Computer-aided high-accuracy testing of reflective surface with reverse Hartmann test

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Abstract: The deflectometry provides a feasible way for surface testing with a high dynamic range, and the calibration is a key issue in the testing. A computer-aided testing method based on reverse Hartmann test, a fringe-illumination deflectometry, is proposed for high-accuracy testing of reflective surfaces. The virtual “null” testing of surface error is achieved based on ray tracing of the modeled test system. Due to the off-axis configuration in the test system, it places ultra-high requirement on the calibration of system geometry. The system modeling error can introduce significant residual systematic error in the testing results, especially in the cases of convex surface and small working distance. A calibration method based on the computer-aided reverse optimization with iterative ray tracing is proposed for the high-accuracy testing of reflective surface. Both the computer simulation and experiments have been carried out to demonstrate the feasibility of the proposed measurement method, and good measurement accuracy has been achieved. The proposed method can achieve the measurement accuracy comparable to the interferometric method, even with the large system geometry calibration error, providing a feasible way to address the uncertainty on the calibration of system geometry.

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References and links


1. Introduction

The development of optical design and fabrication has placed ultrahigh requirement on the precision of measurement tools. The interferometers, such as Fizeau interferometer, Twyman-Green interferometer and point-diffraction interferometer [1–5], have been widely applied as a powerful noncontact testing method. The accuracy of interferometric method can reach the order of nanometers and even subnanometers, however, its dynamic range is quite small [6]. Besides, the interferometric testing has high requirement on the design, fabrication and adjustment of optics in the system [7–9], which makes it costly and inflexible.

The deflectometry, a slope measurement method such as the Ronchi test and the Hartmann test [10], provides a feasible way for surface testing with high dynamic range. With the surface slope (derivative of surface sag), the surface under test can be reconstructed with spatial integration. It has been applied to measure the specular surfaces such as car body parts and progressive eyeglasses. A software configurable optical test system (SCOTS) [11–14], which is based on fringe reflection/deflectometry, was developed at the University of Arizona. It provides a contact-free, high dynamic range, full field metrology method with simple system setup and alignment. The SCOTS has been applied in the measurement of X-ray mirror, solar concentrators, and mirrors for astronomical telescopes at different stages of fabrication.

Due to the fact that the reconstruction of absolute surface shape in deflectometry is based on the integration of surface slope, the additive systematic error could introduce significant shape deviation [15]. The key issue in the absolute shape measurement with deflectometry is the calibration. The calibration determines the achievable accuracy of test system. Various approaches have been proposed to ensure the accurate surface measurement [6, 16–18]. In the SCOTS, a laser tracker is used to calibrate geometrical relation between the camera and the illumination screen [19], similar to the alignment process an interferometric testing for aspheric surfaces [20]. The measurement accuracy comparable to traditional interferometric methods has been reported. However, the calibration process is quite complicate and laborious. Typically the achievable measurement accuracy of the auxiliary calibration tool is in the order of microns, it can introduce significant residual systematic error in the off-axis configuration like SCOTS, especially in the cases such as convex surface testing and small working distance (that is the distance between test surface and test system). The small working distance would make the testing sensitive to the system geometry calibration error. The increase in the distance can reduce the impact of calibration error, however, it requires much larger illumination screen.
In this paper, a computer-aided fringe-illumination deflectometric method, which is based on the configuration of reverse Hartmann test system (RHTS) like SCOTS, is presented to achieve the high-accuracy testing of reflective surfaces, including the convex surface testing and small working distance. With the obtained slope data, the ray tracing of the modeled test system, which is based on the calibrated geometry of test system, is carried out to simulate the virtual “null” testing of the surface. In addition, the computer-aided reverse optimization of the system geometry with iterative ray tracing is used to further remove the system modeling error. The high-accuracy testing of the surface can be achieved even with the large system geometry calibration error. Section 2 presents the principle of the proposed method for reflective surface testing, including RHTS configuration and the basic theory of computer-aided geometry calibration. In Section 3 and 4, the results of computer simulation and laboratory experiments are given to demonstrate the feasibility of the proposed method, respectively. Some concluding remarks are drawn in Section 5.

