Rapid online measurement method for radius of curvature of fine grinding optics based on tool setting system

DAI Lei, ZHANG Jian, GU Yongqiang, Miao Erlong

Engineering Research Center of Extreme Precision Optics,
State Key Lab of Applied Optics, Changchun Institute of Optics Fine Mechanics and Physics, Chinese Academy of Science, Changchun, 130033, China
E-mail: xiaomao_566@ciomp.ac.cn

ABSTRACT

The radius of curvature (ROC) is one of the most important parameters of sphere optic components. In optic fine grinding process, radius of curvature accuracy requires up to 0.1%. We propose a method based on high-precision CNC grinding machine, develop ROC online measurement method for fine grinding optics. This rapid method only takes few measurement points based on spiral route path, attaining enough accuracy and reduce the time cost, furthermore, can greatly reduce the repeated installation error. Analysing the uncertainty sources that affect to the ROC measurement results, calculates the combined standard uncertainty 32.8 micron. Completed comparison experiments with CMM, the standard deviation of the experiment result are about 18 micron that approaches to CMM results.

Keywords: Radius of curvature; online measurement; Uncertainty; Optical fabrication

1. INTRODUCTION

In modern precision optics fabrication, deterministic CNC grinding is widely used. It takes the place of traditional, craftsman driven optic fabrication process with increasing process flexibility and reliability. Traditional sphere generation is followed by grinding before polishing, but newer generators produce a fine grinding surface ready for polishing. As sphere optic components, radius of curvature (ROC) is one of the most important factors that relates to optic system performance [1-5].

AOMATT 2016: Advanced Optical Manufacturing Technologies, edited by Wenhan Jiang,
Li Yang, Oltmann Riemer, Shengyi Li, Yongjian Wan, Proc. of SPIE Vol. 9683, 96830V

The sphere optics generating method is using bound diamond cup/ring tool and symmetric grinding method, which has advantages with both quality and cost. The ROC accuracy of sphere optics generating can reach 0.1%[6]. The common used CNC generating machine is a 4-axies system, linear X, Y, Z and angular A. When sphere optics generating, the workpiece is rotating with ω_2 , the bound diamond tool is rotating with ω_1 , the rotating axis of workpiece and diamond tool are at an angle of α. The sphere generating principle shows in Fig. 1 and generating ROC result can be calculated by Equ. (1)

$$ROC = \frac{D}{2\sin\alpha} \pm r \tag{1}$$

D is the tool-cutting diameter, r is tool lip radius which concave is negative and convex is positive. The characteristics of this generating method are high quality, low non-symmetric error and high materials remove rate. During sphere generating process, tool wear is unavoidable, which will cause D and r change, separately angle α accuracy is related to CNC system accuracy, the generating ROC results turbulence is inevitable. Therefore, the ROC results always need to be measured and make essential correction in times.

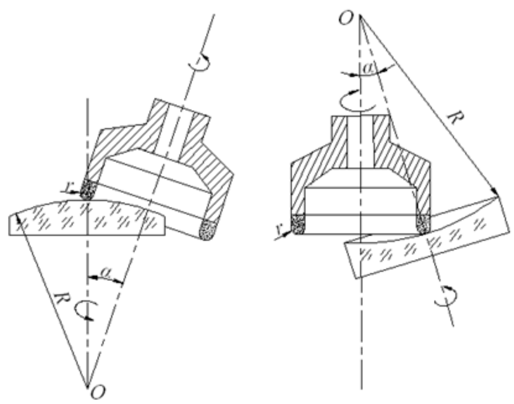

Fig. 1 Principle of Sphere Optic Generating

Due to surface roughness of the grinding surfaces, common optic measurement method such as, Newton rings method, confocal method and figure interferometer method will not be suitable [7-8]. Spheremeter, profiler and coordinate-measuring machine (CMM) are used for measuring ROC of generating sphere optics. However, there are also several drawbacks, CMM and profiler are very expansive and strict environment requirements, and spheremeter accuracy is difficult to reach 0.1%. Furthermore, re-installation of generating workpiece for measurement will introduce installing uncertainty repeatedly; it will not only reduce the efficiency of optical generating, but the generating ROC accuracy.

