The development of cylindrical coordinate measuring machines

Guoxiong Zhang, Jingbin Guo, Shugui Liu, Zurong Qiu, Xinghua Li

State Key Laboratory of Precision Measuring Technology and Instruments
Tianjin University
92, Weijin Road, Tianjin, 300072, China
Tel.: + 86 [22] 87898957 Fax: +86 [22] 27403431 E-mail: gxzhang@tju.edu.cn

Abstract

A method is proposed for measuring a surface of rotation using a cylindrical coordinate system and multiple measuring stands and a single rotary table. This method possesses lots of advantages such as high data collection efficiency, collision avoidance and high accuracy in form error measurement. The key techniques discussed in detail include the determination of stands' coordinate systems offsets with reference to the rotary table, the determination of the effective radii of the probing systems, error compensation, collision avoidance and protection measures, auto-centering the workpiece and data processing. The practice and experiments show that the measuring uncertainty of the machines is less than 0.02mm which meets the general requirement in most cases.

Keywords: Measurement, body of rotation, coordinate measuring machine, cylindrical coordinate system, alignment, calibration

1. Introduction

Bodies of rotation consist of a large portion of manufactured parts and play essential roles in the national economy. A method for measuring the surfaces of rotation in cylindrical coordinate system is proposed. The measurement is realized during the continuous rotation of the workpiece while the probes move along the generatrix of the surface step by step [1]. The method can be used with contact and non-contact probes. Inductive, laser triangulation and photogrammetric probes have been used for measuring different geometric features.

This method possesses lots of advantages such as high data collection efficiency, collision avoidance and high accuracy in form error measurement. After the motorized head and probe have reached a new position a cross section of the surface is measured while the rotary table rotates 360°. Its efficiency is further enhanced by using multiple measuring stands and probes. In the cylindrical coordinate measuring machine (CMM) all the probes move only on one side of the workpiece on a plane. The collision susceptibility is low. All the probes are fixed when a cross section is measured. The error motions of the linear carriages have no effect on the accuracy of roundness, runout, and eccentricity measurements.

However cylindrical CMMs suffer some specific problems. All the measuring lines should intersect with the axis of rotation and z axes of all stands should be parallel to it. The parameters of the part cannot be determined without knowing the relative positions of measuring stands with reference to the rotary table. Machine alignment and calibration are critical. The home positions instability and thermal errors are essential and should be compensated by periodic calibration. The key techniques including alignment and calibration of the probing systems, error compensation, auto-centering of the workpiece, collision avoidance and protection, data processing algorithm, are discussed in detail in the paper.

2. Working principle

The diagram of a cylindrical CMM with three measuring stands A, B and C is shown in Fig. 1. Workpiece 2 is mounted on rotary table 1 and clamped by fixture 10. Stand B is equipped with lateral and axial probes 6 and 7 to measure inner features. For measuring outer features stand A equipped with lateral probe 4 and stand C equipped with axial probe 8 are used. To determine the position of a point in the cylindrical coordinate system it is required to obtain argument angle θ, polar radius ρ and axial position z of the point. The encoder of rotary table 1 provides angle θ, ρ and z are obtained from radial positions x_a, y_b, x_c and axial positions z_a, z_b, z_c of carriages 3, 5 and 9 combined with their probe readings δ_a, δ_b, δ_b' and δ_c .

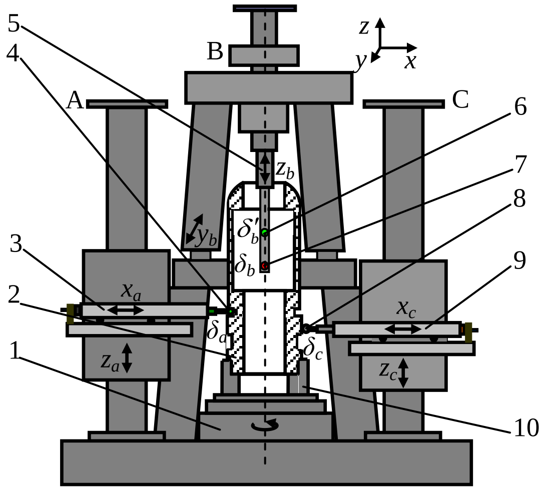
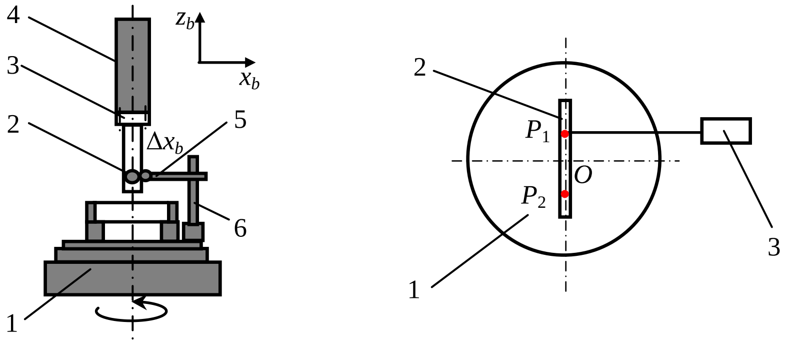


