Geometric errors measurement for coordinate measuring machines

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Abstract: Error compensation is a good choice to improve Coordinate Measuring Machines’ (CMM) accuracy. In order to achieve the above goal, the basic research is done. Firstly, analyzing the error source which finds out 21 geometric errors affecting CMM’s precision seriously; secondly, presenting the measurement method and elaborating the principle. By the experiment, the feasibility is validated. Therefore, it lays a foundation for further compensation which is better for CMM’s accuracy.

1. Introduction
With the development of society and economic, the need for higher quality products appears urgently, which calls for high accuracy manufacturing and measuring equipment. Coordinate Measuring Machines (CMMs) are famous measuring equipment, which are widely used in much field, such as machinery, automobile, aviation and military industry. The precision plays a key role in CMM, so how to improve it is a hot topic among all the researchers.

Generally speaking, two methods can be adopted to enhance the accuracy, one is error avoiding, which costs much time and money to design, manufacture and assemble CMM carefully; the other one is error compensation, which absorbs new errors to counteract the CMM’s original errors, so it is quick and economical[1].

2. The steps to enhance the CMMs’ precision
In order to increase the CMMs’ precision by error compensation, there are 3 basic steps shown as Fig.1, which are source of errors’ analysis, errors modeling and measurement, respectively. The source of errors is analyzed to find out the errors having a strong impact on CMMs’ accuracy. The error is modeled to establish the relationship between each error. The measurements are down for acquiring errors which should be compensated. The last step- measurement is very important, so the paper focuses on the topic.
3. Measurements’ objects
According to previous studies[3], geometric errors have significant impact on precision. So CMMs’ geometric errors should be discussed.

Any object without constraints has 6 degrees of freedom, which means it can moves along or rotate around any direction. In ideal condition, each CMM’s axis should have one degree of freedom, it means that it can moves along or rotate around only one direction. However, due to imperfect manufacture, the axis may have micro movements in every direction, so each axis might have 6 errors. Take Y-axis for example, the positioning error \( \delta_y \), the horizontal straightness error \( \varepsilon_x \), the vertical straightness error \( \varepsilon_z \), the roll error \( \varepsilon_r \), the yaw error \( \varepsilon_y \) and the pitch error \( \varepsilon_p \). The positioning error and straightness errors are translational errors and the rest three are angular errors[2].

Therefore, the other two translational axes of CMMs have similar errors, given as follows.

- X-axis: \( \delta_x \), \( \delta_y \), \( \delta_z \), \( \varepsilon_x \), \( \varepsilon_y \), \( \varepsilon_z \)
- Z-axis: \( \delta_x \), \( \delta_y \), \( \delta_z \), \( \varepsilon_x \), \( \varepsilon_y \), \( \varepsilon_z \)

Besides single axis’s errors, the errors exists between two axes which are squareness errors. They are \( \varepsilon_{xy} \), \( \varepsilon_{xz} \), \( \varepsilon_{yz} \). Therefore, the total number of CMMs’ geometric errors is 21.

4. Measurements’ principle
The CMMs’ geometric errors can be gotten by laser interferometers. There are several brands of laser interferometers, such as Renishaw, Optodyne and Faro. They all develop from Michelson interferometer[4] and they have similar principle for measurement.

The well-known Michelson configuration is shown as Fig.2[5]. A single incoming beam of light from source will be split into two identical beams by a beam splitter (a partially reflecting mirror). Each of these beams travels a different route, called a path, and they are recombined before arriving at a detector. The path difference, the difference in the distance traveled by each beam, creates a phase difference between them. If the phase difference is integer multiples of coherent light’s wave length,
constructive interference will happen; if the phase difference is half of the wave length (except the integer multiples), the destructive interference will occur. When the mobile mirror moves from M1 to M2', the constructive interference and destructive interference will take in turns, and at the detector, the bright fringe and dark fringe will appear alternately, just as Fig.3. The equipment record the times of alternation (N), according to it and the wavelength of the laser (λ), the distance the mobile mirror moves (L) can be calculated, shown as Fig.1.

\[ 2 \times L = n \times \lambda \Rightarrow L = n \times \lambda / 2 \]  

(1)

5. Experiments

In order to avoid redundancy, only one geometric error of CMM is selected to elaborate, which is the angular error (the pitch error) \( \varepsilon_y(y) \).

The brand of CMM for experiment is Zeiss Opton, which model is UMC550S, the work volume is 550x1200x450mm. The measurement accuracy is \( 1.3 \mu m / 350 \). As the CMM has been used for 2 decades, so the precision might be affected.

The equipment for experiment is from Optodyne Inc., named as Laser Doppler Displacement Meter (LDDM), the model is MCV-5002. The equipment can manage to gather the information about positioning errors, angular errors and straightness errors. The measurement accuracy for positioning errors is \( 1 \mu m / m \), it for angular errors is \( 0.2\% \pm 0.2 \) arcsec and it for straightness errors is \( 0.2\% \pm 0.01 \) mm. Therefore, LDDM (MCV-5002) meets the demand of measurement.

The measuring object is Y-axis, which ranges up to 1200mm, the frequent work area is from 5 to 605mm, so the experiment focuses one this area. The process is shown as Fig.4.

The result of Y-axis’s the pitch error is given as Fig.5, 1F is the forward trip, which means Y-axis moves from 5mm to 605 mm; 1B is the backhaul. In the forward trip, the largest positive direction...
error occurs at 55mm, which is 1.87 arc-sec; the largest negative direction error occurs at 605mm, which is 5.63 arc-sec. The result of backhaul is similar with that of forward trip. The largest positive direction error also occurs at 55mm, which is 0.95 arc-sec; the largest negative direction error occurs at 655mm, which is 4.78 arc-sec.

6. Conclusion
In the paper, the error source of CMM is analyzed and 21 geometric errors are found out which affect CMM’s precision seriously. In order to gather the errors’ information, the measurement method is presented and its principle is introduced. By the experiment, the feasibility is validated. Therefore, it is better for later research on error compensation, which might lay a foundation for improving CMM’s accuracy.

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