Testing of aspheric mirror by non-null compensation method

Wang Xiaokun

(Key Laboratory of Optical System Advanced Manufacturing Technology, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China)

Abstract: For the purpose to overcome the difficulty of testing aspheric surfaces by null lens or CGH (Computer-Generated Hologram), the non-null testing was proposed. The basic principle and theory of testing asphere by digital plane, partial compensation and subaperture stitching interferometry (SSI) were analysed and researched, and each testing model and flow chart were established. Combining examples, an asphere of little departure with the aperture of 350 mm was tested by the digital plane and SSI, respectively. As results, the difference of PV and RMS error between SSI and partial compensation is 0.015λ and 0.002λ (λ is 632.8 nm), respectively. The prototype and setup for testing asphere by partial compensation were devised and developed, a precise convex asphere is measured by this method, the PV and RMS of the surface error is 0.183λ and 0.018λ, respectively.

Key words: optical testing; aspheric surface; partial compensation; SSI; digital plane

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非零位补偿检验非球面技术

王孝坤

(中国科学院长春光学精密机械与物理研究所,中国科学院光学系统先进制造技术重点实验室,吉林 长春 130033)

摘 要:为了无需定制补偿透镜或者计算全息等就能实现对非球面光学元件的检测，提出了非零位补偿测试非球面的方法。对非零位补偿检验非球面中的部分补偿法、数字样板法和子孔径拼接法的基本原理和基础理论分别进行了分析和研究,建立了合理的数学模型,并对其具体的实现步骤和测试流程进行了分析和规划。结合工程实例,分别利用数字样板法和子孔径拼接法对一口径为 350 mm 的浅度非球面进行了面形检测，两种方法面形的 PV 值和 RMS 值的偏差分别为 0.015λ 和 0.002λ (λ=632.8 nm),并设计和组建了部分补偿检验装置对一高精度凸双曲非球面反射镜进行了测量,其面形的 PV 值和 RMS 值分别为 0.183λ 和 0.018λ。

关键词:光学检测; 非球面; 部分补偿; 子孔径拼接干涉计测; 数字样板法

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作者简介:王孝坤(1980-),男,副研究员,博士生导师,博士,主要从事光学超精加工和检测技术研究。

Email: jimwxk@sohu.com

0 Introduction

Large aspherical mirror is the key components in the fields such as high –resolution earth observation from space, deep space exploration and astronomical observation. It's very important to a country's national security, national economic development, basic research capacity, disaster prevention and mitigation. It's also an important indicator of a country measuring high – performance optical system[1–3].

Compared with traditional plane and spherical mirrors, the manufacturing and testing difficulty of the aspherical mirrors is the main technical bottlenecks limiting its wide application[4]. Especially for the aspherical mirror testing, there is no universal aspherical testing equipment and methods for now. It has been a difficulty how to accomplish the testing to an aspherical mirror quickly and accurately.

At present, it's still the most common method to test an aspherical mirror with a compensator[5–7]. The compensator can turn the plane or spherical wavefront into an aspherical wavefront which is consistent with the shape of the mirror. After reflecting from the mirror, the reflecting wavefront will interfere with the reference wavefront from the interferometer. Then the surface of the testing mirror can be taken. According to the type of the compensator, the technology can be divided into refractive compensation method and diffractive compensation method. Refractive compensation method originated earlier. In 1927, Couder tested a paraboloid successfully with a double lens compensator. And then in 1963, Offner compensator was born which made the technology widely applied. Especially after the laser interferometer technology is mature, it's still widely used all around the world based on its excellent performance. As the compensation optical design technology is mature and the spherical components used in the compensator can achieve high accuracy, it's still widely used in our high–precision aspherical testing and also the favorite technology in the aspherical mirrors manufacturing enterprises and research institutions.

