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基于重力补偿的立式三平板绝对检测

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摘 要:为了实现高精度平面面形绝对检测,对传统的立式三平板绝对检测方法进行了重力变形补偿.通过有限元软件仿真了平板在水平放置于工装上的重力变形,并将其加入到平面绝对标定的计算中.把平面标定分成旋转对称项和旋转非对称项分别标定后进行综合,并与旋转平移绝对检测方法的测量结果进行了对比,去除离焦项对比结果均方根小于 1nm.为了进一步验证离焦项的标定,对一平板在不同口径环形支撑下的形变量进行了检测和仿真,对比结果的峰谷值小于 9nm,达到较高的离焦项测量精度.实验结果验证了基于重力变形补偿的立式三平板绝对检测方法能够实现立式下平面的高精度绝对检测.

关键词:光学检测;绝对检测;干涉术;重力变形;有限元方法;计算仿真

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Absolute Three-flat Test in Vertical Direction with Gravity Deformation Compensation

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Abstract: In order to get lower uncertainty, a method was proposed to compensate the gravity deformation caused by flipping in vertical absolute three-flat test. The gravity deformation of the flat surface was simulated by finite-element software and added to the three-flat test calculation. The calibrated results were compared with shift-rotation absolute testing method, and the root mean square of the surface map difference was less than 1nm without power term. For power term verification, a flat supported on different rings was tested and subtracted. For power term verification, a flat supported on different rings is tested and the difference between the tests and the simulation was less than 9 nm peak to vally, which was usually sufficient for flat power term testing. This experiment also proves the accuracy of the power simulation indirectly, the improved three-flat test can be applied in high precise flat absolute calibration including the power term in vertical direction.

Key words: Optical testing; Absolute test; Interferoetry; Gravity deformation; Finite element method; Computer simulation

OCIS Codes: 120.6650, 120.3180, 120.4800

0 Introduction

Absolute calibration of the reference surface is a key procedure to achieve high precise results using Fizeau interferometer. Absolute three-flat test is the primary method to calibrate the transmission flat and has been widely studied[1-6]. The basic three-flat test calibrates only the profile of several distinct lines, and the expansion of it gets the entire surface map with the additional rotation or translation test[7-13]. It is

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relatively easy to calibrate the Rotationally Varying (RV) part of a surface by rotation method and the difficulty is to calibrate the Rotationally Invariant (RI) part of the reference flat. The translation method can be used to calibrate the RI term except the power term[14-17]. Power term is really difficult to calibrate using the translation method because of the introduced tilt during the translation, which is derivative of the power term. In addition, the normal three-flat test is also hard to get high accuracy result in the vertical direction due to the gravity deformation change caused by flipping which is a necessary procedure.

To get correct RI term of reference surface, especially the power term in vertical interferometer, we improved the three-flat test by adding the gravity deformation compensation, which is essential to get high accuracy in vertical three-flat test, and made verification. L. A. Selke did a theoretical analysis of the deformation of a flat on a ring support[18]. The finite-element method is used widely to get the deformation of optical surface[19-22]. Burke J and Maurizio Vannoni also did a flat calibration in vertical direction, but no verification of the analysis[11, 13]. In this paper, the surface shape change caused by gravity is simulated by finite-element software and added to the three-flat calculation. The error of the finite-element simulation is calibrated and verified. The Root Mean Square (RMS) of the difference map between this method and shift-rotation absolute testing method without Power term is less than 1 nm.

1 Three-flat test with gravity deformation compensation

Three-flat absolute test method with gravity compensation is an improving of the ordinary three-flat test in the vertical direction. Here the three-flat method based on Evans' N position rotation method is firstly simply described[6]. Through the rotation of a piece of flat at N angles the RV part and the RI part of a surface are separated, except the kN theta item, where k is a positive integer. As a normal three-flat test procedure, the three flat surfaces A, B and C are measured with each other, and C is the surface to be rotated and flipped. To describe the calculation, we use A, B and C as the surface map deviation and the combination of them as the summation, which means to test with each other. So the surface figure of the three flat can be calculated by Eqs. (1)~(3)

