doi:10.3788/gzxb20164507.0722001

大口径离轴凸非球面的加工和检测

郑立功,王孝坤,薛栋林,李锐钢,张峰,张忠玉,张学军
(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,长春 130033)

摘　要:将光学系统波像差检验技术与子孔径拼接测试技术相融合提出了凸非球面系统拼接检测方法,对该方法的原理和实现步骤进行了分析和研究,并建立了合理的子孔径拼接数学模型.依次利用计算机控制光学表面成形技术和磁流变抛光技术对一包含大口径凸非球面的离轴三反光学系统的各反射镜进行加工,并对整个系统进行装调和测试.测定光学系统各视场的波像差分布,通过综合优化子孔径拼接算法和全口径面形数据插值求解得到大口径凸非球面全口径的面形信息.结合工程实例,对一口径为 292 mm×183 mm 的离轴非球面次镜进行了系统拼接测试和加工,其最终面形分布的均方根值为 0.017λ(λ=632.8 nm).

关键词:光学加工;光学检测;凸非球面;计算机控制光学表面成形;磁流变抛光;子孔径拼接
中图分类号:TQ171.65;O436.1　　**文献标识码**:A　　**文章编号**:1004-4213(2016)07-0722001-6

Fabricating and Testing of the Large Off-axis Convex Aspheric Surface

ZHENG Li-gong, WANG Xiao-kun, XUE Dong-lin, LI Rui-gang, ZHANG Feng, ZHANG Zhong-yu, ZHANG Xue-jun
(*Key Laboratory of Optical System Advanced Manufacturing Technology, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun* 130033, *China*)

Abstract: The testing method combining systemic wave aberration testing with subaperture stitching interferometry was proposed for measuring large off-axis convex aspheric mirror. The basic principle and process of the technology were analyzed and researched, and the stitching mathematical model was established. When the large convex surface is polished very well and the primary mirror and tertiary mirror of the optical system are fabricated by computer controlled optical surfacing and magneto rheological finishing, the three mirror astigmatism system can be aligned and adjusted. The wave aberration of each field can be tested by aligning and calibrating the optical system successively, and the phase map of the whole aperture can be calculated by the synthetical optimization stitching algorithm and interpolation. With engineering examples, a three mirror astigmatism optical system with a large convex aspheric mirror with the aperture of 292 mm×183 mm was fabricated and tested by the method. At last, the root mean square of the surface error is 0.017λ (λ=632.8 nm).

Key words: Optical fabrication; Optical testing; Convex asphere; Computer Controlled Optical Surfacing (CCOS); Magneto Rheological Finishing (MRF); Subaperture Stitching Interferometry (SSI)
OCIS Codes: 220.4610; 120.4610; 120.2880; 120.6650

0 Introduction

Aspherical surfaces can balance and correct aberration of optical system, improve the image quality, boost the performance and reduce the weight and complexity of the system at the same time,

Foundation item: The National High-tech Research and Development Program of China(No. O8663NJ090), the National Program on Key Basic Research Projects of China (No. 2011CB0132005), the National Natural Science Foundation of China (No. 61036015)
First author: ZHENG Li-gong(1969—), male, professor, Ph. D. degree, mainly focuses on ultra-precise fabrication and measurement of optics. Email:zhenglg@ciomp.ac.cn
Corresponding author: WNAG Xiao-kun(1980—), male, professor, Ph. D. degree, mainly focuses on ultra-precise fabrication and measurement of optics. Email:jimwxk@sohu.com
Received: Jan. 13, 2016; **Accepted**: Mar. 15, 2016

therefore, aspherical elements are increasingly used in deep space exploration, photoelectric tracking, astronomical observation, and many other optoelectronic devices[1-3].

Especially in the field of space optics, since the off-axis Three Mirror Astigmatism (TMA) system has many advantages, such as less components, long focal length, wide field, wide band and high modulation transfer function, larger aspheric surface has been widely used in space remote sensing[4-6].