Special compensators need to be designed for every aspherical mirror which not only increases the cost of testing, extends the manufacturing cycle, but also bring extra errors to the testing. In addition, it's more difficult to design the compensator for a convex aspherical mirror compared with that of a concave aspherical mirror. There are at least two lens in the convex aspherical mirror compensator, and sometimes compensator itself may also contain aspherical part. To achieve the high –precision testing of this aspherical part, extra compensator need to be designed, which brings many difficulties for the manufacturing and alignment process.

As another widely used method testing aspherical mirrors, CGH (Computer Generated Hologram) testing method accomplishes the large–diameter aspherical null compensation measurements with a diffractive optical element CGH as compensation component[8–10]. This kind of technology was proposed and developed by Lohmann, Paris and Lee in the late 1960s. In 1971, A.J.MacGovern and J.C.Wyant successfully applied it in the optical testing. With the development of lithography, IBF and electron beam lithography, the manufacturing precision of CGH is higher. In the late 1 990 s, it developed into a mature optical testing technique.

However, special CGH needs to be produced for each aspherical mirror. Furthermore, when testing a convex aspherical mirror, a converging reference wavefront is needed which requires the apertures of the interferometer, compensator and CGH are larger than the convex aspherical mirror. There are still many difficulties in the manufacturing and alignment of the compensator and CGH.

In order to avoid the difficulties in the null compensation component design and manufacturing, we presents and analyzes three non –null compensation methods: digital plane method, partial compensation and subaperture stitching method to test aspherical surfaces. At the same time, we establish each mathematical model and accomplish the aspheric measurements with above methods based on practical work.

1 Basic principles

1.1 Digital plane model

Digital plane method is a quick, real-time testing method to small-departure aspherical mirrors [11]. For small-departure aspherical mirrors, a standard spherical surface can be used as a reference surface. The phase distribution of the full aperture can be measured with a digital interferometer. The accurate aspherical surface can be obtained by removing the deviation between the asphere and the sphere wavefront from the testing result. The basic principle and flow chart are shown in Fig.1, and the specific steps are as follows.

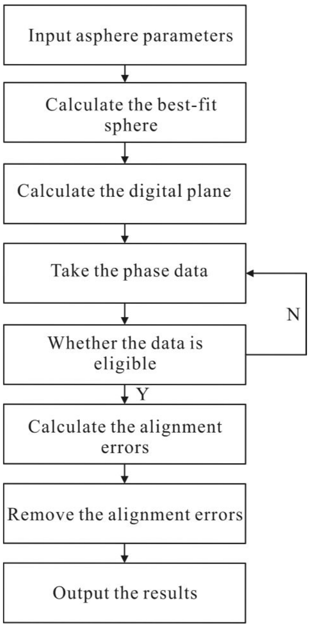

Fig.1 Flow chart of testing asphere by digital plane

Firstly, the radius of the best-fit sphere is calculated according to the three-point method based on the aspherical parameters. Then $[z(x,y)-s(x,y,r)]\cos\theta$ is calculated and turned into data pattern (digital plane). $z(x,y)$ is the height distribution along the optical axis direction of the aspherical surface and $s(x,y,r)$ is the height distribution of the best-fit sphere along the optical axis direction. θ is the normal angle of each point on the aspherical mirror. Secondly, adjust the locations of the interferometer and the aspheric mirror to make the focus of the reference spherical superpose with the center of the best-fit sphere. The phase data can be tested by interferometer with the interference fringes. At last, the surface error of the aspheric surface can be calculated by subtracting the digital plane and alignment errors from the phase data, and the alignment errors can be calculated by the least-squares fitting, the displacement, tilt in the x and y directions and power can be considered as the alignment errors of the system.

This method can test the concave, mild convex aspheric surface directly and precisely without additional optical elements, the data processing, data calculation and experimental operation are simple, and it shortens the testing time and further expands the existing capabilities of the interferometer.

1.2 Partial compensation

Partial compensation method is a single use of spherical lenses compensate partly compensated to achieve accurate optical aspheric surface shape measurement method that simplifies compensation structure[12-13], reducing the compensator design difficulty and production costs, the test basic principles and processes are shown in Fig.2.