$$\begin{cases} B=\dfrac{BC+BA-CA}{2}-\dfrac{C_{\mathrm{RV}}-C_{\mathrm{RV}}^{\mathrm{flip}}}{2} \\ A=BA-B \\ C=CA-A \end{cases} \tag{1}$$

$$C_{\mathrm{RV}} \approx BC-BC_{\mathrm{ave}}^{\mathrm{R}}=C_{\mathrm{RV}}-C_{kN\theta} \tag{2}$$

$$C_{\mathrm{RV}}^{\mathrm{flip}}=[C_{\mathrm{RV}}]^{\mathrm{flip}} \tag{3}$$

where C_{RV} is the asymmetric part of C surface, $C_{\mathrm{RV}}^{\mathrm{flip}}$ is the asymmetric part of the C surface flipped physically, and $[C_{\mathrm{RV}}]^{\mathrm{flip}}$ expressed the flipped data of C_{RV} data. That means C_{RV} and $C_{\mathrm{RV}}^{\mathrm{flip}}$ can be converted to each other in ordinary condition as Eq. (3). But gravity deformation will introduce to the surface when it is flipped in the vertical direction. Then the first line of Eq. (1) will become to Eq. (4) with simple tansform, where $C_{\mathrm{RI(down\text{-}up)}}$ is the RI term change when flipped upside down. And the C_{RV} and $C_{\mathrm{RV}}^{\mathrm{flip}}$ cannot be transformed to each other simply, because the deformation is not the same in different orientation. So the C_{RV} and $C_{\mathrm{RV}}^{\mathrm{flip}}$ should be both calibrated by

$$\frac{BC+BA-CA}{2}=B+\frac{C_{\mathrm{RV}}-C_{\mathrm{RV}}^{\mathrm{flip}}}{2}+\frac{C_{\mathrm{RI(down-up)}}}{2} \tag{4}$$

We proposed a three-flat testing procedure in vertical direction with deformation compensation. The three-flat test procedure with deformation compensation is shown in Fig. 1. The procedure is the same with normal three-flat test except the calculation, and it is in vertical direction. The surface C is on the upper side in step one, and lower side in step two and three, the surface B stands for the reference surface of the transmission flat of the vertical interferometer, which result is the our goal.

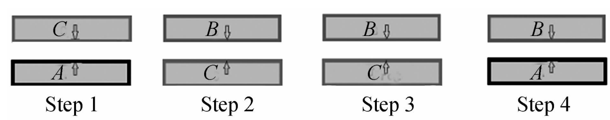

Fig. 1 The three-flat testing procedure

Because the surface C is supposed to be flipped upside down, the deformation will be different in both RV and RI term. And we just focus on the RI term simulation here, because the RV term can be calibrated precisely by rotation method in step 3. So in this three-flat testing procedure, the RI term of support deformation of surface C and the surface figure of it in weightless condition is considered separately. The results of testing procedure shown in Fig. 1 are expressed in Eqs. (5)~(8)

$$C'A=C^{\mathrm{p}}+A+S_{\mathrm{u}} \tag{5}$$

$$BC=B+C+S_{\mathrm{d}} \tag{6}$$

$$BC_{\mathrm{sc\_ave}}=B+C_{\mathrm{RI}}+S_{\mathrm{dRI}} \tag{7}$$

$$BA=B+A \tag{8}$$

where C^{p} means the flip of C that stands for the surface figure in weightless condition. S_{u} is the support deformation of surface C relative to weightless condition when it is testing on upper side as in step 1; S_{d} is the support deformation of surface C when it is testing on lower side as in step 2 to 3; the subscript 'sc_ave' means the average of several BC results, which are obtained by rotating surface C and the support structure together relative to surface B at equal space rotation angles in a circle; and the subscript RI represents the RI term.

It can be seen from the procedure that the RV component is easy to obtain by the rotation method. And the result is shown in Eqs. (9) to (11)

$$SCd_{\mathrm{RV}}=BC-BC_{\mathrm{sc\_ave}} \tag{9}$$

$$B_{\mathrm{RV}}=(BC)_{\mathrm{RV}}-\mathrm{SCd}_{\mathrm{RV}} \tag{10}$$

$$A_{\mathrm{RV}}=(BA)_{\mathrm{RV}}-B_{\mathrm{RV}} \tag{11}$$

where the parenthesis and the subscript RV mean getting the RV term of the data by rotating the data itself. $\mathrm{SCd}_{\mathrm{RV}}$ means the RV term of the sum of surface C and support deformation when it is tested on the lower side as in step 2～3.