Fig. 1. Schematic diagram of a cylindrical CMM.

3. Alignment

For measuring the lateral misalignment of inner radial contact probe 2 magnetic fixture 6 with inductive gage 5 is mounted on rotary table 1 as shown in Fig. 2(a). Gage 5 measures the outer surface of probe 2. Variation Δx_b from gage 5 before and after 180° table rotation indicates twice the lateral misalignment of probe 2. The probe is aligned by changing the position of the mounting plate 3 on ram 4.



(a) Inductive probe. (b) Laser triangulation probe.

Fig. 2. Lateral misalignment measurement.

For measuring the lateral misalignment of laser triangulation probe 3 transparent target 2 with marks is mounted on rotary table 1 perpendicularly to the optical beam emitted from probe 3 as shown in Fig. 2(b). At the original position the spot is at point P_1. After rotating table 1 180° the beam is projected on point P_2. The misalignment of probe 3 equals $P_1P_2/2$.

4. Calibration

For determining the diameter and height of a particular cross section it is needed to know the coordinates of table system origin, i.e. the intersection point of the axis of rotation with the mounting base, in the measuring stand coordinate system. Besides, for measuring a sculptured surface a motorized head is often used. The readings obtained from the CMM are coordinates of the rotational centers of the motorized heads. For knowing the coordinates of the probing points the effective radii R of the probing systems should be calibrated.

For calibrating the coordinates of table system origin (0, y_{b0}, z_{b0}) and effective radius R_b of an inner feature measuring system ring gauge 5 is mounted on supporting ring 6 which rotates with table 1 as shown in Fig. 3(a). Probe 4 measures the right side first. Then motorized head 3 rotates 180° and ram 2 moves to measure the left side [2]. Hence

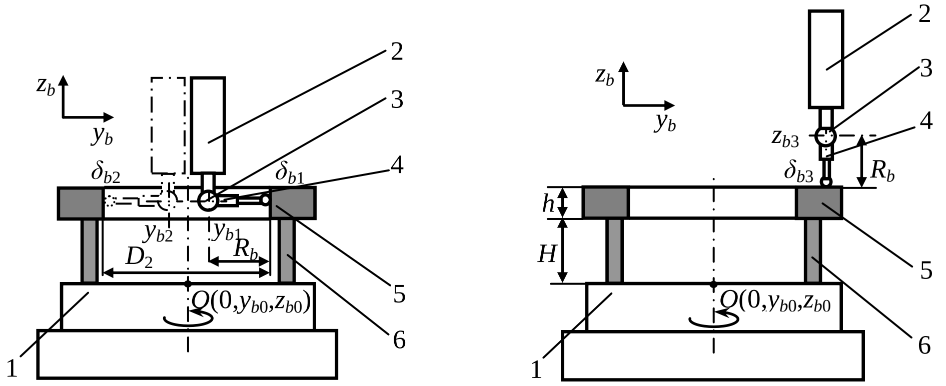
$$R_b = \{D_2 - [(y_{b1} - \delta_{b1}) - (y_{b2} + \delta_{b2})]\}/2 \tag{1}$$

$$y_{b0} = [(y_{b1} - \delta_{b1}) + (y_{b2} + \delta_{b2})]/2 \tag{2}$$

z_{b0} can be calibrated as shown in Fig. 3(b).

$$z_{b0} = (z_{b3} + \delta_{b3}) - R_b - h - H \tag{3}$$

The origin of stand B coordinate system has coordinates (0, -y_{b0}, -z_{b0}) in the table system.



(a) R_b and y_{b0} calibration.

(b) z_{b0} calibration.

Fig. 3. Calibration of an inner feature measuring system.