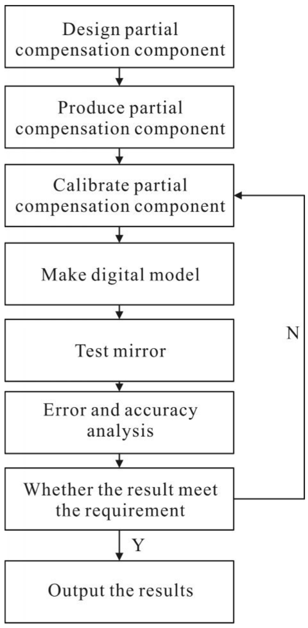

Fig.2 Flow chart of testing asphere by partial compensation

Firstly, a simple lens should be analyzed and designed as a compensation component. A simple lens can only be used to compensate part of the spherical aberration and make the interference waves not exceed the resolution limit of the interferometer.

Secondly, calibrate the partial compensation component. Put the single lens between the interferometer and the standard spherical mirror and adjust the locations of the interferometer, single lens and the standard spherical mirror to form the interference fringes whose phase distribution can be written as W_b. The digital wavefront phase distribution of a virtual model W_y can be obtained by calibrating W_b, theoretical spherical wavefront W_q and theoretical aspherical wavefront W_f. W_f can be deposited into the interferometer system error file as $W_y=W_b+(W_q-W_f)$ which is the digital virtual model.

Finally, put the partial compensation component between interferometer and the mirror tested. Adjust the locations of the interferometer, partial compensation component and the aspherical mirror tested to form the interference fringes whose phase distribution can be written as W_a. The phase distribution of the aspherical mirror can be obtained by subtracting the W_a from the W_y, $W_m=W_a-W_y$. Commonly, the tested asphere is precise, when the relative error between the testing result and the designed value is less than 20%, this method is believable.

1.3 Sub-aperture stitching

Aspherical stitching interferometry is a new aspherical testing method combining the sub-aperture stitching with interferometry technology[14-16]. The technique tests each local region of the aspherical mirror with a standard spherical wavefront. By subtracting the difference between the aspherical mirror and the reference wavefront and the alignment errors, the full aperture phase distribution of the mirror can be obtained with the stitching algorithm. The principle and process of the measurement are shown in Fig.3.

Firstly, select the proper interferometer and standard spherical lens, calibrate the size and number of subapertures according to the aperture and vertex radius of curvature of the aspherical mirror under tested.

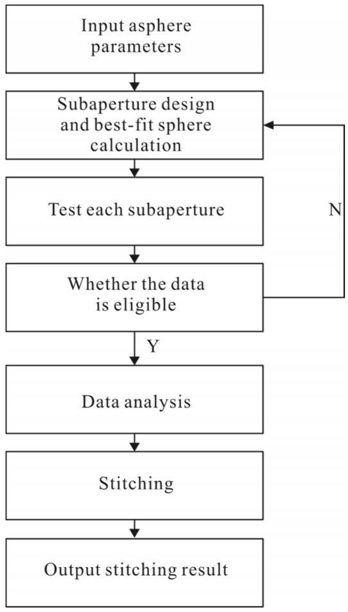

Fig.3 Flow chart of testing asphere by SSI

Secondly, adjust the locations of the interferometer and the aspheric mirror to make the normal line of the standard spherical wavefront in alignment with the normal line of the subaperture region tested, so that the incident lights will be able to return along the same route. The phase distribution of all subapertures will be taken by testing them one by one. When the phase data is missing, the data is not eligible, we will zoom the interferometry and reduce the subaperture, and the subapertures distribution will be calculated and designed again.

Before stitching, all the subaperture testing data should be unified into a global coordinate according to the coordinate transformation. After removing the difference between the aspherical mirror and the standard spherical wavefront from each subaperture testing result, the relative alignment errors can be calculated and removed according to the phase data in the overlapping areas. Finally, aspheric surface error distribution in the full aperture can be obtained by removing the full aperture aspheric system adjustment error from the full aperture stitching result with least-squares fitting. In order to examine the stitching accuracy, we can choose a subaperture different from the subapertures used for stitching as a self-examine subaperture. By subtracting the data between stitching result and self-examine subaperture testing result, when the relative error is less than 10% , the testing results is precise.

