurement of three-axes linkage trajectory, Professor Fan[7] proposed a 14-line method for measuring the workspace of translational axes by using Wollaston prism schlieren interferometer and laser interferometer; combined with the established error model, 21 geometric errors were identified. This method assumes that the sum of straightness errors in linkage axis is zero, lacking universality[4]. Built on the analysis of the above measurement methods, Professor Su[8] proposed a 12-line translational axes error identification algorithm. In the process of using the model to solve the geometric error, the influence of angular errors on the positioning error of the linkage track was not considered. Li et al.[9] systematically analyzed the effects of angular errors of single axis movement and linkage process on positioning error, and designed the auxiliary equipment of laser interferometer, put forward the positioning error of 13 lines through measuring the workspace, and combined with the model, identified 18 errors of translation axes. Liu et al.[10] put forward a 9-line measurement method (Figure 1.), which utilizing laser interferometer and Wollaston prism schlieren interferometer, the positioning error and straightness errors of 9 single axis motion tracks of translational axes are measured. This method avoids the problem of multi axis linkage optical path adjustment, but comparable to the 14-line method, straightness error and positioning error should be measured at the same time in a single measurement.

Based on the above analysis, we have not seen the use of high-precision measuring instruments. Through simple measurement methods, we can directly obtain all geometric error parameters of CNC machine tools. In this paper, a new 9-line linear error measurement method is proposed. Only one value is measured at a time. It can directly measure 6 values of a single translational axis, effectively avoiding the deviation caused by linkage adjustment and error model. It calls 9-line direct measurement method.

![Figure 1. 9-line direct measurement method.](image)

2. 9-line Direct Measurement Method

This method considers the practical application in the factory. Compared with other methods, it is relatively simple for light, and directly measures various error values, avoiding the deviation of calculation results caused by various assumptions of the error model, and the results are more reliable
and accurate. Considering that the effective movements of X-axis is 1000mm, Y-axis and Z-axis are 510mm and 540mm respectively, in order to obtain more effective values, the following space division is adopted, and the detection model diagram for geometric errors is shown in Figure 2.

According to the working space of the CNC machine tools, the above measurement dimensions are designed, in which the error values of X-axis are measured by line 1, 2 and 3, the error values of Y-axis are measured by line 4, 5 and 6, and the error values of Z-axis are measured by line 7, 8 and 9. The method of obtaining the error parameters is shown in Table 1. The above angular errors and positioning error shall meet the following requirements (Table 2.).

![Detection model diagram for geometric errors.](image)

**Table 1.** Comparison of line number and measurement parameters.

| Line no. | The initial point of the line on the coordinate | The final point of the line on the coordinate | Measurement content of errors |
|---------|-----------------------------------------------|-----------------------------------------------|------------------------------|
| 1       | 0, 0, 0                                       | 1000, 0, 0                                   | Positional displacement error of X-axis (Exx) |
| 2       | 0, -255,270                                   | 1000, -255,270                               | Pitch (EBX), yaw (ECX) and rolling (EAX) error of X-axis |
| 3       | 0, 0, 540                                     | 1000, 0, 540                                 | Straightness errors of Y (Ey) and Z-axis (Ez) |
| 4       | 0, 0, 0                                       | 0, -510, 0                                   | Positional displacement error of Y-axis (Ey) |
| 5       | 500, 0, 270                                   | 500, -510, 270                               | Pitch (EAY), yaw (ECY) and rolling (EBY) error of Y-axis |
| 6       | 0, 0, 540                                     | 0, -510, 540                                 | Straightness errors of X (Ex) and Z-axis (Ez) |
| 7       | 0, 0, 0                                       | 0, 0, 540                                    | Positional displacement error of Z-axis (Ez) |
| 8       | 500, -255,0                                   | 500, -255,540                                | Pitch (EAZ), yaw (EBZ) and rolling (ECZ) error of Z-axis |
| 9       | 0, -510, 0                                    | 0, -510, 540                                 | Straightness errors of X (Ex) and Y-axis (Ey) |
### Table 2. Description of measurement axis error symbols.