2. Principle of computer-aided reverse Hartmann test

2.1 System layout

The proposed testing method is based on the configuration of SCOTS, which basically is a reverse Hartmann test, as is shown in Fig. 1. The flat display acts as the illumination screen, and a CCD camera with a finite size of aperture captures the image of the reflective surface under test. When a single pixel on the display is lit up, the image of test surface on the CCD will show a bright region corresponding to a certain part on the test surface. According to the law of reflection, the incident ray and the corresponding reflected ray is uniquely defined by the illumination screen pixel, the center of camera aperture and the reflection part on the test surface. Based on the triangulation, the local surface slopes ($w_x$ and $w_y$) of the test surface can be determined with the coordinates of these three points. The surface figure can be obtained from the integration of the slopes.

![Fig. 1. Schematic diagram of computer-aided reverse Hartmann test system. (a) System layout, (b) model for geometrical aberration analysis](image)

The one-to-one correspondence between the illumination screen pixel and the reflection region on test surface can be determined by the sinusoidal fringes illumination and phase shifting method. The surface error under test, that is the departure from its ideal shape, can be measured according to the virtual “null” testing based on ray tracing method. By ray tracing the test system with ideal test surface, in which the camera is modeled as an ideal point source and illumination screen as image plane, the ideal spot distribution ($x_{\text{model}}$ and $y_{\text{model}}$) corresponding to each individual ray defined by the sampling test surface can be obtained. In the experiment, the actual spot distribution ($x_{\text{actual}}$ and $y_{\text{actual}}$) can be measured by sinusoidal-fringe phase shifting method. The system wavefront aberrations can be estimated from the transverse ray aberrations, according to the transverse ray model [21]. The slopes ($w_x$ and $w_y$) can be obtained by dividing the spot coordinate differences ($\Delta x_{\text{spot}}$ and $\Delta y_{\text{spot}}$) with the distance $d_{m2s}$ between test surface and illumination screen. We have the slope differences ($\Delta w_x$, $\Delta w_y$) between the measured slope ($w_{x,\text{actual}}$ and $w_{y,\text{actual}}$) and the ideal slope ($w_{x,\text{model}}$ and $w_{y,\text{model}}$).
\[
\begin{align*}
\Delta w_x &= w_{x, \text{actual}} - w_{x, \text{model}} = \frac{\partial W(x, y)}{\partial x} = \frac{\Delta x_{\text{spot}}}{2d_{n2s}}, \\
\Delta w_y &= w_{y, \text{actual}} - w_{y, \text{model}} = \frac{\partial W(x, y)}{\partial y} = \frac{\Delta y_{\text{spot}}}{2d_{n2s}},
\end{align*}
\]

where \( W(x, y) \) is the wavefront aberration, \((x, y)\) are the exit pupil coordinate of the system; \( \Delta x_{\text{spot}} = x_{\text{actual}} - x_{\text{model}}, \Delta y_{\text{spot}} = y_{\text{actual}} - y_{\text{model}} \). With the surface integration, the test surface error can be calculated from the slope differences \( (\Delta w_x, \Delta w_y) \).

### 2.2 Computer-aided calibration of system geometry

#### 2.2.1 Geometrical aberrations in reverse Hartmann test

According to Fig. 1, the RHTS is an off-axis system setup, where both the illumination screen and camera are displaced laterally from the optical axis of the surface under test. The system geometry, including the lateral and longitudinal displacement of camera and illumination screen, tilt of illumination screen and test surface, could introduce significant systematic error. Taking the lateral displacement of the camera as an example, it would result in the off-axis aberrations including astigmatism and coma. In the case where the camera and illumination screen placed at near-paraxial conjugate position of test surface, as is shown in Fig. 1(b), we have the Seidel coefficients \( W_{222} \) and \( W_{131} \) \[14\],

\[
\begin{align*}
W_{222} &= \frac{h^2r^2}{Rd^2}, \\
W_{131} &= \frac{hr^3(d - R)}{R^2d^2},
\end{align*}
\]

where \( r \) and \( R \) are the semi-diameter and curvature radius of the test surface, respectively, \( h \) and \( d \) are the lateral displacement of camera and the object distance.

