Design of Fiber-Coupled Light Source for Reflective Single Star Simulator

Zou Yangyang[1] Zhang Guoyu[1,2,3] Zhang Jian[1] Yang Liyan[1] Zhang Jianliang[4]

[1]*School of Photo-Electronic Engineering, Changchun University of Science and Technology, Changchun, Jilin* 130022, *China*

[2]*Key Laboratory of Optical Control and Optical Information Transmission Technology, Department of Education, Changchun, Jilin* 130022, *China*

[3]*Optical Measurement and Control Instrumentation, Jilin Province Engineering Research Center, Changchun, Jilin* 130022, *China*

[4]*Aviation University of Air Force, Changchun, Jilin* 130022, *China*

Abstract In order to meet the requirements of ground calibration of star sensor and assorted usage with single star simulators, a light source coupled by integrating sphere and multiple optical fibers is designed based on the characteristics of conventional light source of star simulators. The luminance of each single star emitted by star simulation is controlled by each coupled beam. According to the requirements of indicators, the types of light source, integrating sphere and optical fiber can be confirmed by analyzing the energy in perspective of photometry. Using simulation model established by Light tools and analyzing the simulation results, it is found that the fiber-coupled light source meets the design requirements, and the illumination simulation error of each magnitude is similar to the practical illumination error and both of them are not more than ±10%.

Key words optical devices; star simulator; integrating sphere; optical fiber; Light tools simulation

OCIS codes 060.2330; 060.2380; 230.6080; 220.2945

反射式单星模拟器光纤耦合光源设计

邹阳阳[1] 张国玉[1,2,3] 张 健[1] 杨礼艳[1] 张建良[4]

[1]长春理工大学光电工程学院, 吉林 长春 130022

[2]光电测控与光电信息传输技术教育部重点实验室, 吉林 长春 130022

[3]吉林省光电测控仪器工程技术研究中心, 吉林 长春 130022

[4]空军航空大学, 吉林 长春 130022

摘要 为了满足星敏感器地面标定及配合多个单星模拟器使用要求,针对传统星模拟器光源的特点,设计了一种积分球与多光纤耦合的模拟器光源,每一单星模拟器星点亮度由每一路耦合光束控制。根据指标要求,在光度学角度上对能量进行分析,并确定光源、积分球以及光纤的选取。利用Light tools建立仿真模型,分析仿真结果,最终结果表明该光纤耦合光源满足设计要求,每个星点用Light tools模拟照度误差与实际模拟照度误差相近且两者均不大于±10%。

关键词 光学器件;星模拟器;积分球;光纤;Light tools仿真

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1 Introduction

Star simulator is a ground calibration device for star sensor. We conduct a research by using the relative parameters such as spectral types, absolute luminosity and point image quality in order to simulate single-

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作者简介: 邹阳阳(1991—),女,硕士研究生,主要从事航天器地面模拟技术与光电检测技术方面的研究。E-mail: 1006268633@qq.com

导师简介: 张国玉(1969—),男,教授,博士生导师,主要从事光电检测与航天器地面模拟设备等方面的研究。E-mail: zh_guoyu@163.com star or multi-star simulator. In this way, the characteristics of the star points like star magnitude, star size and spectrum can be accurately simulated with high precision. The calibration of both the detection ability and spatial resolution of the star sensor could be achieved on the ground [1-2]. Traditional star simulator has two approaches to design star map display device. One is liquid crystal display (LCD) back light meshing with fixed star tester, and the other is liquid crystal light valve controlling back light [3]. The disadvantage of these two light sources is that they can only realize one light source employed by one star simulator. Aiming at the requirements of a star sensor, a kind of light source with a combination of integrating sphere and optical fiber is designed in this paper to realize one light source utilized by several star simulators.

2 Design of fiber-coupled light source

2.1 Design requirements of fiber-coupled light source

The fiber-coupled light source includes integrating sphere light source and fiber coupling transmission system. The incident lights are diffused countlessly in the integrating sphere and then coupled into fiber directly, finally they are emerged from the output port of optical fiber. Here, the output port of optical fiber is exactly the simulated star point. The light traveling path is shown in Fig.1.

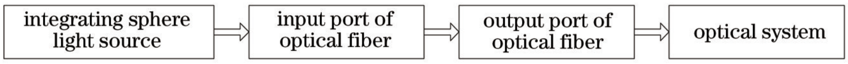


Fig.1 Light traveling path

According to the calibration requirement of the star sensor, the main technical specifications of fiber-coupled light source are shown in table 1.