Aspherical stitching interferometry can not only widen the horizontal and vertical dynamic range of the interferometer but also test large aperture concave, convex and off-axis aspherical surfaces without additional optical components, in low cost, short duration.

2 Experiments

2.1 Digital plane and stitching testing experiments

With engineering examples, we applied both the digital plane method and stitching testing to a hyperboloid mirror whose aperture is 350 mm; vertex radius of curvature R is 4 200.7 mm; quadratic curvature constant k is -2.18; aspheric departure is 1.36 μm. The setup of this two kinds of testing method are consistent which are shown in Fig.4. Firstly, calculate the radius of the best-fit sphere is 4 204.67 mm, and compute the phase distribution of the digital model is shown in Fig.5. Secondly, align the interferometer and the aspheric surface, when the power of the phase distribution is nearly to zero, we can affirm that the focus of the reference spherical is superposed with the center of the best-fit sphere. The full aperture testing result can be obtained with a Φ100 mm Zygo interferometer and a $F^{\#}$ 11 standard spherical lens which is shown in Fig.6, the main distribution is primary spherical. After removing the digital plane and alignment errors, the figure error distribution of the mirror is shown in Fig.7, which the PV and RMS is 0.319λ and 0.044λ, respectively.

Five subapertures were tested by adjusting the relative locations between interferometer and the aspherical mirror. The subaperture testing results are shown in Fig.8 and the stitching result is shown in Fig.9 with integrated optimization stitching algorithm [17-18]. The PV and RMS is 0.334λ and 0.046λ, respectively. To examine the stitching accuracy, we choose the central subpaerture used for stitching as a self-examine subaperture [19]. By subtracting the data between stitching result and self-examine subaperture testing result point by point, we can