According to Eq. (2), the residual astigmatism and coma introduced by the calibration errors of the camera lateral displacement are shown in Fig. 2. Figure 2(a) shows the astigmatism and coma for the concave spherical surface, and Fig. 2(b) is those for the convex spherical surface. The semi-diameter and absolute curvature radius of both the test surfaces are 50 mm and 250 mm, respectively. It can be seen from Fig. 2 that the residual \( W_{131} \) is independent of the lateral displacement and grows linearly with the calibration error of the lateral displacement, the residual \( W_{222} \) grows linearly both with lateral displacement and the...
corresponding calibration error. The calibration error of the lateral displacement would introduce significant residual off-axis aberrations. The residual $W_{22}$ and $W_{13}$, reach about 0.6 μm and 0.3 μm for 20 μm calibration error at 100 mm lateral displacement. Besides, the residual $W_{13}$ error for the convex surface is much larger than that of the concave surface, because of the divergence of rays from the convex surface. For the small working distance, the obvious systematic error due to system geometry calibration error would be expected according to Eq. (2). Thus, further reducing geometry calibration error is needed to achieve the measurement accuracy better than the order of sub-waves.

2.2.2 Computer-aided system geometry calibration

The virtual “null” testing of the surface error, which is based on the ray tracing of the test system, enables the calibration of the system geometrical error. However, the error in modeling test system is not negligible in the high-accuracy testing, especially in the cases of convex surface testing and small working distance. To achieve the accurate calibration of the system geometry measurement error (that is the system modeling error), the computer-aided reverse optimization method can be applied to further remove the residual aberrations. With geometrical aberrations corresponding to the geometrical parameter $GP$ of test system, the measured wavefront aberration $W_{\text{meas}}$ can be expressed by an implicit function $F$ as

$$ W_{\text{meas}} \equiv F \left( W_{\text{surf}} + W_{\text{syst}}(GP) \right), \quad (3) $$

where $W_{\text{surf}}$ and $W_{\text{syst}}$ are the surface error under test and the systematic error introduced by the system geometry, respectively; $GP = \{T_{i,j}; D_{i,j}\}_{i=1,2; j=x,y,z}$ indicates the geometrical parameters including tilt ($T_{i,j}$) and decenter $D_{i,j}$ of the $i_{th}$ component in $j_{th}$ direction. The geometrical parameters include tilts in $x$, $y$ and $z$ directions, decenter in $x$ and $y$ directions, axial displacement of test surface relative to the camera aperture, and the same errors of illumination screen relative to test surface. We have the test surface error $W_{\text{surf}}$,

$$ W_{\text{surf}} \equiv F^{-1}(W_{\text{meas}}) - W_{\text{syst}}, \quad (4) $$

In the test system model built in ray tracing program according to the pre-calibrated system geometrical parameters, we obtain

$$ \hat{W}_{\text{syst}} \equiv F^{-1}(\hat{W}_{\text{meas}}), \quad (5) $$

where the test surface is set as an ideal one, $\hat{W}_{\text{syst}}$ and $\hat{W}_{\text{meas}}$ are the simulated systematic error and wavefront aberration in the model corresponding to Eq. (4), respectively. Due to the fact that the surface error can be taken as the global minimum of the departure from its ideal shape, it can be obtained with the reverse optimization method. In the optimization procedure, the geometrical parameter $GP$ of test system is set as a variable, and optimized according to the objective function,

$$ O(GP) = \min \left\{ \left( W_{\text{surf}} \right)^2 + c \right\} = \min \left\{ \left[ F^{-1}(W_{\text{meas}}) - F^{-1}(\hat{W}_{\text{meas}}) \right]^2 + c \right\}, \quad (6) $$

where $c$ is an additional constraint to restrict the solution space.

The objective function in Eq. (6) can be further modified according to the various aberration weights, we have

$$ O(GP) = \min \left\{ \sum_{j=1}^{N} \alpha_j \left( C_j - \hat{C}_j \right)^2 + c \right\}. \quad (7) $$
where $C_j$ and $\tilde{C}_j$ are the coefficients for the orthogonal polynomials fitting (with $N$ terms) of the measured wavefront $W_{\text{meas}}$ and modeled wavefront $\tilde{W}_{\text{meas}}$, respectively, and $\alpha_j$ is the corresponding optimization weight. The dominant aberrations corresponding to the system geometry are astigmatism and coma. With optimal solution $\mathbf{GP}^*$ after optimization, the test surface error can be estimated as

$$W_{\text{surf}} = F^{-1}(W_{\text{meas}}) - W_{\text{sys}}(\mathbf{GP}^*).$$

(8)