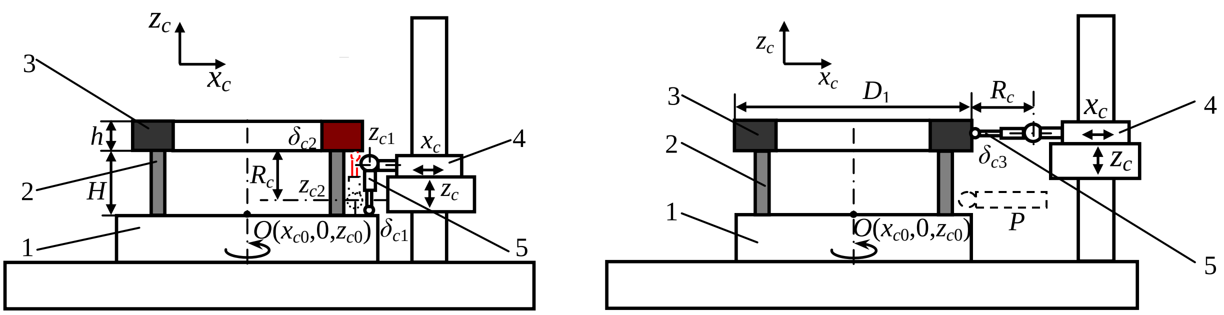
The effective diameter R_c of an outer feature measuring system might be calibrated by measuring the top and bottom surface of ring gage 3. In case of insufficient z_c travel the top surface measurement might be replaced by measuring that of table 1 as shown in Fig. 4(a) and

$$R_c = [(z_{c1} + \delta_{c1}) - (z_{c2} - \delta_{c2}) + H]/2 \tag{4}$$

$$z_{c0} = [(z_{c1} + \delta_{c1}) + (z_{c2} - \delta_{c2}) - H]/2 \tag{5}$$

where H is the height of supporting ring 2. Actually carriage 4 should have the same x_c position during both measurements. They are shown with different x_c just for a better view. After R_c has been calibrated x_{c0} can be determined as shown in Fig. 4(b). Probe 5 measures the outer surface of ring gauge 3. Hence

$$x_{c0} = x_{c3} + \delta_{c3} - R_c - D_1/2 \tag{6}$$



(a) R_c and z_{c0} calibration

(b) x_{c0} calibration

Fig. 4. Calibration of an outer diameter measuring system.

5. Error compensation

It is essential to assure all the z axes of measuring stands be parallel to the axis of rotation. Parallelism errors of axes z_b and z_c with reference to the axis of rotation are calibrated by measuring the diameter of the ring gage at different heights. D_{s4} and D_{s5} are measured results at z_{s4}, z_{s5} respectively, where s might be b or c. Positive parallelism error β_s of z_b or z_c indicates that $+z_b$ or $+z_c$ goes to $+y_b$ or $+x_c$ direction when $+y_b$ and $+x_c$ sides of the gage are measured. Error compensation should be introduced for the parallelism errors [3, 4].

$$\beta_s = (D_{s4} - D_{s5}) / [2(z_{s5} - z_{s4})] \tag{7}$$

6. Workpiece centering

For centering fragile workpieces an auto-centering system is developed. Its working principle can be explained by Fig. 4(b). Probe 5 monitors the variation of workpiece surface position while table 1 rotates 360°. Maximum and minimum probe readings $\delta_{\max}$ and $\delta_{\min}$, and angular position $\varphi_{\max}$, at which $\delta_{\max}$ appears are recorded. Rotary table 1 continues to rotate until the point with $\delta_{\max}$ is reached. Rod P is moved forward until probe 5 reads $(\delta_{\max}+\delta_{\min})/2$. Due to the form error of the workpiece and creep in motion the eccentricity will not be fully eliminated. The whole process repeats again when the eccentricity is larger than required.

7. Collision avoidance and protection

Safety is important especially for inner measurements since the measuring procedures cannot be seen. A virtual reality system for avoiding the possible collision has been developed. The motion of the measuring carriages can be seen on the computer screen. Once the distance between the probes and the workpiece becomes less than the minimum value in case of using non-contact probes, or the probe readings become smaller than minimum allowed, the measuring system stops immediately. Besides, a protection device shown in Fig. 5 is developed. Motorized head 2 with probe 1 is not mounted directly on ram 3. It is positioned on ram 3 through three balls 5 under springs 4. At least one of balls 5 will leave from contact when there is a collision from any side and the electric loop breaks down. The CMM stops.