In this paper, we reported a new online ROC measurement method. The method is based on CNC generating machine, using tool-setting system, without introducing the other measurement instruments and re-installation uncertainty. Rapidly make measurements of few points of the sphere surface without releasing the generating workpiece, then calculating by a simple equation to obtain the ROC results. Uncertainty analysis and experiments implement the repeatability of ROC results is approximately 0.06%, satisfying the demands of precision sphere optics generating measurement.

2. METHODOLOGY

Workpiece coordinate system defines as Fig. 2, point $O(x_o, y_o, z_o)$ is the center of the workpiece surface, and R is ROC of workpiece sphere which negative is concave. Arbitrary point P(X, Y, Z) is one of the measurement points at workpiece surface, and point P satisfies with Equ. (2). At least four different point P should be measured, then to get the R and sphere center.

$$(X - x_o)^2 + (Y - y_o)^2 + (Z - z_o)^2 - R^2 = 0 \tag{2}$$

In this paper, we used measurement route path is based on spiral route path, which can be express as Equ. (3) In polar coordinates, and a is a constant of interval of spiral route, φ is radian. When workpiece is rotating with ω, the tool setting probe move with υ from the workpiece edge to the center, which only workpiece spindle and X axis will make movement. The probe route on workpiece is spiral, as shown in Fig. 2. The interval arc length of the near two points Δs is a constant. In machine coordinates, the measurement points of spiral route expresses as Equ. (4), then the Δs can be expressed as (5) and we can obtain specified spiral route path points (X, Y) coordinates on workpiece with limiting conditions. Using tool setting probe to getting the Z coordinates and calculating with Equ. (2) and (4), the ROC results can be calculated.

$$r = a\varphi, \varphi > 0 \tag{3}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} ax(w,t) \\ ay(w,t) \\ f(X,Y) \end{bmatrix} = \begin{bmatrix} \upsilon t \cdot \cos(wt) \\ \upsilon t \cdot \sin(wt) \\ f(X,Y) \end{bmatrix} \tag{4}$$

$$\Delta s = \int_{t_i}^{t_{i+1}} \sqrt{x'^2(\mathrm{t}) + y'^2(\mathrm{t})}dt \tag{5}$$

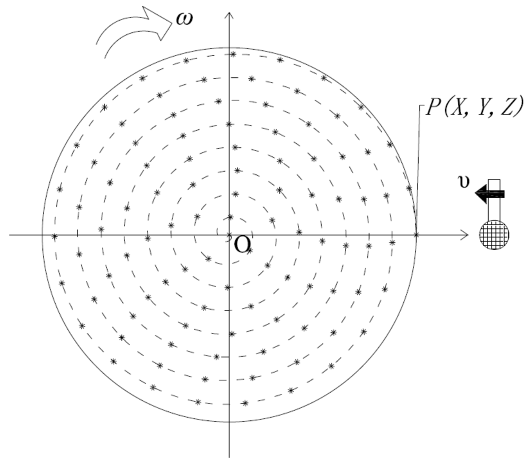

Fig. 2 Radius of curvature measurement principle

3. UNCERTAINTY ANALYSIS

3.1 CNC axis positioning error

The measurement point coordinates are determined by CNC accuracy. Assuming CNC axis positioning error is e_{CNC} , the new coordinates is as (6) (only consider X and Y axis, Z axis will discuss later).

$$\begin{bmatrix} X' \\ Y' \end{bmatrix} = \begin{bmatrix} X + e_{xCNC} \\ Y + e_{yCNC} \end{bmatrix} \tag{6}$$

If the maximum e_{CNC} is 2 micron with uniform distribution, e_{xCNC} and e_{yCNC} are random among e_{CNC} . Using Monte Carlo method, taking 10 thousand sample points with adding random e_{xCNC} and e_{yCNC} , then calculating the ROC results. The distribution is shown as Fig.3 and the distribution is Normal. The relating ROC uncertainty u_1 is less than 18 micron (3σ) [9-10].