The second mirror of the TMA system is a convex aspheric mirror, sometimes it is an off-axis convex aspheric surface. There are many difficulties in fabricating and testing of large convex aspheric mirror. The Computer Controlled Optical Surfacing (CCOS) method is one of the most common methods for fabricating asphere[7-8]. But for large mirror, the efficiency of CCOS is low, and it is very difficult to control the edge effect of the surface. The classic test method of convex asphere is by means of the large Hindle sphere, but for large off-axis convex aspheric surface testing, the Hindle sphere has several times the size of the tested mirror, manufacturing large and precise Hindle sphere is very difficult and expensive, and because of the center block, the central area of the asphere can't be measured. At present, the improved classical Hindle testing which is called Hindle-shell method can test the convex aspheric surface very well, but fabrication and measurement of the Hindle-shell lens are very difficult[9-11].

Using null lens or diffraction optical element Computer Generated Hologram (CGH) can test small convex aspheric surface directly[12-14]. But the null compensation of convex asphere is very difficult and complicated, because it also contains aspheric lens itself, it should design and fabricate a set of compensating elements for the null lens[15]. Using CGH can well realize the test of mild convex asphere, but for deep convex aspheric surface, the holographic line frequency density is very high, the existing lithography equipment cannot be realized. In addition, in order to accord with measured surface, the incident wavefront from the interferometer need to be gathered, so the aperture of the interferometer, null lens and CGH should be larger than the size of the tested mirror. At present, manufacture of large null lens and CGH is very difficult, and the price of the large interferometer is much high.

Subaperture Stitching Interferometry (SSI) can test each small area of large mirror one by one, using the subaperture stitching algorithm can reconstruct the phase map of large asphere[16-18]. But for large and deep aspheric surface, there are many subapertures so that the analysis and calculation are very complicated, and the erroneous transmission and accumulation will be introduced[19-20].

In order to overcome the above difficulties, we fabricate the large convex aspheric mirror by CCOS and Magneto Rheological Finishing (MRF)[21-22], the efficiency is high, and the edge effect can be controlled very well. The surface is tested by system aberration measurement combined with subaperture stitching technique, the full surface map of the large mirror can be obtained by testing and stitching wave aberration of every field of optical system. Because each subaperture testing is a null testing and the number of the subaperture is very little, the stitching algorithm can be simplified, the erroneous transmission and accumulation can be reduced and controlled.

1 Theory and principle

The flow chart of fabricating and testing large off-axis convex aspheric mirror is given in Fig. 1. Firstly, the large convex surface can be fabricated by CCOS and MRF alternatively, the surface error of the mirror is very big, the mirror will be grinded by CCOS which recur to the numerical control machine FSGJ-2 (which was designed and developed by our team), as shown in Fig. 2.

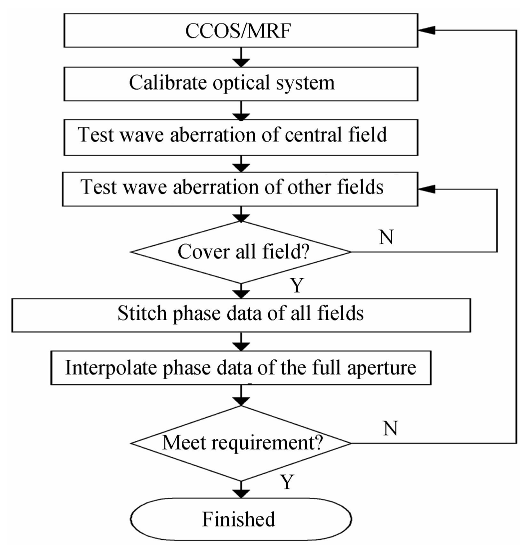


Fig. 1 Flow chart of fabricating and testing large off-axis convex asphere

In order to meet different processing requirements, FSGJ-2 contains 6 Degree of Freedom (DOFs), X, Y, Z for translational degree of freedom, U, V, W for rotational degree of freedom. It is established on the basis of CCOS technology and can grind and polish aspheric surfaces consecutively, the maximum fabricating capacity of the machine is 1 000 mm. When the Peak to Valley (PV) of the surface error is less than 2 μm, the mirror will be polished by

CCOS and MRF alternatively. The removal function of MRF is more stable and determined than CCOS, because of its efficient convergence, it often brings print through and some middle and high frequency error of the mirror, in order to eliminate the error, the mirror should be polished by CCOS which using large tool, after several periods, the surface error can be well converged.