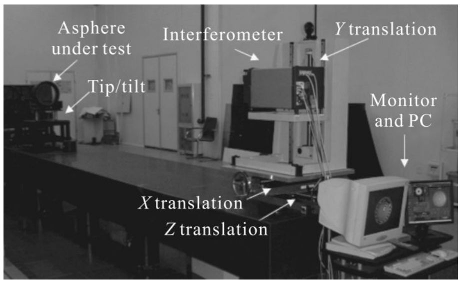

Fig.4 Setup of testing asphere by digital plane and SSI

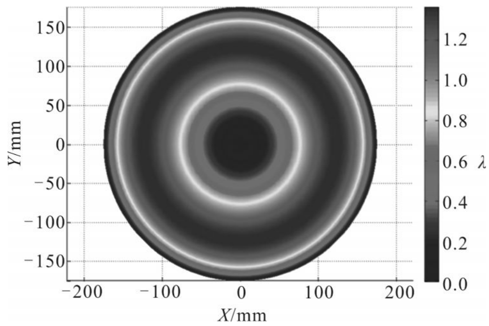

Fig.5 Phase map of the digital plane

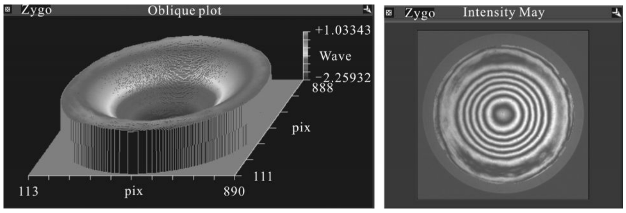

Fig.6 Testing results by digital plane

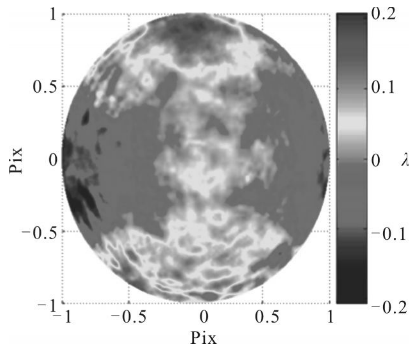

Fig.7 Figure error testing by digital plane

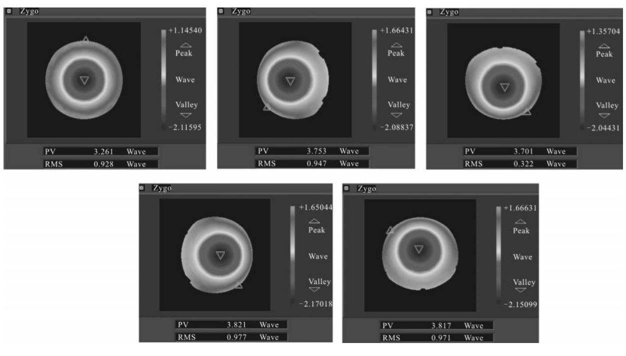

Fig.8 Phase maps of five subapertures

get the residual map as shown in Fig.10. The RMS error of the residual map is 0.004λ, and the relative error is less than 10% which makes the stitching algorithm and experiment result credible.

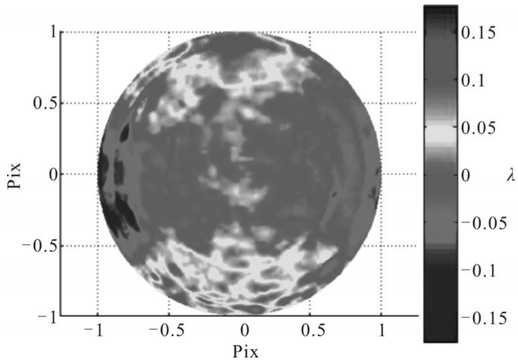

Fig.9 Figure error testing by SSI

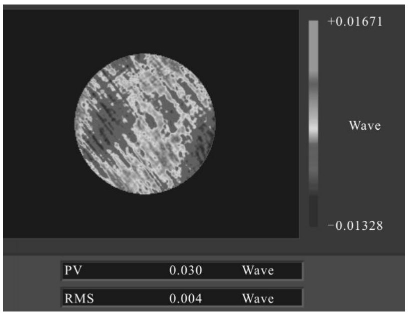

Fig.10 Residual map between stitching result and testing result of self-examine subaperture

The SSI testing results is consistent with the digital plane method, and the difference of the PV and RMS between them is only 0.015λ and 0.002λ, respectively. Furthermore, the PV and RMS of residual error of phase distribution of these two methods are calculated. The map of the residual error is given in Fig.11, where PV (δ_w) = 0.085λ, RMS $(\delta_w)=0.012\lambda$. It proved the accuracy and reliability of the both methods. Because the datum and the sample density of the two methods are different, the tiny differences of the testing results are reasonable and acceptable.

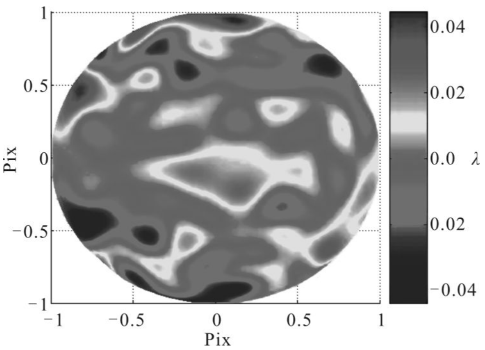

Fig.11 Residual error of SSI and digital plane method

2.2 Partial compensation experiment

A Φ132 mm convex aspherical mirror with the vertex radius of curvature R 1 091.402 mm, quadric coefficient k -1.873 was tested with partial compensation. A partial compensation lens was analysed and designed. The compensation lens not only compensate part of the spherical aberation but also expand the testing beam. The relative testing equipment is shown in Fig.12 with a Φ150 mm interferometer and a $F^{\#}$11 standard spherical lens.