Figure 3 shows the procedure for the proposed computer-aided system geometry calibration. The experimental system is set up and its geometrical parameters are pre-calibrated with three-dimensional positioning equipment like CMM and laser tracker, etc. The test system model is built in the ray-tracing software according to the pre-calibrated geometrical parameters. The wavefront aberration $W_{\text{meas}}$, including the test surface error $W_{\text{surf}}$ and systematic error $W_{\text{sys}}$, is measured in the RHTS, in which the virtual “null” test and surface integration are performed. Subsequently, the reverse optimization in the system model is carried out, in which the geometrical parameter $\mathbf{GP}$ is set as variable and the pre-calibrated value as initial value. In the meantime, the iterative ray tracing is performed once after each round of geometrical parameter optimization to update the wavefront data $\tilde{W}_{\text{meas}}$ in the model. In the optimization process, the $N$-term orthogonal polynomials are employed to fit the measured wavefront $W_{\text{meas}}$ and modeled wavefront $\tilde{W}_{\text{meas}}$, respectively, with the corresponding coefficients $C_j$ and $\tilde{C}_j$ ($j = 1, 2, \ldots, N$). Then the coefficients $C_j$ and $\tilde{C}_j$ are taken into the objective function $O(\mathbf{GP})$, and the optimization repeats until the objective function reaches a threshold $\varepsilon$, the optimal geometrical parameter $\mathbf{GP}^*$ and the corresponding test surface error $W_{\text{surf}}$ can be obtained.

3. Numerical simulation results

According to the ray tracing method, the proposed computer-aided test was simulated for a simulated convex spherical surface with an aperture diameter of 100 mm and curvature radius of 250 mm. A Hartmann test system with the same configuration shown in Fig. 1(b) was modeled in the ray-tracing software (Zemax), in which the camera aperture was set as an ideal point source and illumination screen as the image plane. The distance $d_{\text{m2s}}$ between the test surface and the image plane was 250 mm, and the lateral displacement in $x$ direction ($D_x$) and tilt about $y$ axis ($T_y$) of test surface were set to 20 mm and 5 degrees, respectively. The actual surface error of the test spherical surface is shown in Fig. 4(a), whose peak-to-valley (PV) value is set to 14.3523 $\mu$m and root-mean-square (RMS) value 3.1063 $\mu$m.

In the simulation, the spot diagram on the image plane was obtained with the Zemax software by ray tracing the test system with the actual surface error, but without system geometry error. To analyze the effect of system geometry calibration error, an additional deviation of the lateral displacement $D_x$ and tilt $T_y$ from its original value, 0.03 mm and 0.05
degree, respectively, were added to the test surface. Then the virtual “null” testing of spherical surface was carried out according to the testing method introduced in Section 2.1, where the test surface in the system model is set to an ideal one. Figure 4(b) shows the testing surface error with the system geometry calibration error, and Fig. 4(c) is the corresponding residual error. From Fig. 4(c), a significant residual error with the PV value 2.9495 μm and RMS 0.5119 μm, can be seen in the testing surface.

Figure 5 shows the testing surface error corresponding to various calibration errors of the lateral displacement $D_x$ and tilt $T_y$ for the test surface, in which the surface testing errors were measured with the surfaces (concave and convex surfaces, respectively) located at different positions. According to Fig. 5, the surface testing error grows linearly with the lateral displacement error and tilt error. In the testing of concave surface, the effect of system geometry error can be well controlled by placing the image plane (and point source) at the curvature center plane of test surface. However, the significant surface testing error can be seen in the testing of convex surface with system geometry error, and the testing error grows with the decrease of working distance. Thus, further calibration is required to minimize the residual systematic error.