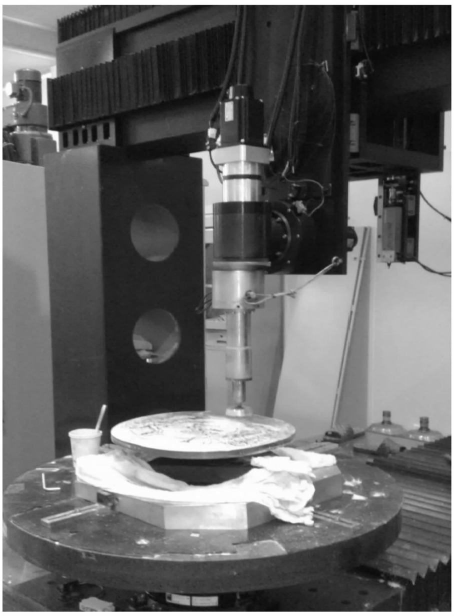


Fig. 2 Fabricating large convex aspheric mirror by FSGJ-2

Secondly, after the primary mirror and tertiary mirror of the optical system finished, the TMA system will be aligned and adjusted by laser tracker, which is shown in Fig. 3. Laser tracker is a kind of portable three coordinates measuring equipment with high precision and large capacity, it contains two rotating angle encoders and a laser distance measuring system, so the relative position of each mirror can be measured and monitored precisely.

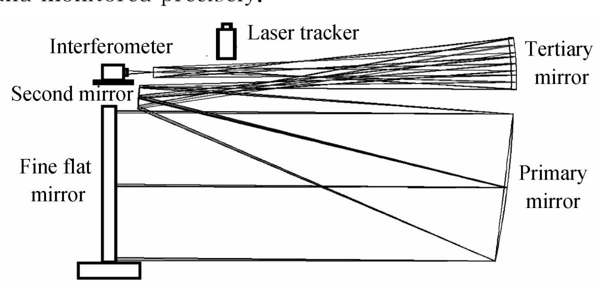


Fig. 3 Sketch and principle of testing large off-axis convex asphere by systemic stitching method

After the optical path well adjusted, the designed tolerance geometric position errors of the optical system are more than 20 μm and 1arc sec, but the precision of the laser tracker are better than 5 μm and 0. 02 arc sec, which can make sure that all the geometric position errors are less than designed tolerance by using laser tracker[23]. Then the phase map of the central field of the optical system can be tested by interferometry, the surface error of the flat mirror is very tiny, and the surface error of the primary mirror and tertiary mirror can be tested by null compensation. So the surface error of the second mirror (convex aspheric surface) can be obtained by subtracting the surface error of the primary mirror and tertiary mirror from the half of the wave aberration of the central field (because of back and forth twice reflection). Each field of the optical system can be tested by aligning the interferometer and the flat mirror, and the surface error of each subaperture can be obtained by the proposed method.

Assume that there are M fields of the TMA system, it should have M subapertures to cover the full aperture of the large convex mirror. The subaperture stitching diagram is shown in Fig. 4, there is a certain overlap between each subaperture, because the full aperture is bigger than the area superposed by all the fields, there is a small uncovered area.

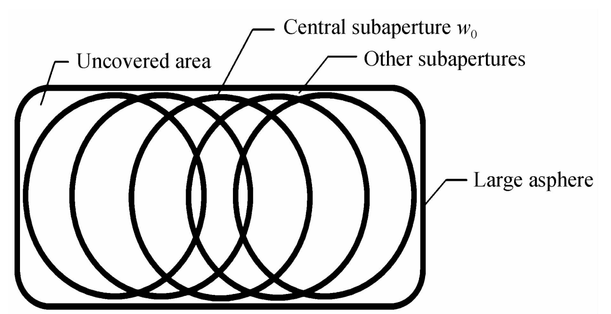


Fig. 4 Sketch of subaperture stitching

Generally choosing the central subaperture as a benchmark, because the aberration of each subaperture has been compensated and all the geometric position errors are calibrated by using laser tracker, the misalignment of adjacent subapertures will induce several aberrations which just contain piston, tilt and power as