Table 1 Technical specifications of fiber coupling light source

Parameter	Performance index
Star point radius /μm	12
Star magnitude spectrum /nm	0 to +6 450 to 800
Aperture of reflective optical system /mm	100
Incident angle of optical system /(°)	5.723
Illumination simulation error /%	≤±10

2.2 Selection of integrating sphere and optical fiber

For integrating sphere light source, in view of the practical application, the opening area of integrating sphere should be not more than 10% of the total area of the inner wall. So increasing the volume of integrating sphere can improve illuminance uniformity at the outlet. Besides, the experience shows that, the diameter of the hole should be less than 1/10 of the integrating sphere diameter in order to guarantee the illuminance at the outlet with the uniformity of about 1%. For overall consideration, the parameters of the integrating sphere are determined in Table 2 as follows.

Table 2 Parameters of integrating sphere

Parameter	Performance index
Diameter of integrating sphere /m	1
Reflectance	0.98
Spectrum range /nm	300 to 850

In the practical application of optical fiber, the coupling efficiency of the optical fiber and light beam is determined by the following factors, including the matching of source luminous area and fiber core area, the matching of light source divergence angle θ_{light} and optical fiber numerical aperture angle θ_{c} [4]. In optical fiber, the condition of total reflection for light beam is

$$\begin{cases} D_{\mathrm{light}} \leqslant D_{\mathrm{core}} \\ \theta_{\mathrm{light}} < \theta_{\mathrm{c}} \end{cases}, \tag{1}$$

Where D_{light} and D_{core} are the diameters of source luminous area and fiber core area.

Combining with the technical index of light source, the relative parameters of optical fiber are displayed in table 3.

Table 3 Parameters of optical fiber

Parameter	Performance index
Diameter of core /μm	20
Numerical aperture *NA*	0.5
Angular aperture /(°)	60
Length /m	10

3 Energy and structure analysis of coupled light source

In order to design the coupled light source, a mass of calculation needs to be done about energy in perspective of photometry. Firstly, the luminous flux is assumed to be Φ_o, which unit is lm, the direct illumination intensity produced by light on the internal surface of integrating sphere is E_1, and the diffused light luminance in the integrating sphere produced by direct light is L_1. L_1 can be derived as

$$L_1 = \frac{\rho_s E_1}{\pi}, \tag{2}$$

where ρ_s is the reflectance of integrating sphere.

All the diffused light on the inner wall of integrating sphere for the first time can bring the second diffusion and give another illumination intensity E_2. The illumination on unit area at permanent position produced by differential area of the inner wall of the integrating sphere is known and the integral is done for the whole inner surface of the integrating sphere [5]. Then E_2 has following relation:

$$E_2 = \rho_s \Phi_o / 4\pi R^2, \tag{3}$$

where R is the radius of integrating sphere, which unit is mm.

Then the illumination at a certain point in the integrating sphere after heaps of times diffusion is

$$E = E_1 + E_2 + \cdots + E_n = E_1 + \frac{\rho_s \Phi_o}{4\pi R^2 (1-\rho_s)}. \tag{4}$$

The secured fiber bundle is installed at the hole of integrating sphere. According to the working principle of integrating sphere, the illumination that each fiber accepts is equal to be E_f. The aperture angle of fiber is θ_c, the diameter of fiber core is D_{core}, and the fiber length is L. Thus the effective illumination at the exit port of fiber within the aperture limits is

$$E_f = \frac{\Phi_o (1-\cos 2\theta_c)}{8\pi R^2} \cdot \frac{\rho_s}{1-\rho_s}. \tag{5}$$

Then the luminous flux transmitted into each fiber is

$$\Phi_{incident} = E_f \cdot 4\pi \left(\frac{D_{core}}{2}\right)^2. \tag{6}$$

The light beam transmits by means of diffusion in the optical fiber until reaching the output port. The number of diffusion times [6] is

$$N = \frac{L \sin\frac{\theta_c}{2}}{D_{core}}, \tag{7}$$

where L is the length of fiber, which is 10 m, however, the aperture of fiber is only tens of micrometers, and the estimated numbers of reflection may be thousands of times. Therefore, it is obvious that the energy loss is nearly zero in the process of total reflection. This suggests that the flux $\Phi_{incident}$ at the input port is equal to the flux $\Phi_{emergent}$ at the output port of the optical fiber. According to the aperture angle of optical fiber θ_c, solid angle of emergent light of optical fiber can be calculated as

$$\Omega = 2\pi(1-\cos\theta_c). \tag{8}$$

The luminous intensity which enters into the optical system from output port of optical fiber can be calculated as

$$I = \frac{\Phi_{emergent}}{\Omega} = \frac{\Phi_{incident}}{2\pi(1-\cos\theta_c)}. \tag{9}$$