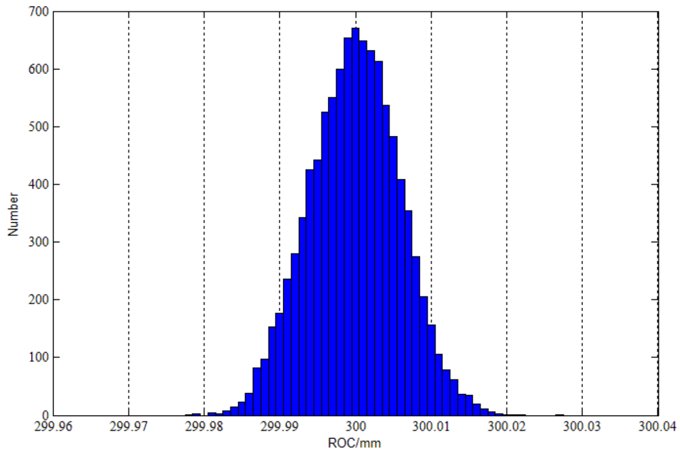

Fig. 3 Distribution of ROC by Monte Carlo analysis

3.2 Touching point error

Because of probe radius, the touching point of sphere surface will not be the lowest point of the probe. The actually touching point is shown in Fig. 4[11-12]. When point A is the actual touching point with measuring point B, line AB is the tangent line of the sphere, BC is the touching point error.

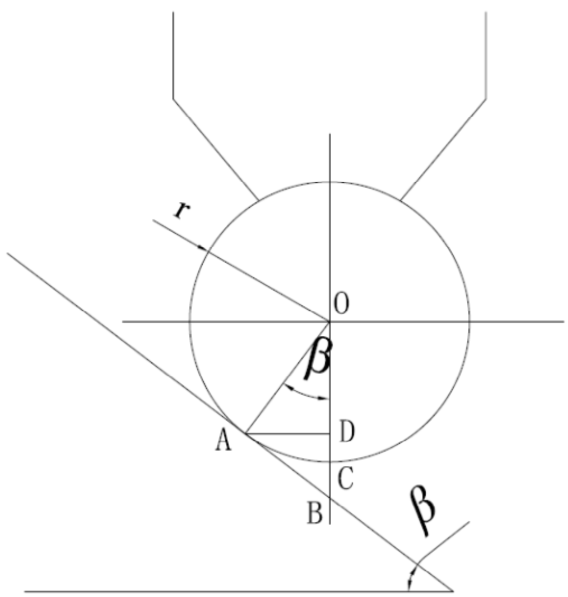

Fig. 4 Diagram of touching point error

$$\sin(\beta) = \frac{\sqrt{X^2 + Y^2}}{R - r} = \frac{d}{R - r} \tag{7}$$

r is the radius of probe, β is the included angle of probe and sphere surface and d is the half of measurement diameter. According the triangle principle, calculation by (8)

$$\begin{aligned} e_z &= BC = r \cdot (\sec \beta - 1) \\ &= \frac{1}{\sqrt{1 - d^2 / (R - r)^2}} - 1 \end{aligned} \tag{8}$$

When measuring, e_z is used to compensate to Z coordinates. Un-compensable part is uncertainty of touching point u_2 can be calculated by (9). Provided d is 50mm, r is 3mm, R is 300mm and u(r) is 0.02mm, u(R) is 0.01mm, u(d) is 0.002mm, u_2 is below 0.02 micron and can be neglected.

$$u_2^2 = (\frac{\partial e_z}{\partial d} u(d))^2 + (\frac{\partial e_z}{\partial r} u(r))^2 + (\frac{\partial e_z}{\partial R} u(R))^2 \tag{9}$$

3.3 Tool setting system error

The Z coordinates value of measurement point is taken by tool setting system cooperated with CNC system. Simply we define them all tool setting system error. We choose MARPOSS T25 tool setting probe which repeatability can reach 0.5μm (2σ). However, the actual measurement is influenced by measurement feedrate, temperature, probe material and other factors. Using well-polished fused silica Plano with nominal height 26.804mm to test repeatability of tool setting system, in well temperature controlled room, the results are shown in Fig. 5. When feedrate is at 300mm/min, the repeatability is better than 0.24μm (2σ), and feedrate is at 200mm/min, it is better than 0.08μm (2σ). By choosing 200mm/min feedrate, the variation of tool setting system is much small than CNC positioning error. Therefore, tool setting system uncertainty u_3 can be neglect.