$$w_i' = w_i + p_i + a_i x_i + b_i y_i + c_i(x_i^2 + y_i^2) \tag{1}$$

where w_i is the measured surface error of the i-th subaperture, w_i' is the real surface error of the i-th subaperture, p_i is the coefficient of relative piston, a_i, b_i, c_i are the coefficients of the relative X tilt, Y tilt and power respectively.

The Least-squares method is used to minimize the sum of the squared differences in all overlapping areas, as

$$\min = \sum_{i\cap j\neq 0}^{M} \sum_{\substack{q=1\\ q\subset w_i, w_j}}^{N} \{[(w_{iq} + p_i + a_i x_{iq} + b_i y_{iq} + c_i(x_{iq}^2 + y_{iq}^2)] - [w_{jq} + p_j + a_j x_{jq} + b_j y_{jq} + c_j(x_{jq}^2 + y_{jq}^2)]\}^2 \tag{2}$$

where M is the number of subaperture and N is the number of data point of the overlapping area, Eq. (2)

can be described simply as

$$S=\sum_{i=1}^{M}\sum_{q=1}^{N}[\Delta w+\Delta p_i+\Delta a_i x+\Delta b_i y+\Delta c_i(x^2+y^2)]^2=\min \quad (3)$$

Taking the differentiations of Eq. (3) with respect to these unknows

$$\begin{cases}\dfrac{\partial S}{\partial \Delta p_i}=0\\ \dfrac{\partial S}{\partial \Delta a_i}=0\\ \dfrac{\partial S}{\partial \Delta b_i}=0\\ \dfrac{\partial S}{\partial \Delta c_i}=0\end{cases} \quad (4)$$

The best stitching coefficients can be calculated by Eq. (4), then the real surface error of each subaperture and the stitched surface map can be obtained.

Since the aperture of the mirror is bigger than the superposition, there are no data points in the uncover area. The data can be calculated by interpolation of the existent data points, so the surface error of the full aperture can be obtained. When the Root Mean Square (RMS) of the surface error is less than $\lambda/50$, the large mirror is finished, if not, it will be fabricated by CCOS or MRF sequentially.

2 Experiments

Combined with engineering examples, a TMA optical system with a large off-axis convex aspheric mirror has been fabricated and tested by the proposed method, the field of view of the system is 2°, the aperture of the convex mirror is 292 mm×183 mm, the vertex radius of curvature is 1 348.935 mm, the conic constant is 4.387, off-axis quantity is 109.341 mm. The primary mirror and tertiary mirror have been well finished and have been tested by null lens, the RMS are both less than $1/50\lambda$, and the amount of geometric errors (vertex curvature radius deviation, off-axis quantity error, etc.) are controlled within the optical design tolerance range.

Firstly, the convex mirror has been grinded by FSGJ-2, and the surface error is measured by Coordinate Measuring Machine (CMM), which is given in Fig. 5, when the PV is less than 2 μm, the mirror is pre-polished and the TMA system is founded and adjusted by the laser tracker.