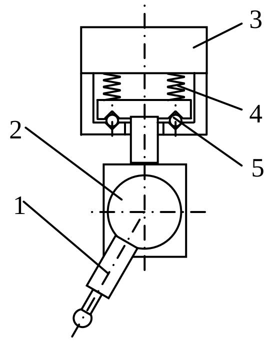


Fig. 5. Collision protection.

8. Data processing

The flow chart of data processing software is shown in Fig. 6. Five sets of data, CMM readings x_i (or y_i), z_i, rotation of motorized head α_i, probe reading δ_i and rotation of rotary table θ_i, are sampled. Based on these sampled data and the effective radii R and coordinates of the stand origins in the table system the coordinates of the measured points in cylindrical system are obtained. They are preprocessed to eliminate the noise, coarse errors and to introduce compensation for machine errors. After that all the data are transformed into the workpiece coordinate system and fitted to the theoretic surface. All the specific parameters of the surface can be determined from this fitted surface. Statistic analysis and other types of analyses are carried out based on these data for different purposes.

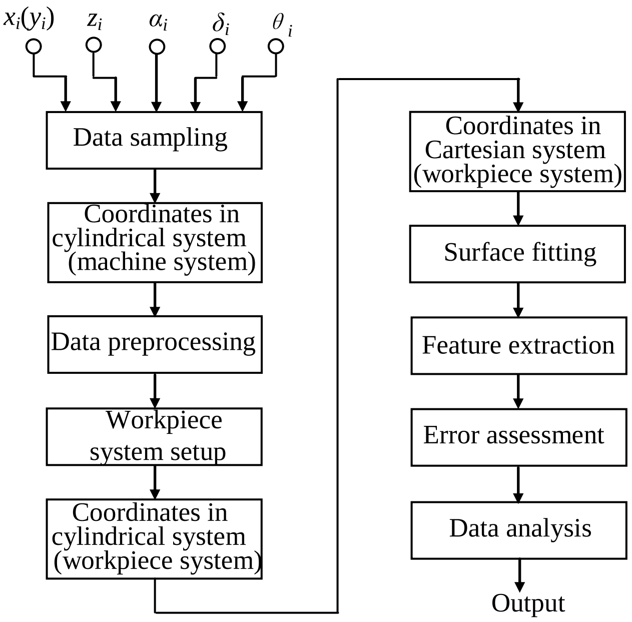


Fig. 6. Data processing algorithm.

9. Practice and experiments

Three types of cylindrical CMMs have been developed which work well in industries. The practice and experiments show that all the machine parameters can be calibrated with an accuracy of better than 0.006mm. The workpieces can be centered with eccentricity less than 0.1mm within three runs. The overall measurement uncertainties are less than 0.01mm for contact measurements and 0.02mm for non-contact measurements. Generally speaking, the achieved accuracy can meet the requirement for measuring different parts in most cases.

10. Conclusion

1. Measuring a surface of rotation in cylindrical system possesses advantages of high efficiency, collision avoidance and high accuracy in form error measurement.
2. The key techniques include linking the coordinate systems of the stands with the rotary table, calibration of the effective radii of the probing systems, error compensation collision avoidance and protection, and auto-centering the workpiece.
3. The aligning and calibrating techniques proposed in this paper have been successfully used in three types of cylindrical CMMs which work well in industries.

11. Acknowledgements

The authors would like to express their sincere thanks to the National Natural Science Foundation of China under grant 50775160 for their financial supports.

References

1. G.X. Zhang, S.G. Liu, Z.R. Qiu, et al. *Non-contact Measurement of Sculptured Surface of Rotation.* Chinese Journal of Mechanical Engineering. 2004, 17/4, pp. 571-574.
2. C.J. Evans, R.J. Hocken, W.T. Estler. *Self-Calibration: Reversal, Redundancy, Error Separation, and 'Absolute Testing'.* Annals of the CIRP. 1996, 45/2, pp. 617-634.
3. S. Sartori, G.X. Zhang. *Geometric Error Measurements and Compensation of Machines.* Annals of the CIRP. 1995, 44/2, pp. 599-609.
4. G. Zhang, R. Veale, T. Charlton, et al. *Error Compensation of Coordinate Measuring Machines.* Annals of the CIRP. 1985, 34/1, pp. 445-448.