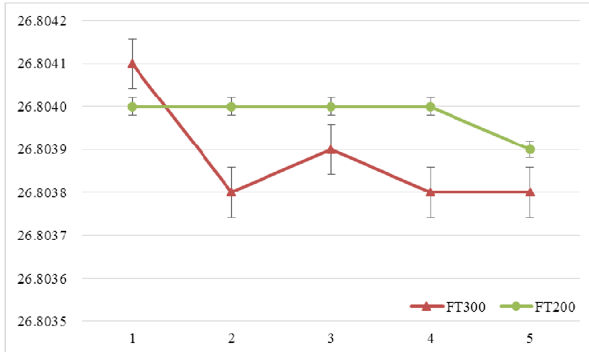

Fig.5 Repeatability of tool setting system with different feedrate

3.4 Surface form error

In fact, the generating surface has inherence surface form error. The generating surface form error can be measured by interferometer after a short time smoothing. In our experience, the generating surface form error is stable under uniform generating process. Fig. 6 is the surface map by interferometer of generating surface after 10mins smoothing; pv is about 1.1 micron with diameter 100mm and almost symmetrical.

Using Zernike polynomial describes the surface form error e_{sf}, which is shown as (10), where a_i are the coefficients of the Zernike terms, Z_i are the Zernike terms, and K is the number of Zernike terms which is commonly as 36.

Surface form error in Fig. is supposed to be the common generating from error, then we receive the common generating Zernike terms $a_i{}'$. Therefore, $e_{sf}{}'$ with uniform generating process should be considered as (11). If workpiece ROC is -300mm and DIA is 100mm, the relating uncertainty u_4 is smaller than 65 micron.

$$e_{sf} \approx \sum_{i=1}^{K} a_i Z_i \tag{10}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} ax(w,t) \\ ay(w,t) \\ f(X,Y) + e_{sf}{}' \end{bmatrix} \tag{11}$$

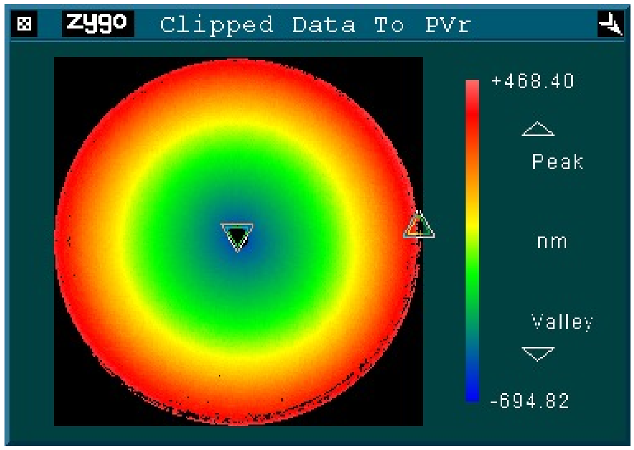

Fig. 6 surface form error by interferometer

3.5 Combined standard uncertainty

All the quantified uncertainty terms can be combined by RSS method to obtain the combined standard uncertainty is about 32.8μm [13], the relative uncertainty of ROC is about 0.01% which can satisfy the need of grinding online ROC measurement. The detailed conditions introduce above and results are shown in Tab. 1.

Tab. 1. Combined standard uncertainty.

	Error source	Uncertainty(μm)
1	CNC axis positioning error	18
2	Touching point	0.02
3	Tool setting system	-
4	Surface form	65
RSS		33.7

4. EXPERIMENTS

In order to verify the effect of this method, an experiment was implemented. CNC grinding machine G1 is produced by Satisloh, whose XYZ axis repeating accuracy is ±1μm [14]. Tool setting probe T25 is produced by MARPOSS [15]. The workpiece diameter is 100mm and nominal ROC is -300mm (minus sign represents concave surface). The measuring photo is shown in Fig. 7. 30 sampling points are chosen on spiral route of the whole 100mm DIA and repeat measurement five times. The same sample was measured by CMM.

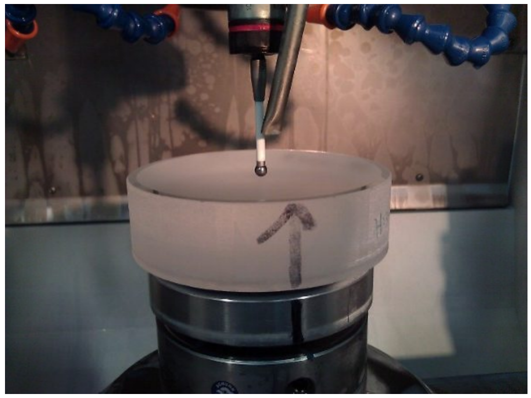

Fig.7 Photograph of measurement experiments

The experiments results are shown in Fig. 8, which are combined standard uncertainty values (k=3) in the form of error bars. This online ROC measurement method achieved repeatability about 18 microns RMS; difference between online ROC measurement method and CMM is about 0.06%, both of which can satisfied the online measurement demands 0.1% relative accuracy.