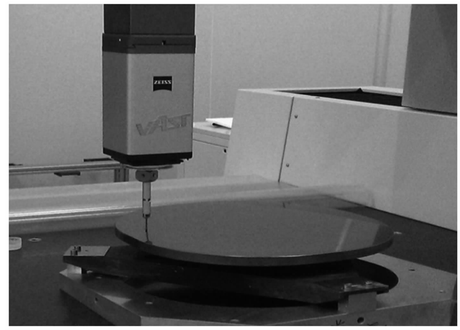
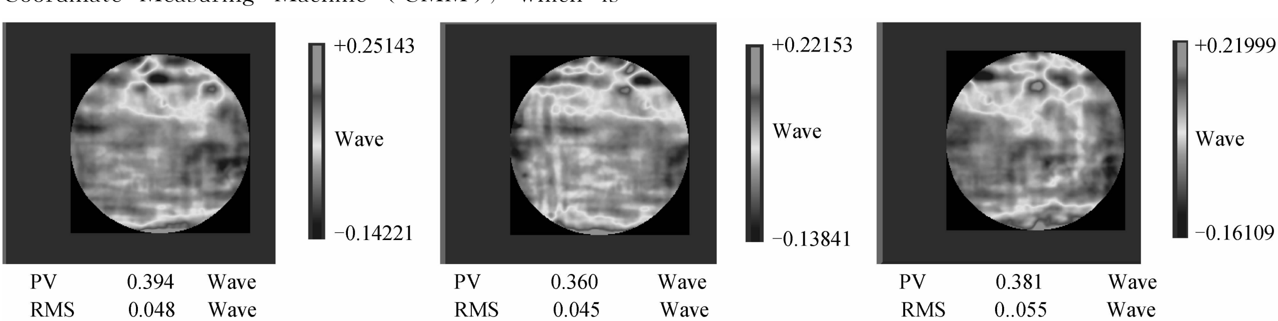


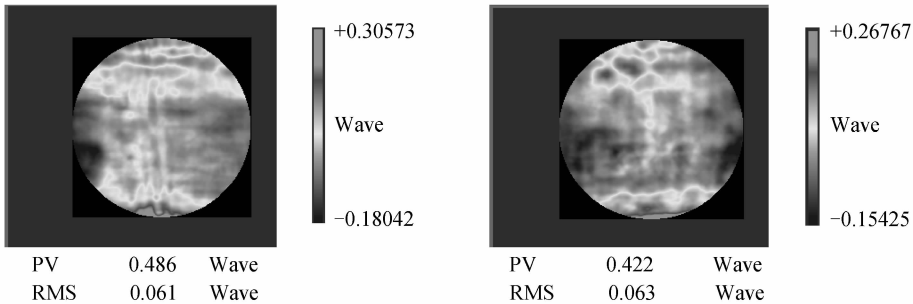
Fig. 5 Testing convex asphere by CMM

There are five fields of the optical system, five subapertures are tested to cover the full aperture, the phase map of each field is shown in Fig. 6, after subtracting surface error from the primary mirror and tertiary mirror, the surface error of the full aperture is obtained by stitching and interpolation, which is given in Fig. 7, the PV and RMS are 0.890λ and 0.078λ, respectively.

It can be seen that the surface is not very well, in order to save time and converged quickly, convex aspheric mirror is fabricated by MRF as shown in Fig. 8, after polishing the mirror for 1 h, the figure error obtains a very good convergence, as shown in Fig. 9, the PV and RMS of the surface error were 0.470λ and 0.031λ, respectively. The high efficiency and convergence could bring some middle and high frequency errors, so the mirror is transferred on to FSGJ-2 for polishing by large tool, after polishing one cycle, the stitched surface map is given in Fig. 10, it can be seen that the PV and RMS of the surface error have a little convergence, but the middle and high frequency error and print though have been reduced. After polishing the mirror by CCOS and MRF for three iterations, the final stitched surface map is shown in Fig. 11, the PV and RMS of the surface error are 0.285λ and 0.017λ, respectively.



(a) Phase map of 0° field (b) Phase map of −0.5° field (c) Phase map of 0.5° field