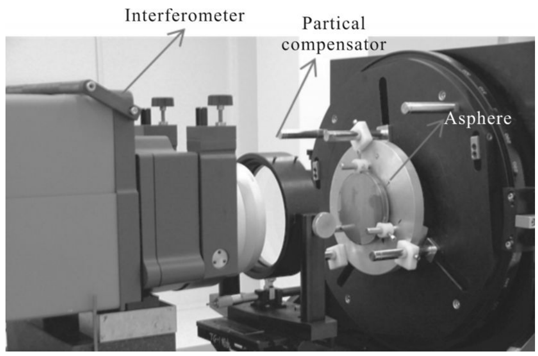

Fig.12 Setup of testing asphere by partical compensation test

The phase distribution and interference of the errors of the partially compensated system are shown in Fig.13. We can get from the Figure 14 that the accuracy of the partially compensated lens is not high. However, this does not affect the measurement of aspherical mirror, as these deviations will be compensated in the digital virtual model.

The phase distribution of the digital virtual model is shown in Figure 14 which can be treated as the system error. The phase distribution of the aspherical mirror is

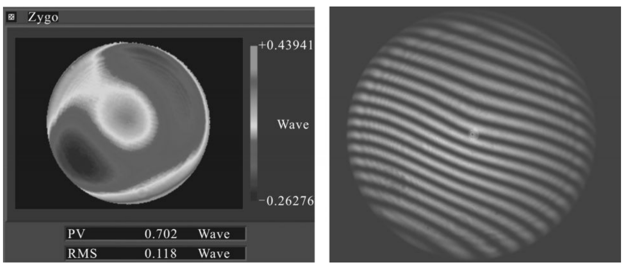

Fig.13 Phase map and interferogram of calibration

shown in Figure 15 whose PV and RMS is 0.183λ and 0.018λ, respectively.

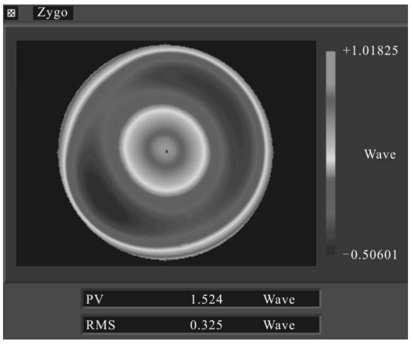

Fig.14 Phase map of digital virtual plane

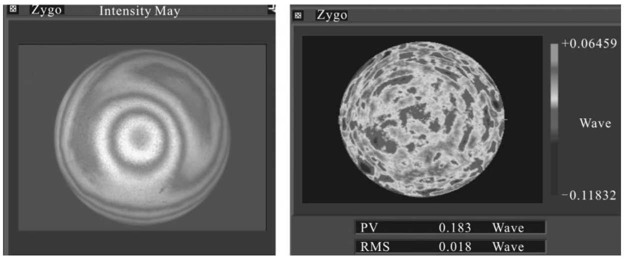

Fig.15 Interferogram and surface map by part compensation

3 Conclusion

We studied the digital plane method, partial compensation method and the subaperture stitching method when testing an aspherical mirror. The digital plane method expanded the capabilities of the interferometer. We accomplished the direct testing to small−departure aspherical mirrors (departure is within 10 μm) within the resolving power of the interferometer. There are many advantages for this method such as simple data processing and math modal, convenient experimental operation and low cost. Partial compensation method reduces the difficulty of compensator designing and the number of pieces of compensating lens which make the alignment easier. It also saves the testing time and increases efficiency. Based on the stitching method, the horizontal and vertical dynamic ranges of the interferometer are broadened. Other auxiliary optical elements are not needed for this method to accomplish the testing for large aperture aspheres, even off−axis aspheres. With engineering examples, a Φ350 mm hyperboloid asphere was tested with both digital plane method and subaperture stitching method. The relative deviation of both PV and RMS are less than 5%. We also designed and produced a partial compensation lens to accomplish the measurement of a Φ132 mm convex aspherical mirror and got the accurate surface distribution.

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