Actually, the surface shape of the Transmission Flat (TF) surface B which is installed on the interferometer is the result we want to get. So the problem is how to get the RI term of surface B. The Eq. (4) is used and transformed to Eq. (12)

$$B=\frac{BC+BA-CA}{2}-\frac{C_{\mathrm{RV}}-C_{\mathrm{RV}}^{\mathrm{flip}}}{2}-\frac{S_{\mathrm{d}}-S_{\mathrm{u}}}{2} \tag{12}$$

The RI term is only to be cared about here. So

$$B_{\mathrm{RI}}=\left(\frac{BC+BA-CA}{2}\right)_{\mathrm{RI}}-\frac{S_{\mathrm{dRI}}-S_{\mathrm{uRI}}}{2} \tag{13}$$

the last term in Eq. (13) is simulated by finite-element software to get the RI term of surface B. Finally the surface of transmission flat B is got by adding RV term and RI term of it obtained by Eqs. (10) and (13).

$$B=B_{\mathrm{RV}}+B_{\mathrm{RI}} \tag{14}$$

Finite-element simulation should be implemented in two situations. One is that the part is supported in orientation of used surface up, and another is that the part is supported upside down with the same structure. An ideal ring is used as the model of the lens mounting. The model is symmetrical and relatively easy to analyze. Hexahedral finite-element mesh is used for the main body simulation with fix constraint boundary conditions on the ring, and contact is applied between the ring and the lens. The model is illustrated in Fig. 2.

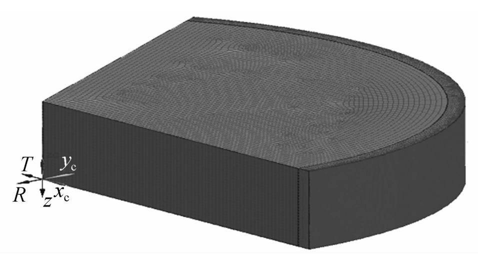

Fig. 2 The part of finite-element model for simulation

2 Experiment

An experiment is performed using 300 mm vertical wavelength shifting interferometer and 300 mm flats. In this experiment, flat B is a TF which is installed on the vertical interferometer and it is the surface to calibrate. Flat A is a Return Flat (RF) which has its individual stable support structure. Flat C is also used as a TF. The vertical wavelength shifting Fizeau interferometer is used for this experiment, so flat C needn't to be installed to the vertical interferometer as the normal TF flat B. Flat C is put on a ring structure, which is going to be simulated in finite-element software to get the deformation, mainly the RI term. And in step 1, the structure for supporting C is put on several poles which are mounted on the platform of the vertical interferometer, so that the lower surface A is not influenced by the structure. The same structure can be used in step 2 to 3 by flipping the surface C and simply covering the RF surface A.

The RI term of the surface deformation simulated by finite-element software when it is on the lower side as in step 2 is shown in Fig. 3.

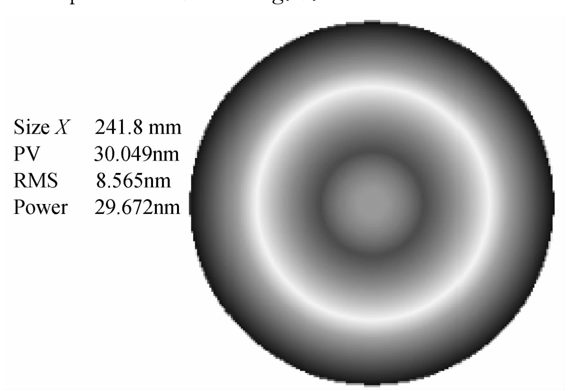

Fig. 3 The RI term of the surface deformation simulated by finite-element software when it is in lower side as in step 2

The simulated RI term of the surface deformation when it is on the upper side as in step 1 is shown in Fig. 4.