Bring Eq.(5) into Eq.(9), the luminous intersity I can be obtained

$$I = \frac{E_f \cdot 4\pi \left(\frac{D_{core}}{2}\right)^2}{2\pi(1-\cos\theta_c)}. \tag{10}$$

The angle of beam that enters into the reflective optical system of star simulator is known as $U = 5.732°$. The actual solid angle of emergent light beam from optical fiber to optical system is

$$\Omega_M = 2\pi(1-\cos U). \tag{11}$$

The luminous flux, which enters into parabolic mirror, can be calculated as

$$\Phi_{IM} = I\Omega_M. \tag{12}$$

In fact, there is energy loss in the optical system. Reflective optical system of single star simulator is shown in Fig.2. The light beam from fiber enters into parabolic mirror after reflected by plane mirror and finally images are at infinity.

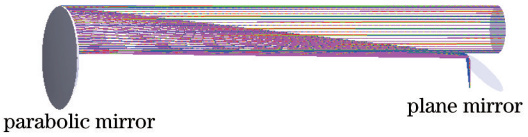


Fig.2 Sketch diagram of reflective optical system

The parabolic mirror in this system is plated with aluminum. The average reflectance of aluminum coating is shown in table 4.

Table 4 Reflectance of aluminum coating

Wavelength /nm	200 to 400	400 to 700	700 to 1000	1000 to 10000
Reflectance	≥85%	≥90%	≥90%	≥95%

In the wavelength range from 450~800 nm, the reflectance of aluminum coating is $\rho_{\mathrm{M}} = 0.9$.

After passing through the optical system, the emergent flux is

$$\Phi_{\mathrm{EM}} = \Phi_{\mathrm{IM}} \cdot \rho_{\mathrm{M}}. \tag{13}$$

The aperture of optical system is known to be $A = 100\ \mathrm{mm}$, and the emergent light area is $S = \pi\left(\frac{A}{2}\right)^2$.

So the light illumination obtained eventually is

$$E_{\mathrm{n}} = \frac{\Phi_{\mathrm{EM}}}{S} = \frac{\Phi_{\mathrm{IM}} \cdot \rho_{\mathrm{M}}}{\pi\left(\frac{A}{2}\right)^2}. \tag{14}$$

At this point, E_{n} is the illumination of a magnitude which needs to be simulated.

Magnitude is divided by luminance. For each magnitude, luminance differs 2.512 times. Luminance here is the illumination in photometry. According to the rules, the illumination of zero magnitude is $E_0 = 2.56 \times 10^{-6}\ \mathrm{lx}$ under the condition of atmospheric extinction[7]. According to the design requirements, 0 to +6 magnitude stars need to be simulated, and then the illumination range which needs to be simulated is 2.56×10^{-6} to $6.654 \times 10^{-10}\ \mathrm{lx}$. Taking the maximum illumination which needs to be simulated into Eqs.(3)~(14), we can calculate out that the minimum flux of the light source is $\Phi_{\mathrm{o}} = 404\ \mathrm{lm}$. The relative parameters of light source are shown in table 5.

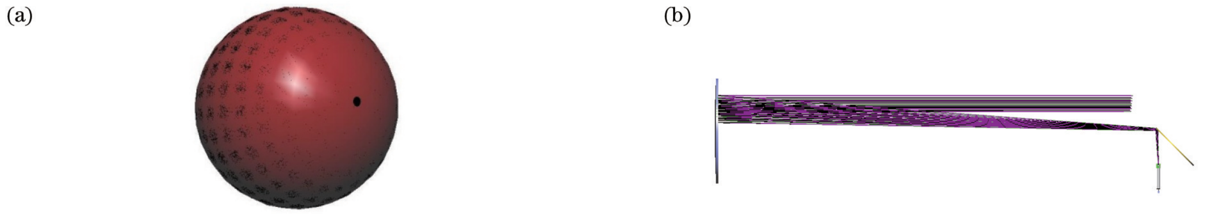
Table 5 Parameters of light source

Parameter	Performance index
Voltage /V	6
Power /W	20
Spectrum range /nm	380 to 820
Luminous flux /lm	410

Now, the selection of light, integrating sphere and optical fiber is determined, and the design of light source by integrating sphere and optical fiber coupling is completed. Different wave ranges and magnitude energy simulation can be realized by controlling filters and attenuator.

