A laser differential confocal radius measurement system with high measurement accuracy is developed for optical manufacturing and metrology. The system uses the zero-crossing point of the differential confocal intensity curve to precisely identify the cat’s-eye and confocal positions and uses an interferometer to measure the distance between these two positions, thereby achieving a high-precision measurement for the radius of curvature. The coaxial measuring optical path reduces the Abbe error, and the air-bearing slider reduces the motion error. The error analysis indicates the theoretical accuracy of the system is up to 2 ppm, and the experiment shows that the system has high focusing sensitivity and is little affected by environmental fluctuations; the measuring repeatability is between 4 and 12 ppm. © 2012 Optical Society of America

1. Introduction

Radius of curvature (ROC) is one of the key parameters in spherical component measurement, and the measurement accuracy required in the precise optical system and optical metrology is increasing. In metrology, the standard ball’s radius is measured to calculate its volume and density [1–3]. In the manufacturing of precision optical components, the radius is directly related to the focal length and aberrations of the assembling optical system. The traditional radius measurement method uses a test plate with opposite radius as a template and compares the curvature differences by Newton rings, but this method makes it difficult to meet the requirement of high-accuracy radius measurement.

At present, the main methods used for ROC measurement include test plate, spherometer, coordinate-measuring machining (CMM), traveling microscope, and figure measuring interferometer (FMI) [4]. The test plate, spherometer, and CMM are contact measurements and have better measurement repeatability, but they have certain limitations due to easy scratching of the optical surface and coating during contact with the measured surface. The traveling microscope and FMI are noncontact radius measurements widely used in precision spherical measurement, and the accuracy of the radius measurement is direct related to the focusing sensitivity because they usually use the sharpness of the image or the Zernike coefficients of interference fringes to precise identify the cat’s-eye and confocal positions corresponding to the surface and the center of the test spherical surface and obtain the radius by measuring the distance between these two points [4,5]. The focusing accuracy of the traveling microscope is limited by diffraction; it has focal depth, and its measurement beam cannot be convergent into a point [6]. The interferometer has a higher focusing accuracy, but the fringes are very sensitive to vibration, air turbulence, and a variety of environmental factors [1,7]. Instantaneous phase-shifting interferometry was developed to improve the stability of the fringes, but the optical path is complex.

Therefore, the differential confocal technique is used to achieve accurate focusing [8,9], which has higher focusing sensitivity and stronger anti-interference capability. In addition, a new high-precision measuring instrument for ROC is established using this technique; it uses a distance-measurement interferometer (DMI) to ensure the
accuracy of the length measurement between the two points.

2. Measurement Principle

Differential confocal microscopy is a high-sensitivity detection technology with an antienvironmental interference capability, but the aperture and the working distance of the light path are short and are not suitable for precision parameter measurement of optical components. To this end, the following improvements are requested to make it applicable for the radius measurement of concave and convex surfaces: using the nonparallel optical path design, increasing the aperture and working distance, and reducing the number of large-diameter components in the optical path.

The differential confocal focusing principle is shown in Fig. 1. The laser from the point source S is converged by the objective and illuminates the test surface. The measurement laser beam is reflected back by the test surface when the test surface is moved near the cat’s-eye and confocal positions along the optical axis. It is divided into two beams after passing the beam splitters and is received by two detectors behind the pinholes. The pinholes have small offsets from the focus of the collimator lens Lc, +M and −M respectively, which make the phase shifts of the two sensors’ intensity response curve equal and opposite.

The differential response curve \( I(u, u_M) \) is obtained by subtraction of the two detectors’ signals, which satisfies [9]

\[
I(u, u_M) = \left| \int_0^1 e^{j2(2u+u_M)} \rho d\rho \right|^2 - \left| \int_0^1 e^{j2(2u-u_M)} \rho d\rho \right|^2 = \left( \operatorname{sinc} \frac{2u + u_M}{4} \right)^2 - \left( \operatorname{sinc} \frac{2u - u_M}{4} \right)^2, \quad (1)
\]

where \( \rho = \frac{z}{D} \) is the axial normalized coordinate of \( z \), and \( D/f \) is the relative aperture of the differential confocal objective.

The zero-crossing point of the differential confocal response curve \( I(u, u_M) \) corresponds to the focal point of the objective according to Eq. (1), and the linearity and sensitivity is the best near the zero-crossing point. The cat’s-eye and confocal positions can be precisely identified by the zero-crossing points \( O_A \) and \( O_B \) respectively. During data processing, noise filtering and curve fitting can be used to further improve the anti-interference capability of the cat’s eye and confocal positions, thereby achieving high-precision measurements of the radius of curvature.