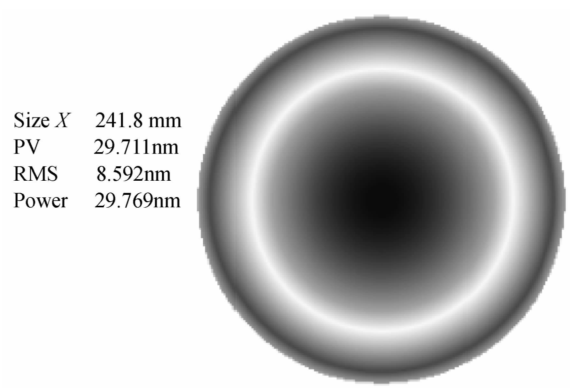

Fig. 4 The RI term of the surface deformation simulated by finite-element software when it is in upper side as in step 1

The RV term of reference surface B is obtained by the rotation method according to Eq. (10); the RI term is get using Eq. (13) based on the three-flat test with simulated RI deformation change. The S_{dRI} is

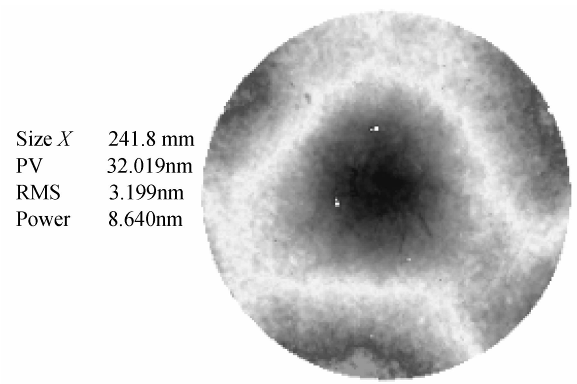

Fig. 5 The surface map of B got by the improved three-flat test with Power term

shown in Fig. 3 and S_{uRI} is shown in Fig. 4. The RI term form normal three-flat test is calculated by mathematical method, which involves rotating the data mathematically to find the RI term of one data. Finally the whole surface map of surface B is get and shown in Fig. 5 by adding RV and RI term.

To verify the result further, the shift-rotation method is utilized to calibrate the reference surface of the transmission flat, which can reach a high accuracy with a short cavity and can be used as a reference. But the power term of the flat cannot be calibrate by shift-rotation method because of the tilt when shifting. The calibration result of the same transmission flat is shown in Fig. 6, and also the pixel by pixel difference with the three-flat method without power term. The RMS of the difference map is 0.7 nm, which verifies partially the accuracy of the three-flat calibration based on gravity deformation compensation less than 1nm. And if Zernike 36 terms are fitted to the difference map, 0.4 nm can be reached shown in Fig. 7.

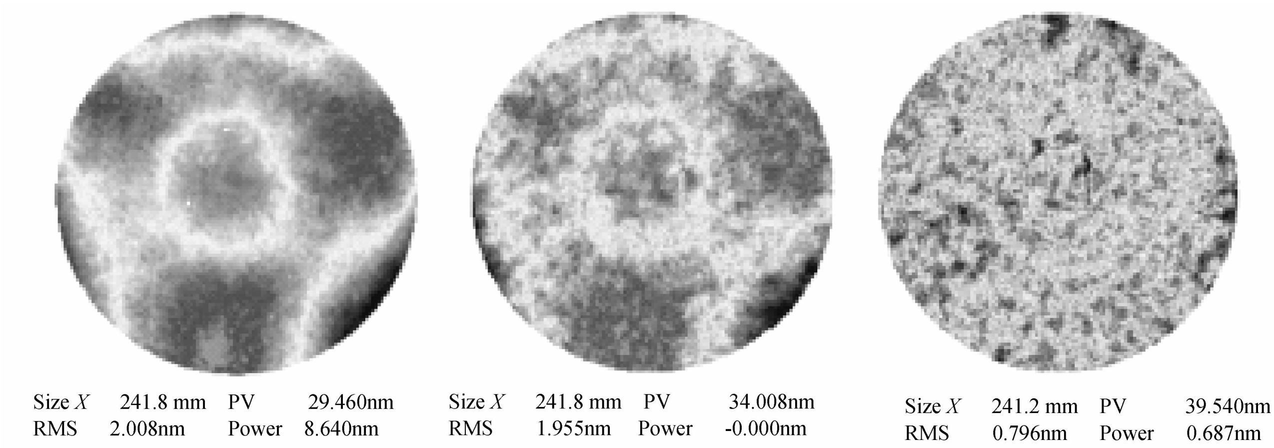

Fig. 6 Comparisons of three-flat and shift-rotation (removing the power term)