| Geometric errors | Linear errors | Straightness errors | Angular errors |
|------------------|---------------|---------------------|---------------|
| Axis             | Positional    | Straightness       | Pitch         |
| X                | Exx           | Eyx Ezx            | EBX EAX       |
| Y                | Eyy           | Exy Ezy            | EAY ECY EBY  |
| Z                | Ezz           | Exz Eyz            | EBZ EAZ ECZ  |

### Table 3. Main characteristic parameters of Renishaw XL-80 laser interferometer test system.

| XL-80 Laser Interferometer measurement system characteristics |
|--------------------------------------------------------------|
| Axial Range        | 0-80m          |
| Accuracy           | 3ppm           |
| Resolution         | 0.001 μm       |
| Straightness measurement | |
| Axial Range        | 0-4m           |
| Straightness Range | ±2.5mm         |
| Accuracy           | ±0.5% ±0.5 ±0.15M2μm |
| Resolution         | 0.01 μm        |
| Angular measurement |               |
| Axial Range        | 0-15m          |
| Angular Range      | ±175mm/m       |
| Accuracy           | ±0.2% ±0.5 ±0.1Mμm/m |

According to this method, 18 error values of translational axes of three-axes CNC machine tools can be measured, in addition, 3 squareness error values of three-axes can be obtained by using ball bar, and 21 error values can be directly obtained by using high-precision instruments.

### 3. 9-nine Direct Measurement Process

This measurement adopts Renishaw XL-80 test system, and the main parameters are shown in Table 3. At present, laser interferometer is the instrument with the highest error measurement accuracy of CNC machine tools. It provides a simple direct measurement method to measure the error directly, which can not only verify the reliability of other measurement methods, but also verify various error models. All preparations before measurement shall be done in strict accordance with the operation specifications, including preheating of machine tools, environmental temperature control, elimination of surrounding vibration sources and so on, so as to minimize the interference of the random error in measurement.

According to the requirements of the international standard ISO 230-1, the measurement gap is no more than 20 mm for the axis with a length of no more than 500 mm. No more than 1/10 of the length for the axis with a relatively long length, so as to increase the measurement points and obtain more data. Set a 3-second pause time for each measurement points to obtain a more stable measurement value. Depending on this, the X-axis interval of this test is 40mm, and the Y-axis and Z-axis interval is 20mm. For the positioning error and angular errors, each single error will go back and forth 5 times; for the straightness errors, each single error will go back and forth 3 times. The installation and measurement of Z-axis are shown in Figure 3.
4. Results and Analysis of 9-line Direct Measurement Method

According to the above measurement specifications, our research team's relevant literature [11] has given the results and methods of five round-trip measurement of Y-axis, and this paper gives the average measurement results of five positive and negative measurements of each error of X-axis and Z-axis. (Figure 4-13.)

Figure 3. Positional displacement error measurement of Z-axis (left) and Straightness errors measurement of X and Y-axis (Right).

Figure 4. X-axis positioning error (Exx).

Figure 5. X-axis Yaw error (ECX).

Figure 6. X-axis Pitch error (EBX).

Figure 7. X-axis Straightness error in Y direction (Eyx).
Figure 8. X-axis Straightness error in Z direction (Exz).

Figure 9. Z-axis positioning error (Ezz).

Figure 10. Yaw error of Z-axis (ECZ).

Figure 11. X-axis Pitch error (EBX).

Figure 12. Z-axis Straightness error in X direction (Exz).

Figure 13. Z-axis Straightness error in Y direction (Eyz).

After the measurement system is debugged and completed according to the rules, the above measurement values can be automatically output by the measurement system, which has high reliability. At the same time, according to the international standard ISO-230, the error parameters of each measurement axis can be calculated as follows Table 4. (Taking the Z-axis as an example).

In order to provide a complete set of 21 error measurement methods of high-level measuring instruments, the squareness error of three-axes of the machine tools is measured by ball bar. Taking X-Y plane as an example, the measurement device is shown in Figure 14. The actual measurement result is that the squareness error of the X-Y plane is $86.8 \, \mu M / m$. (Figure 15.)