The differential confocal technique is less susceptible to environmental fluctuations compared with FMI due to the focus identification by the differential confocal intensity curve. The common mode noise is suppressed by the use of two defocus intensity sensors with opposite offsets. The differential detection is beneficial to further improve the anti-interference capability of the measurement system.

3. Instrument Design and Description

A. Virtual Pinholes

According to the differential confocal principle shown in Fig. 1, the device under testing (DUT) axis needs to be adjusted to coincide with the axis of the measurement beam to ensure the light reflected from the test surface just passes through the detectors’ pinholes.

The adjustment bias of the DUT gives almost no effect on differential confocal detection in the cat’s-eye position, as shown in Fig. 2. The measuring beam returned by the measured surface still coincides with the center of the detector pinhole, with no significant deformation in the response curve, when the tile angle is less than 18° [10].

Precise adjustment of the DUT is required to ensure the sphere center \( O_s \) coincides with the axis of the measurement light beam near the confocal position. The axis misalignment of the adjustment...
causes the measurement beam deflection, resulting in the Airy disk of the measurement beam deviating from the center of the detectors’ pinholes (see Fig. 2) so the detectors have no intensity response signal. The deviation between the axis and the sphere center needs less than a few micrometers, due to only a few micrometers in the pinholes’ diameter.

The coarse aiming light path and the virtual pinhole are introduced into the light path for reducing the difficulty of adjustment (see Fig. 3). The view angle of the coarse aiming optical path is about ±3°, and the light spot can be searched in a wide field of view. The crosshair reticle is used to adjust the DUT in the rough alignment, with alignment accuracy in dozens of micrometers on the focal plane. Besides the coarse alignment, two CCD-based virtual pinholes (VPHs) replace the traditional physical pinholes and detectors for the light-spot detection. The virtual pinhole uses a microscope objective to magnify the Airy disk and image on the CCD. The measurement software tracks the Airy disk center in each image and calculates the intensity values of the spot center so as to eliminate the focusing error caused by misalignment of the DUT axis. As the VPH software can track the center of the light spot on the CCD automatically, the tracking range is about ±100 μm, with 6 mm CCD and 25× objective lens. Thus the difficulty of adjusting the measuring surface is significantly reduced.

B. Axial Offset

The axial offset of the pinhole affects the focusing sensitivity of the differential confocal system; when the normalized axial offset \( u_M = 5.21 \), the differential curve has the optimal slope and linearity at the zero-crossing point. According to Eq. (2), when \( u_M = 5.21 \), the axial offset \( M \) satisfies

\[
M = \frac{10.421}{\pi} \left( \frac{f}{D} \right)^2. \tag{3}
\]

Equation (3) shows that the optimal pinhole offset \( M \) is related to the diameter of the measurement beam. The diameter \( D \) of the measurement beam changes for test pieces with different radius and aperture, so the offset of the pinhole needs be adjusted accordingly.

Two translation stages with electronic control are set up in the light path, driving the microscope objective lens and CCDs moving along the optical axis so as to adjust the offset and ensure the largest slope of the differential confocal curve at the zero-crossing point.

It is difficult for the offsets of the VPHs to be just equal under the adjustment. Assume the offset are \( M + \delta \) and \(-M\) with the normalized values \( u_M + u_\delta \) and \( u_M \), and the bias between the zeros and the focus are \( \Delta z_A \) and \( \Delta z_B \) with the normalized values \( u_A \) and \( u_B \) (as shown in Fig. 4).

The differential confocal curve at \( O_A \) and \( O_B \) satisfies [9]

\[
\begin{align*}
I(u_A, u_M) &= \left[ \sin \frac{2u_A + u_M + u_\delta}{4} \right]^2 - \left[ \sin \frac{2u_A - u_M}{4} \right]^2 = 0 \\
I(u_B, u_M) &= \left[ \sin \frac{2u_B + u_M + u_\delta}{4} \right]^2 - \left[ \sin \frac{2u_B - u_M}{4} \right]^2 = 0.
\end{align*}
\]

(4)

The bias between the zero-crossing point and the focus at the cat’s-eye and confocal positions can be obtained by Eq. (4):

\[
u_A = u_B = -u_\delta/4. \tag{5}
\]

The biases caused by the offset of the detectors have the same value and direction after the light-path adjustment, so they can counteract each other. Therefore, the misadjustment of pinhole axial offset has no effect on the radius measurement result, and this feature greatly reduces the adjustment difficulty of the optical path.