![Surface testing error in the simulation. (a) Actual surface error of test spherical surface, (b) testing surface error and (c) residual error with existence of system geometry measurement error, (d) testing surface error and (e) residual error after system geometry calibration.](image)

![Surface testing error introduced by system geometry calibration error in the simulation. Surface testing errors corresponding to (a) lateral displacement error and (b) tilt error.](image)
The reverse optimization of the system geometry according to the procedure shown in Fig. 3 was performed to remove the system geometry calibration error in Fig. 4(b). The first 37 orthogonal Zernike standard polynomials were employed to fit the surface errors and the downhill simplex method [22, 23] was applied to optimize the geometrical parameter $GP$. Figure 6 shows the change of the testing result on the surface error in the reverse optimization process, the testing result converged after three optimization cycles. The increase in the pre-calibration accuracy for the test system geometry can further improve the efficiency of optimization convergence. Figure 4(d) shows the surface error after twenty optimization cycles, and Fig. 4(e) is the corresponding residual error with respect to the actual surface error in Fig. 4(a). The simulation results on the computer-aid system geometry calibration are summarized in Table 1.

According to Fig. 4 and Table 1, the accurate calibration of system geometry is realized with the proposed computer-aided reverse optimization method, with the PV and RMS values of residual error being 0.0372 μm and 0.0053 μm, respectively. The deviation of distance $d_{m2s}$, lateral displacement $D_{x}$, and tilt $T_{y}$ after optimization from their original true value are 0.32 μm, 1.57 μm and 0.001 degree, respectively. Thus, the proposed testing method is validated to be effective, even in the cases of convex surface testing and small working distance. It enables the high-precision testing of reflective surfaces with the accuracy better than the order of nanometers. Moreover, this method is not limited to only spherical surfaces, it is applicable for the more complicate surfaces such as aspheric and freeform, as long as the surface departure is within the high dynamic range of deflectometry. Besides, the proposed method is applicable even with the large system geometry pre-calibration error, providing a feasible way to loosen the requirement on the calibration of system geometry.

<table>
<thead>
<tr>
<th>Table 1. PV and RMS Values of Surface Testing Error in the Simulation</th>
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<tr>
<td>PV (μm)</td>
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<tr>
<td>Actual surface error</td>
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<tr>
<td>With system geometry measurement error</td>
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<tr>
<td>Testing surface error</td>
</tr>
<tr>
<td>Residual error</td>
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<tr>
<td>After system geometry calibration</td>
</tr>
<tr>
<td>Testing surface error</td>
</tr>
<tr>
<td>Residual error</td>
</tr>
</tbody>
</table>

4. Experimental results

A RHTS as Fig. 1 has been set up to demonstrate the feasibility of the proposed computer-aided high-accuracy method for the reflective surface testing. The pixel number of imaging sensor is 1328 (H) × 1048 (V), the focal length of imaging lens on camera is 12 mm, and the size of illumination screen is 410.4 mm (H) × 256.5 mm (V). The reflective surface to be
tested is a diamond-turning convex spherical surface with 250 mm in radius and 50.8 mm in diameter. The distance $d_{m2s}$ between the test surface and the illumination screen is about 250 mm. Thus, the slope dynamic range is $\Delta S = P/2d_{m2s} = 513$ mrad, where $P$ is the diameter of the illumination screen. The test surface tilt was adjusted slightly so that the beams from the illumination screen could be reflected back to the camera. The system geometry, including the positions of camera aperture, test surface and illumination screen, was pre-calibrated with a three-dimensional coordinate measuring machine (CMM) (TESA micro-hite 3D, accuracy 7.0 μm). The actual three-dimensional positions of camera aperture center, illumination screen, and test surface are recorded with CMM, and then the corresponding tilt and displacements can be determined. The system was modeled in the ray-tracing software Zemax according to the pre-calibrated system parameters. Figures 7(a) and 7(c) show the acquired illumination sinusoidal fringes in $x$ and $y$ directions after reflection at test surface, and Figs. 7(b) and 7(d) are the corresponding measured $x$-slope data and $y$-slope data, respectively. The four-step phase shifting algorithm was applied to obtain the slope data and the Southwell integration algorithm to reconstruct the surface figure.

Figure 7. Acquired sinusoidal fringes and measured slope data in the experiment. Acquired fringes in (a) $x$ direction and (c) $y$ direction after reflection at test surface; (c) measured $x$-slope data and (d) measured $y$-slope data.