(d) Phase map of −1° field

(e) Phase map of 1° field

Fig. 6 Phase map of five fields

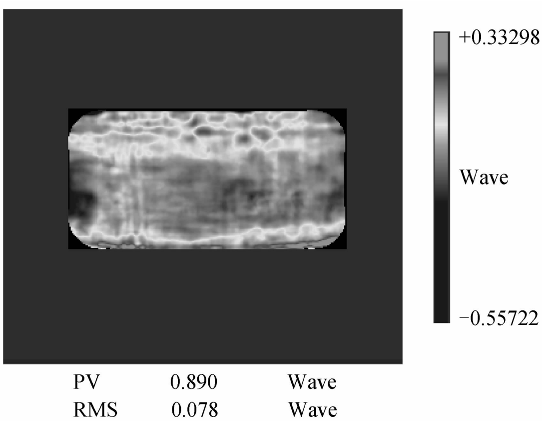


Fig. 7 Surface error of the full aperture after stitching and interpolation

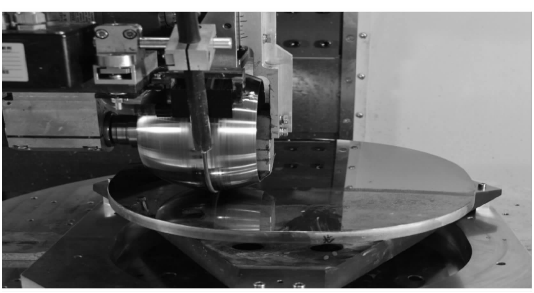


Fig. 8 Fabricating convex aspheric mirror by MRF

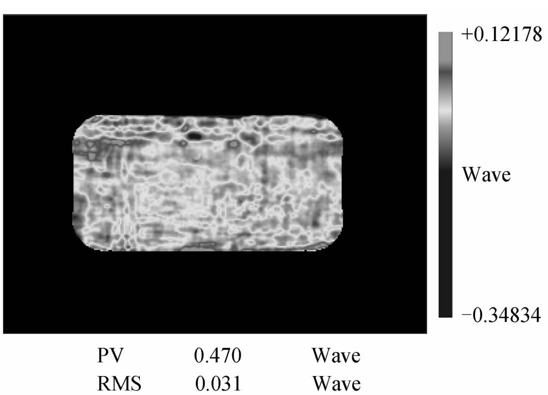


Fig. 9 Surface map after polishing by MRF

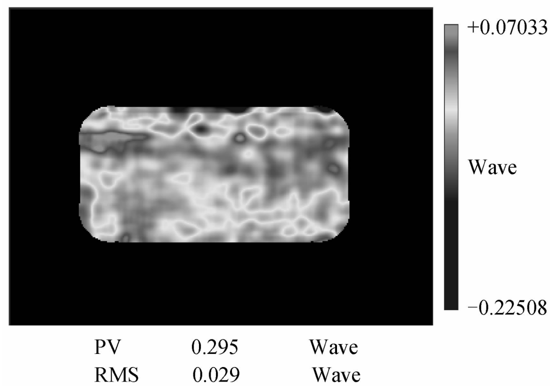


Fig. 10 Surface map after polishing by CCOS

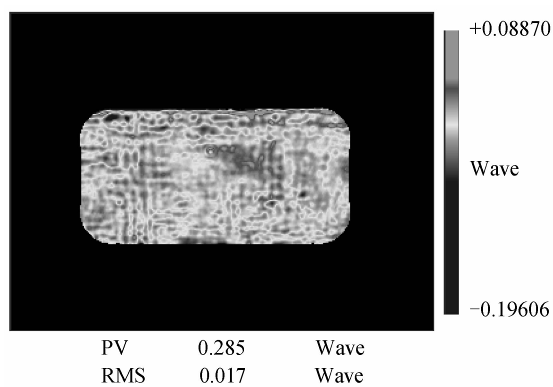


Fig. 11 The final distribution

3 Conclusions

On the basis of summing up conventional testing and fabricating methods for large convex aspheric mirror, the manufacture method integrates CCOS, MRF, systemic wave aberration testing and SSI is proposed. The basic principle, stitching algorithm and flow chart are researched. The proposed method reduces the number of subaperture and eliminates the accumulation of the stitching error. The surface error can be decreased swiftly by using CCOS and MRF alternatively, and the middle and high frequency error

is controlled effectively. With engineering examples, a TMA optical system which contains five fields with a large convex asphere has been fabricated and tested by the proposed method, finally, the RMS of the stitched surface map is better than 1/50λ.

Reference

[1] MALACARA D. Optical shop testing[M]. J Wiley & Sons, New York, 1992.