C. Design of Instrumental Structures

Finally, the differential confocal radius measurement instrument is shown in Fig. 5. The main optical components of the instrument are integrated inside the shell of the differential confocal system, so stray light and environmental fluctuation of the light path is suppressed effectively; the objective lens uses the
standard interferometer transmission sphere with 0.100 mm diameter, which has little aberration and is interchangeable for measuring different radii of the DUT; the DUT is fixed to the five-dimensional adjustment stage on the air-bearing slider, and it moves along the optical axis with the slider and adjustment stage. A pentagonal prism is mounted at the back of the adjustment stage and works as a reflector of the DMI, indicating the position of the DUT.

The air-bearing slider is made of granite, with traveling range of 1 m and straightness of 0.5 μm, which can reduce the motion error and radius measurement error effectively [11–13]. The system also uses a coaxial design; the optical paths of the differential confocal system and the DMI have been set on the same line, which reduces Abbe error.

The main software controls the motor of the air-bearing slider, driving the DUT scanning around the cat's-eye and confocal positions after the measurement of ROC begins. At the same time, the software obtains the light intensity signal of the Airy disk center on the two CCDs by the image-processing algorithm and records the position data from the DMI. All the raw measurement data is sent to the data processing software module after the scan is finished and is processed with a noise filter and curve-fit algorithm to calculate the axial coordinate of the zero-crossing point, thereby achieving radius measurement.

The lower limit of the radius measurement range is equal to the length of the Air-bearing slider; the upper limit corresponds to a smaller value of the back vertex focal distance (BVD) of the objective and the length of the air-bearing slider. Therefore, the measuring range of the measurement system meets the criteria given in Table 1, when the standard spherical lens (ZYGO TS-6024) is used as the objective lens.

The f/10.7 spherical lens has the largest measurement range, but its focusing sensitivity is the worst due to the small relative aperture [9]. Therefore, a large-relative-aperture objective with appropriate measurement range should be selected to increase the focusing sensitivity so as to ensure the radius measurement accuracy.

4. Error Analyses

The main errors of the radius measurement are Abbe error, axis alignment error, focusing error, and distance measurement error [5,14]. The Abbe error is significantly inhibited by the coaxial design; only three main errors remain.

A. Axis Alignment Error

The measurement axis d of DMI, the motion axis m of the translation stage, and the axis t of the measured lens should coincide with each other. The deviation angle caused by the optical path misalignment introduces the cosine error and reduces the accuracy of the radius measurement. Assume the angle between axes t and m is β and the angle between axes m and d is γ, and the ROC measurement error satisfies

$$\sigma_{\text{axial}} = r(1 - \cos \beta \cdot \cos \gamma).$$  \hspace{1cm} (6)

The angle β is measured and compensated for by the VPH software automatically [9], and γ can be less than 0.5 mrad through careful adjustment [1,5,7,9];

<table>
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Fig. 4. Light path with different offsets of VPHs.

Fig. 5. Differential confocal radius measurement system.
then, the error introduced by axis misalignment should satisfy

\[ \sigma_{\text{axial}} = r(1 - \cos \gamma) \]
\[ = r(1 - \cos 0.0005) \approx r \times 0.12 \text{ ppm}. \quad (7) \]

B. Focusing Error

The zero-crossing point of the differential confocal curve has the largest slope when the normalized offset of pinhole \( u_M = 5.21 \), and the relation between the focusing error \( \sigma_z \) and the relative aperture \( D/f' \) satisfies [9]

\[ \sigma_z = \frac{1.18 \lambda}{\text{SNR} \cdot (D/f')^2}. \quad (8) \]

where \( \lambda \) is the laser wavelength and \( \text{SNR} \) is the signal-to-noise ratio of the differential confocal data. It can be seen from Eq. (8) that the focusing accuracy is improved as the relative aperture increases.