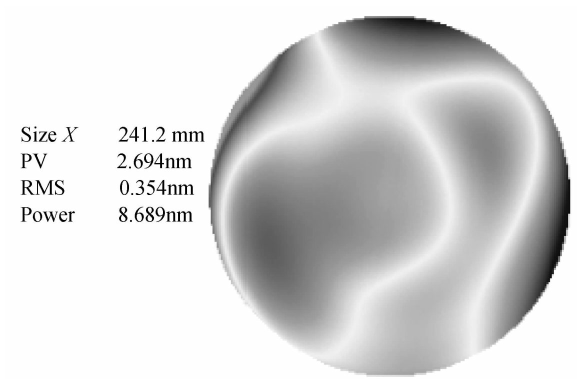

Fig. 7 The 36 Zernike term fit result of the difference of three-flat and shift-rotation

3 Power confirmation

An important application of this improved three-flat test is calibrating the power term of transmission flat, which is difficult by other method. As we can see, the key problem of the method is the accuracy of simulation. And we verified the result by the difference of the improved three-flat test and shift rotation test except power term. It proved the accuracy of simulation to a certain extent, but it is still not very convincing because of the power term. In order to confirm the result of power, we did another experiment to verify the simulation. This experiment compares the test result of power term of a flat surface in the two situations. One is the case that the 285 mm aperture flat is measured supporting by a bigger ring of 270 mm diameter at the edge bottom, another is by a smaller ring of 170 mm diameter. The difference of measurement result is showed in Fig. 8, where the power value is 42 nm. The two situations are also simulated by finite-element software and the RI difference is illustrated in Fig. 9, where the power term is 51 nm. So the simulation error of power is about 9 nm, which is generally sufficient for the power tolerance. This confirmation experiment shows to some extent the accuracy of the power calibration.

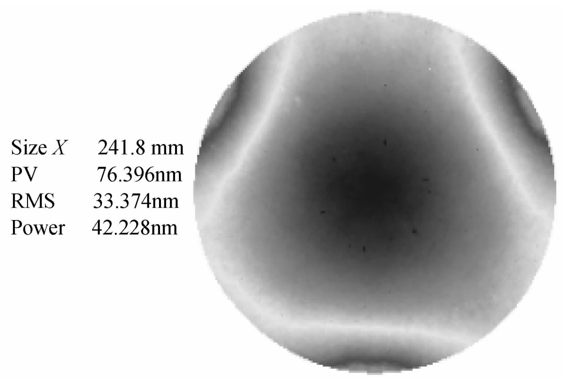

Fig. 8 The difference of test results of one flat supported by two different size of ring, one big and one small

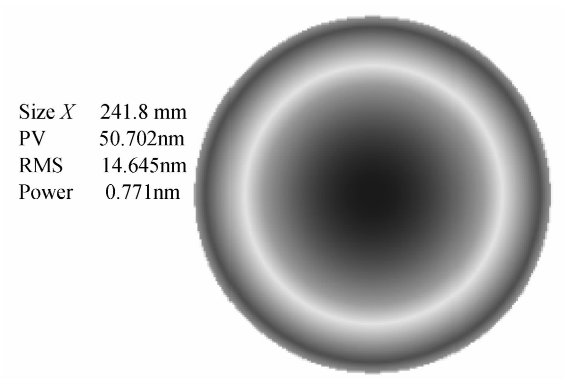

Fig. 9 The difference of simulation results of one flat supported by two different size of ring, one big and one small

4 Conclusion

The method of three-flat testing with gravity compensation solved the problem of flat calibration in vertical direction. The deformation caused by gravity is simulated by finite-element analysis and added to the calculation. The result is verified by comparison with shift-rotation calibration method without power term and another experiment for the power term verification. So it is believable that the method of three-flat test with gravity compensation achieves high precision and is useful to calibrate the power term of a vertical TF which is difficult to calibrate by other method.

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