Figure 8(a) shows the surface error obtained with a ZYGO GPI interferometer, in which the PV value is 0.1668 μm and RMS 0.0213 μm. For comparison, the measurements of the test surface were carried out in the RHTS with only CMM pre-calibrated system geometry and computer-aided calibrated system geometry, respectively, and the corresponding measured results are shown in Figs. 8(b) and 8(c). Compared with the ZYGO interferometer testing result in Fig. 8(a), the absolute PV and RMS differences in Fig. 8(b) are 0.0215 μm and 0.0022 μm, and those in Fig. 8(c) are 0.0131 μm and 0.0012 μm after 75 optimization iterations, respectively. To demonstrate the robustness of the proposed method, additional system geometry error is added to the test surface in pre-calibrated system geometry for the ray-tracing model, which is 0.01 mm and 0.10 mm for the longitudinal and lateral displacement, respectively, 0.05 degree for the tilt. Figure 8(d) shows the measured result with additional geometry error. Table 2 is a summary of the convex spherical surface testing results.

According to Fig. 8 and Table 2, the deviation is obvious in the measured surface error for the case with only CMM pre-calibrated RHTS. In contrast, a good agreement can be seen between ZYGO interferometer testing result and that from the proposed computer-aided testing method, both in the surface shape and error magnitude. Besides, good repeatability is achieved with the proposed method. Thus, the proposed computer-aided testing method provides a feasible way to realize the accurate calibration of the systematic error introduced by system geometry calibration error, and high-accuracy surface testing comparable to the interferometer is achieved.
Fig. 8. Surface error measured in the experiment. Surface errors measured with (a) ZYGO interferometer, (b) pre-calibrated reverse Hartmann test system, computer-aided calibrated reverse Hartmann test system (c) based on pre-calibrated parameter and (d) with additional geometry error.

Several factors can also result in the measurement error in the control experiment with the ZYGO interferometer, and they can be divided into two groups: systematic errors and random errors. Both the imperfection of system components and deficiency of measurement principle based on RHTS can introduce the systematic errors. The detailed analysis of the test uncertainty with reverse Hartmann test and the corresponding calibration method, including the camera mapping distortion, lens pupil aberration, and screen substrate shape errors, etc. have been discussed in detail in [12]. The errors due to the performance of system components can be negligible if they are well calibrated (for example, with a flat mirror). The simulation result in Section 3 shows the achievable measurement accuracy in the order of nanometers with the proposed method, addressing the deficiency of measurement principle. With the large working distance and improvement in surface reconstruction algorithm from slope data, reverse optimization algorithm and surface error fitting accuracy, the measurement accuracy is expected to be higher. To minimize the effect of random errors, the testing results are averaged from multiple measurements, in which the fringe patterns are acquired for several times.

Table 2. Comparison of Convex Surface Testing Results in the Experiment

<table>
<thead>
<tr>
<th>Surface error PV (μm)</th>
<th>Testing error PV (μm)</th>
<th>Surface error RMS (μm)</th>
<th>Testing error RMS (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZYGO interferometer</td>
<td>0.1668 0.0213</td>
<td>0.0215 0.0022</td>
<td></td>
</tr>
<tr>
<td>Pre-calibrated RHTS</td>
<td>0.1883 0.0235</td>
<td>0.0215 0.0022</td>
<td></td>
</tr>
<tr>
<td>Computer-aided calibrated RHTS</td>
<td>0.1537 0.0201</td>
<td>−0.0131 −0.0012</td>
<td></td>
</tr>
<tr>
<td>Computer-aided calibrated RHTS with additional geometry error</td>
<td>0.1701 0.0227</td>
<td>0.0033 0.0014</td>
<td></td>
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</table>

5. Conclusion

A computer-aided fringe-illumination deflectometric method, which is based on the reverse Hartmann test, is present for high-accuracy testing of reflective surfaces. Based on the acquired slope data, the virtual “null” test is realized with the ray tracing method in the modeled test system. Due to the off-axis configuration of test system, the system modeling error can introduce significant residual error in the testing result, especially in the cases of convex surface testing and small working distance. To realize accurate calibration of the system geometry measurement error, the computer-aided reverse optimization with iterative ray tracing is used to further improve the measurement accuracy. Both the numerical simulation and experiments have been carried out to demonstrate the feasibility of the proposed measurement method, and a good measurement accuracy has been achieved. The proposed method can obtain the high-accuracy measurement of reflective surfaces, and also provides a feasible way to loose the requirement on the calibration of system geometry.
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