C. Distance Measurement Error

The distance measurement accuracy directly depends on the DMI, and a Renishaw XL-80 is chosen for measuring the moving distance of the DUT. The index variation of atmosphere is compensated by the environment monitor of the XL-80 in real time, and the distance measurement accuracy is up to 0.5 ppm after the temperature, pressure, and humidity are compensated. Hence, the distance measurement error satisfies

\[ \sigma_L = 0.5 \times r \text{ ppm}. \quad (9) \]

D. Synthetic Error

Considering the three main error sources of the measurement, the system’s measurement error \( \sigma_r \) is given by

\[ \sigma_r = \sqrt{\sigma_{\text{axial}}^2 + 2 \cdot \sigma_z^2 + \sigma_L^2}. \quad (10) \]

Assuming \( \lambda = 632.8 \) nm, the focal length of the objective \( f'_{\text{obj}} = 150 \) mm, the aperture \( D = 50 \) mm, the DUT radius \( r = -100 \) mm, and the signal-to-noise ratio of the differential confocal data \( \text{SNR} = 40:1 \); then the errors can be obtained by Eq. (6) through Eq. (9) as \( \sigma_{\text{axial}} \approx 0.012 \mu \text{m}, \quad \sigma_z \approx 0.17 \mu \text{m}, \quad \) and \( \sigma_L \approx 0.05 \mu \text{m}, \) respectively.

Hence, the radius measurement error of the instrument is

\[ \sigma_r \approx \sqrt{(0.012)^2 + 2 \times (0.17)^2 + (0.05)^2} \]
\[ \approx 0.24 \mu \text{m}. \quad (11) \]

The relative error satisfies

\[ \frac{\sigma_r}{r} = \frac{0.24}{100000} \approx 2 \text{ ppm}. \quad (12) \]

The theoretical analysis shows the ROC measurement error is up to 2 ppm, and taking into account the air fluctuation and the instrument vibration during the actual measurement, the relative measurement error of the radius result can be better than 5 ppm with careful environment control.

5. Experiments

A comparison measurement experiment was established to verify the accuracy and reproducibility of ROC measurement. As shown in Fig. 6, two spherical components were selected as DUTs. They were DUT1, an SiN₄ ball, and DUT2, a K9 test plate. The nominal ROC values were calibrated by the high-precision CMM UA3P (repeatability of 50 nm) as \( r_{\text{DUT1}} = 5.55730 \) mm and \( r_{\text{DUT2}} = -100.95651 \) mm, respectively.

The single measurement curve of DUT1 is shown in Fig. 7, where \( I(z) \) and \( I_B(z) \) are the normalized intensity response curves of the Airy disk center obtained by the two VPHs, and after differential subtraction there are the differential confocal signals \( I_A(z) \) and \( I_B(z) \). The coordinate values of the zero crossings are calculated by the software as \( z_A = 0.000774 \) mm and \( z_B = 5.557978 \) mm, and ROC \( r = z_A - z_B = 5.557204 \) mm.

The experimental curves \( I_A(z) \) and \( I_B(z) \) match theoretical curves well; this shows that air turbulence and environment vibration caused no significant effect on the differential confocal curve and the differential confocal radius measurement instrument has a good anti-interference capability.

An experiment was established to verify the repeatability of the system by repeated measurement of DUT1 for six times. The average of the repeatability experiment data of 5.5573858 mm, the standard deviation of 0.00006 mm (k = 1), and the relative standard deviation of 12 ppm are consistent with the UA3P measurement results (see Fig. 8).

Three repeated measurements of DUT2 were established to verify the system’s reproducibility with different users in different locations on different days. The first repeatability test was completed...
at Beijing Institute of Technology, and measurement repeatability was up to 4 ppm. The other two repeatability tests were finished at the National Institute of Metrology (NIM), China, after disassembly, transport, and reassembly of the equipment. The measurement repeatability decreased slightly, to 8 ppm and 5 ppm, respectively, but the measurement results were still consistent with UA3P. The experimental data are shown in Table 2 and Fig. 9.

The entire experiment was completed in a normal laboratory environment with room temperature at 20 °C. The system repeatability can be further improved by enhancing the environment stability through strict environmental control. At the same time, the offset between the measurement results and the nominal value can be reduced by compensating for the environmental parameters, misalignment, and motion errors to further improve the accuracy of the system [7,12,13].

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6. Conclusion

In summary, the differential radius measurement system identifies the cat’s-eye and confocal positions by the zero-crossing point of the differential confocal curve, and precisely obtains the distance between two positions through the interference length measuring technology, thereby achieving high-precision radius measurement. The experiments indicate that the system has high focusing sensitivity and is insensitive to environmental fluctuations, and its measuring accuracy is between 4 and 12 ppm, which provides a practical approach for high-precision radius measurement.

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