A study on the Model of 3D-coordinate Measuring Machine Error Compensation Based on Finite Element Simulation

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Abstract:

Additional inertial force will cause the deformation of some parts when 3D-coordinate Measuring Machine (CMM) runs quickly. It will result in the difference between real results and reading of raster sensor, that is, dynamic error will be produced. This paper presents the theoretical model of CMM dynamic error compensation. The Z-direction deformation of crossbeam is analyzed based on Ansys, one kind of finite element simulation software, when slide carriage is in different position under three different load conditions (accelerating, uniform speed, decelerating). Dynamic error compensation model is acquired under any kind of load according to the analysis results, which can improve the measuring accuracy of CMM greatly.

Keywords: CMM, Error Compensation, Finite Element Analysis, Dynamic Errors

1. Introduction

With the development of modern mechanical manufacturing, fast movement and high precision is required for 3D-coordinate Measuring Machine (CMM). In order to improve the accuracy of CMM, more and more researchers are attracted by dynamic error compensation. The dynamic error of CMM is caused by the offset of moving parts around the joint with guide way and their own deformation. The stiffness of guide way and moving parts is limited. So the offset and deformation occurs when CMM accelerates or decelerate, because of the additional inertial force. It will results in the difference between real results and reading of raster sensor, that is, dynamic error will be produced. Some error compensation models are built by many researchers, which are required according to much experimentation. This paper presents a theoretic dynamic error compensation model in Z-direction, which can reduce measurement error extraordinary.

2. Theoretic Analysis

The gantry CMM (400mm×400mm×400mm) designed by this paper is shown in Fig.1.

The crossbeam glides in Y-direction. The slide carriage moves in X-direction, and the feeler pin runs in Z-direction. In the process of fast movement, additional

inertial force is produced when slide carriage and

Fig.1 Simplified schematic diagram of CMM the crossbeam glides in Y-direction. The slide carriage moves in X-direction, and the feeler pin runs in Z-direction. In the process of fast movement, additional inertial force is produced when slide carriage and Z-direction spindle accelerates or decelerates. So the crossbeam will bend and deflect. The load condition is shown in Fig.2 in Z-direction.

p is the sum of all forces in Z-direction including additional inertial force, gravity of Z-direction spindle and slide carriage. q is the load of unit length. The crossbeam will bend round Y-direction and deflect round the joint with guide way, if Z-direction spindle changes its speed when slide carriage moves in X-direction. The following relational expression can be acquired

Fig.2 The deformation schematic diagram of crossbeam under load

according to Fig.2.

$$\Delta Z = \Delta A + \Delta Z_1 - \Delta Z_2 \quad (1)$$

$$\Delta Z_2 = l(1 - \cos \alpha) \quad (2)$$

$$\Delta Z_1 = \frac{1}{2}(\Delta B - \Delta A) \quad (3)$$

$$\Delta Z = \Delta A + \frac{1}{2}(\Delta B - \Delta A) - l(1 - \cos \alpha) \quad (4)$$

If $\alpha \rightarrow 0$, then $\sin \alpha \sim \alpha \sim \tan \alpha$. So the following can be deduced.

$$1 - \cos \alpha \sim \frac{1}{2}\alpha^2 \quad (5)$$

$$\Delta Z \approx \Delta A + \frac{1}{2}(\Delta B - \Delta A) - \frac{1}{2}\alpha^2 l \quad (6)$$

The offset of Z-direction spindle along X-direction is given in Eq.7.

$$\Delta X_l = l \sin \alpha = l \tan \alpha \quad (7)$$

The offset error caused by deformation of crossbeam is relative to the position of Z-direction spindle, that is, l . If $l=1\text{m}$, then

$$\Delta X \approx \tan \alpha = \frac{|\Delta B - \Delta A|}{|AB|} \quad (8)$$

3. Finite Element Analysis

The crossbeam is made of granite. The density is 3g/cm^3 . The elastic modulus is 120GPa , and the Poisson ratio is 0.3 . The dimensions is shown in Fig.3. The model is meshed using SOLID95(3D elements) of ANSYS, which has 20 nodes. The load step is applied every 20mm , in order to simulate the load condition of crossbeam. Three different kind of load conditions are

given in this paper. p is 500N when Z-direction spindle accelerates. p is 450N when spindle moves at uniform speed. p is 400N when spindle decelerates. The speed and position is controlled by the motor. p and q can be calculated according if acceleration is certain. Then the offset error of feeler pin can be calculated according to Eq.6 and Eq.8 in different position under the three load condition. The error of the feeler pin in Z-direction and in X-direction is shown in Fig.4 and Fig.5.