In the same way, the squareness error between plane X-Z and plane Y-Z can be measured, and all 21 errors can be directly measured with high precision. Through the above steps, a direct error
measurement method is provided, which is relatively simple and easy to realize the light of the interferometer and the reflector.

| Z-axis      | Ezz (μm) | Exz- Eyz (μm) | EBZ-EAZ (arc-seconds) |
|-------------|----------|---------------|------------------------|
| Reversal (B) | 1.740    | --            | 0.23                   |
| Mean Reversal       | -0.0464  | -0.18         | -0.03                  |
| Mean deviation (M)  | 50.750   | 5.31          | 8.87                   |
| Deviation (E)       | 52.20    | --            | 9.01                   |
| Repeatability       | 9.249    | 2.50          | 1.18                   |
| Accuracy (A)        | 58.709   | 6.67          | 9.79                   |

Figure 14. Ball bar measurement.

Figure 15. Measurement process and results of X-Y plane squareness error.

5. Measurement Test of Work-piece Cutting Error

In order to further verify the measurement results and analyze the error source of the machine tools, the following (Figure 16.) test work-piece is designed. The work-piece material is 45# steel, which is utilized to verify the relationship between the positioning error and the measurement error of the work-piece. The processing process is illustrated in Figure 17.
Figure 16. Test piece diagram.
Figure 17. Test workpiece processing site.

Take three work-pieces to measure the CMM (Figure 18.), and you can get the actual measurement of 6 different command values of X-axis and Y-axis. The command values of Z-axis are all set to 10mm, and you can also get the corresponding error values of different height. Taking X-axis as an example, the measurement results are presented in Table 5., and the average error of each measurement position is shown in Figure 19.

Figure 18. Workpiece error measurement.

The purpose of this paper is to provide a direct measurement method for the errors of the existing high-precision instruments, and to provide a method for further verification of the measurement results by using the CMM, and further analysis of the measurement values is not carried out here. CMM can identify the difference between the actual machining value and the instruction value. There is an inevitable mapping relationship between the difference and the actual machine error (obtained by the 9-line direct measurement method). It is equally the result of the interaction between the machine errors and their coupling and dynamic characteristics. It is the aim of the majority of scientific and technological workers to explore the influence mechanism.

Table 5. Actual machining measurement error of X-axis workpiece (mm).

| No. | Design value | Work-piece 1 (X-axis) | Work-piece 2 (X-axis) | Work-piece 3 (X-axis) |
|-----|--------------|----------------------|----------------------|----------------------|
|     |              | Measured value | Error value | Measured value | Error value | Measured value | Error value |
| 1   | 14.14        | 14.0827     | -0.0573     | 14.0532      | -0.0868     | 14.1311      | -0.0089    |
| 2   | 28.28        | 28.2518     | -0.0282     | 28.2722      | -0.0078     | 28.2860      | 0.0060     |
| 3   | 42.43        | 42.3815     | -0.0485     | 42.4254      | -0.0046     | 42.4246      | -0.0054    |
| 4   | 56.57        | 56.5435     | -0.0265     | 56.5268      | -0.0432     | 56.5784      | 0.0084     |
| 5   | 70.71        | 70.7045     | -0.0055     | 70.6890      | -0.0210     | 70.6894      | -0.0206    |
| 6   | 84.85        | 84.8222     | -0.0278     | 84.7619      | -0.0881     | 84.8304      | -0.0196    |
6. Conclusion

1) The shortcomings of the original linear measurement method or error modeling are analyzed, and a new direct 9-line geometric error measurement method is proposed, and 21 geometric error measurement processes and results of three-axes CNC machine tools are given.

2) The proposed measurement method can directly obtain 21 geometric errors of the three-axes machine tools, avoid the uncertainty brought by the error model and its error modeling assumptions, with high measurement accuracy and good reliability.

3) The new measurement method can be used to verify the accuracy of the existing error model, and will play an important role in exploring the coupling relationship between errors and studying the dynamic characteristics of geometric errors, which will be reported later.

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