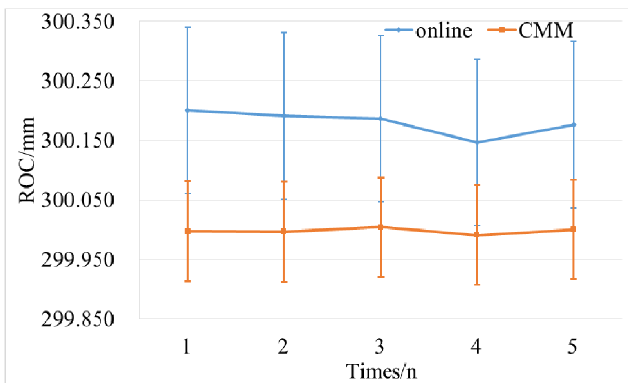

Fig. 8 Experiments Results

5. CONCULSION

A new online measurement method for ROC is proposing. Sampling method and uncertainty analysis are discussing, the designing result is better than convention spheremeter. Experiments results approach CMM results; the repeatability is 18 micron RMS and relative accuracy is 0.06%. The results difference between this online method and CMM should be study in next, calibration method could be introduced.

6. ACKNOWLEDGEMENTS

This work was supported by National Funding 2009ZX02205. Thanks for our colleague Shi Zhenguang and Liu Jian provided helpful advices.

REFERENCES

[1] Y.Lin and H.Huang, "Brittle materials in Nano-abrasive fabrication of optical mirror-surfaces," Precision Engineering, Papers 32, 336–341(2008).

[2] J. SŁADEK et al., "The Hybrid Coordinate Measurement System as a Response to Industrial Requirements Metrol,". Meas. Syst., Papers 1 109-118 (2010).

[3] Guido Bartl, Michael Krystek, Arnold Nicolaus, Walter Giardini, "Interferometric determination of the topographies of absolute sphere radii using the sphere interferometer of PTB," Meas. Sci. Technol., Paper, 21 115101 (2010).

[4] Xiang Hao, Cuifang Kuang et al., "From microscopy to nanoscopy via visible light Light: Science & Applications," Paper, 2 1-10 (2013).

[5] Ray Williamson, "Field Guide to Optical Fabrication," SPIE press 25-30 (2011).

[6] WANG Yangyang, YAN Dequan, "Application of Diamond Grinding Wheel in Optics Process," Journal of Applied Optics, Paper 33 170-174 (2012).

[7] L. A. Selberg, "Radius measurement by interferometry," Optical Engineering, Paper 31 1961-1966 (1992).

[8] Tony L. Schmitz, Angela D. Davies, Chris J. Evans "Uncertainties in interferometric measurements of radius of curvature," Proceedings of SPIE. 4451 432-447 (2001).

[9] M Kovacevic, D Nikezic, A Djordjevich, "Monte Carlo simulation of curvature gauges by ray tracing," Meas. Sci. Technol., Paper, 15 1756-1761 (2004).

[10] Liu Chunlai, Huang Wei et al., "Compensation Using Clocking Lens Elements in High Imaging Performance Optical Systems," ACTA OPTICA SINICA, Paper, 33 11-16 (2013).

[11] JIA L D, WANG J W, ZHENG Z W, "Optimization algorithm for the measurement of vertex radius of aspherics with a swing-arm profilemeter," Chinese Journal of Scientific Instrument, Paper, 30 1996-2000 (2009).

[12] Adam Wozniak and J R R Mayer, "A robust method for probe tip radius correction in coordinate metrology," Meas. Sci. Technol., Paper, 23 025001 (2012).

[13] International Organization for Standardization, "Guide to the Expression of Uncertainty in Measurement," (1995).

[14] Satisloh, "Optical Manufacturing Solutions-G1," (2011).

[15] MARPOSS, "Touch Probe Line catalog," (2005).