[2] CHEN Wei, XUE Chuang. Design of wide field of view off-axis three-mirror telescope for imaging spectrometer[J]. *Acta Photonica Sinica*, 2013, **42**(8): 950-955

[3] CHANG Jun, WANG Yong-tian, ZHANG Ting-cheng, *et al*. All reflective zoom systems for infrared optics[C]. SPIE, 2006, **6342**: 63421Q.

[4] HUXFORD R B. Wide FOV head mounted display using hybrid optics[C]. SPIE, 2004, **5249**: 230-237.

[5] BURGE J H, KOT L B, MARTIN H M. Design and analysis for interferometric measurements of the GMT primary mirror segments[C]. SPIE, 2006, **6273**: 361-367.

[6] OBICHAUD J, SCHWARTZ J, LANDRY D, *et al*. Recent advances in reaction bonded silicon carbide optics and optical systems[C]. SPIE, 2005, **5868**(02): 1-7.

[7] BURGE J H, BENJAMIN S, CAYWOOD D. Fabrication and testing of 1.4-m convex off-axis aspheric optical surfaces[C]. SPIE, 2009, **7426**: 692-697.

[8] ZHANG Xue-jun, ZHANG Zhong-yu, LI Zhi-lai. Manufacturing and testing of 1-m class SiC aspherical mirror [C]. SPIE, 2007, **6721**: 672109.

[9] MA Jie, ZHU Zheng. Testing convex aspherical surfaces with optimized modified Hindle arrangement[J]. *Infrared and Laser Engineering*, 2011, **40**(2): 277-281.

[10] CHEN Qin-fang, MA Zhen, ZHAO Meng, *et al*. Testing of large relative aperture lens with doublets[J]. *Acta Photonica Sinica*, 2014, **43**(3): 0322004.

[11] TAO Chun, PAN Jun-hua, HU Min-gyong. A new method of convex aspheric surface compensation tests[J]. *Optical Technique*, 2009, **3**(51): 123-126.

[12] FU Lian-xiao, WU Yong-gang, HAO Pei-ming, *et al*. The study and analysis of lens comoensation[J]. *Acta Photonica Sinica*, 2007, **36**(11): 2057-2061.

[13] GUO Pei-ji, YU Jing-chi. Design and certification of a null corrector to test hyperboloid convex mirror[C]. SPIE, 2006, **6150**: 259-263.

[14] QI Yue-jing, WANG Ping, XIE Jing-hui. A novel method of measuring convex aspheric lens using hologram optical elements[C]. SPIE, 2005, **6024**: 60241F.

[15] LIU Hua, LU Zhen-wu, LI Feng-you. Redistribution of output weighting coefficients for complex multiplexed phase-diffractive elements[J]. *Optics Express*, 2005, **12**(19): 4348-4352.

[16] MURPHY P, FLEIG J, FORBES G. Subaperture stitching interferometry for testing mild aspheres[C]. SPIE, 2006, **6293**: 62930J.

[17] WANG Xiao-kun, ZHENG Li-gong ,ZHANG Bin-zhi, *et al*. Test of an off-axis asphere by subaperture stitching interferometry[C]. SPIE, 2009, **7283**: 72832J.

[18] SU Peng, Absolute measurements of large mirrors[D]. The University of Arizona,2008.

[19] YAN Li-song, WANG Xiao-kun, ZHENG Li-gong, *et al*. Experimental study on subaperture testing with iterative triangulation algorithm[J]. *Optics Express*, 2013, **21**(19): 22628-22644.

[20] ZHANG P F, ZHAO H, ZHOU X, *et al*. Subaperture stitching interferometry using stereovision positioning technique[J]. *Optics Express*, 2010, **18**(14): 15216-15222.

[21] HU H, DAI Y, PENG X, *et al*. Research on reducing the edge effect in magnetorheological finishing[J]. *Applied Optics*, 2011, **50**: 1220-1226.

[22] SHOREY A, KORDONSKI W I, TRICARD M. Magnetorheological finishing of large and lightweight optics [C]. SPIE, 2004, **533**: 99-107.

[23] WANG Xiao-kun. Measure of aspherical surface by laser tracker[J]. *Acta Photonica Sinica*, 2012, **41**(4): 379-383.