Fig.3 Simplified schematic diagram of crossbeam structure

4. Error Modeling

The error in Z-direction and in X-direction is produced by the deformation of crossbeam when Z-direction spindle accelerates. There is one point in crossbeam (the abscissa is X_m). The offset error of the point in X-direction is zero. So the mathematical model of the offset error can be built in two parts. Firstly, the point must be found in which the offset error in Z-direction is maximal. The point is dividing point of error compensation functions. The error compensation functions in Z-direction and in X-direction can be built in terms of Lagrange Interpolation. These functions are given in Eq.9~Eq.11.

In a similar way, the error compensation models can be acquired when Z-direction spindle moves at uniform speed, as shown in Eq.12~Eq.14. The model is shown in Eq.15~Eq.17 when the spindle decelerates.

Fig.4 Error curve in Z-direction

Fig.5 Error curve in X-direction

The error compensation model is given in the Eq.9~Eq.11 when Z-direction spindle accelerates.

$$\Delta Z_1'(x) = (-0.204925x^2 + 77.219x + 17707) \times 10^{-4} \mu m \quad (9)$$

$$\Delta X_1'(x) = (-0.5074072x^2 - 81.55555x + 32818.52) \times 10^{-4} \mu m \quad (10)$$

$$(0 \leq x \leq X_M)$$

$$\Delta X_1''(x) = (-0.4755953x^2 + 466.0441x - 72433.03) \times 10^{-10} \mu m \quad (11)$$

$$(X_M \leq x \leq 400 \text{ mm})$$

The error compensation model is given in the Eq.12~Eq.14 when Z-direction spindle moves at uniform speed.

$$\Delta Z_2'(x) = (-0.163940887x^2 + 61.77635x + 14165.75) \times 10^{-4} \mu m \quad (12)$$

$$\Delta X_2'(x) = (-0.40601825x^2 - 65.194445x + 26251.847) \times 10^{-4} \mu m \quad (13)$$

$$(0 \leq x \leq X_M)$$

$$\Delta X_2''(x) = (-0.38115x^2 + 373.21043x - 57997.4752) \times 10^{-4} \mu m \quad (14)$$

$$(X_M \leq x \leq 400 \text{ mm})$$

The error compensation model is given in the Eq.15~Eq.17 when Z-direction spindle accelerates.

$$\Delta Z_3'(x) = (-0.1844178x^2 + 69.49055573x + 15936.94624) \times 10^{-4} \mu m \quad (15)$$

$$\Delta X_3'(x) = (-0.45509275x^2 - 73.694415x + 29548.147) \times 10^{-4} \mu m \quad (16)$$

$$(0 \leq x \leq X_M)$$

$$\Delta X_3''(x) = (-0.429563664x^2 + 420.2977167x - 65302.39413) \times 10^{-4} \mu m \quad (17)$$

$$(X_M \leq x \leq 400 \text{ mm})$$

5. Error Evaluation

The results of error compensation model are compared with finite element simulation. The residual error curves in Z-direction and in X-direction are shown in Fig.6 and Fig.7.

It can be concluded that the measuring error is decreased greatly from Fig.6 and Fig.7.

Fig.6 The residual error curves in Z-direction

Fig.7 The residual error curves in X-direction

6. Universal mathematical model

A rule is found through much analysis. The ratio of the corresponding coefficients of error compensation functions is same with the ratio of applied force under any two kinds of load condition, which accords with Hooke Law. So according to one certain error compensation function, any other functions can be obtained. The universal error compensation function of CMM in Z-direction is given in Eq.18, and the functions in X-direction are shown in Eq.19 and Eq.20.

$$\Delta Z'(x) = \frac{P(-0.204925x^2 + 77.219x + 17707)}{500} \times 10^{-4} \mu m \quad (18)$$

$$\Delta X_l'(x) = \frac{P(-0.5074072x^2 - 81.55555x + 3281852)}{500} \cdot l \times 10^{-4} \mu m$$

$$(0 \leq x \leq X_M) \quad (19)$$

$$\Delta X_l'(x) = \frac{P(-0.4755953x^2 + 4660441x - 72433.03)}{500} \cdot l \times 10^{-4} \mu m$$

$$(X_M \leq x \leq 400 \text{ mm}) \quad (20)$$

Where, l — the displacement of feeler pin in Z-direction.

7. Conclusion

This paper simulates the deformation of crossbeam in Z-direction under three different load conditions (accelerating, uniform speed, decelerating). Three error compensation models are presented. An universal mathematical model under any kind of load conditions is deduced based on the former three models. The calculating results of the models are compared with simulation results from Ansys. The comparison verifies the validity of the theoretical model of CMM dynamic error compensation, so the measurement error can be reduced greatly using the model in this paper.

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