4 Simulation analysis of light source of optical fiber coupling

The simulation model of fiber-coupled light source is established by using Light tools, which mainly includes integrating sphere source, optical fiber and effective optical system. The established model and illumination simulation results are described in Fig.3.



(a)

Illumination	
Minimum (*M*): 210.63 lx	Contrast ratio: 0.38143
Maximum (*X*): 470.39 lx	Standard deviation: 64.874
Average (*A*): 377.58 lx	Average deviation: 0.17182

(b)

Illumination	
Minimum (*M*): 138.24 lx	Contrast ratio: 0.54621
Maximum (*X*): 471.02 lx	Standard deviation: 78.246
Average (*A*): 299.11 lx	Average deviation: 0.26160

Fig.3 Simulation model and results. (a) Integrating sphere; (b) optical fiber system

The data shows that simulation results conform to the calculation results. So the fiber-coupled light source can realize the simulation of magnitudes ranging from 0 to +6. For the technical requirement that the illumination simulation error must be not more than ± 10%, and the zero magnitude illumination accuracy calculation can be shown as an example. The raster chart of receiver by tracing 1000000 rays is shown in Fig.4 and the illumination grids of receiver are shown in table 6.

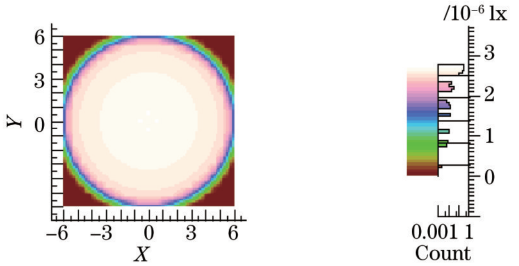


Fig.4 Raster chart of zero magnitude simulation

Table 6 Illumination grids of receiver

Illumination	
Minimum(*M*): 0 lx	Contrast ratio: 1
Maximum (*X*): 2.7473×10^{-6} lx	Standard deviation: 9.7426×10^{-7}
Average (*A*): 2.0812×10^{-6} lx	Average deviation: 0.4683

The simulated illumination value shown in the table is 2.747×10^{-6} lx. The illumination of zero magnitude is 2.56×10^{-6} lx[8], and the simulation error of illumination is $\frac{(2.747-2.56)\times10^{-6}}{2.56\times10^{-6}}=7.3\%$, which can meet the demand that the required error is not more than ±10%.

The calculation of illumination simulation error for 0 to +6 magnitudes can be done according to the methods above. The results are shown in table 7.

Table 7 Illumination simulation error

Magnitude	Theoretical illumination /10^{-6}	Simulation illumination /10^{-6}	Simulation error /%
0	2.56	2.747	7.3
1	1.01	0.9257	−8.3
2	0.406	0.4398	8.3
3	0.162	0.1750	8.0
4	0.0645	0.05875	−8.9
5	0.0256	0.02773	8.3
6	0.0101	0.01041	3.0

In the practical application,the illumination can be detected by illuminometer[9], and the detected results are shown in table 8.

Table 8 Practical illumination error

Magnitude	Theoretical illumination /10^{-6}	Practical illumination /10^{-6}	Simulation error /%
0	2.56	2.75	7.4
1	1.01	0.93	−7.9
2	0.406	0.439	8.1
3	0.162	0.176	8.6
4	0.0645	0.0591	−8.3
5	0.0256	0.0277	8.2
6	0.0101	0.02106	4.9

The results in the table show that the practical illumination error is similar to the simulation error. Simulation errors are all within ±10%, and the fiber-coupled light source meets the simulation accuracy requirement.

5 Conclusion

In conclusion, the fiber-coupled light source designed in this paper achieves the goal that one source can be employed by several star simulators. The selection of light, integrating sphere and optical fiber can be made by precise calculation according to technical specifications. After the simulation and

analysis of the fiber-coupled light source using optical simulation software, the analysis result shows that the light source can be adjusted from 0 to +6 star magnitudes, and the simulation accuracy is within ±10% as well, which meets the technical requirements. On the whole, the designed fiber-coupled light source has a practical significance for the design and development of light source of star simulator.

Refrences

1 Li Qing.Design on Illiminant of Star Simulator [D]. Changchun：Changchun University of Science and Technology, 2010. 9-11.
李　庆. 星模拟器光源设计[D].长春: 长春理工大学, 2010. 9-11.

2 Li Jing, Yang Baoxi, Hu Zhonghua, *et al*.. Development and performance testing of optical system for star sensor [J]. Acta Optica Sinica, 2013, 33(5): 0522005.
李　璟, 杨宝喜, 胡中华, 等. 星敏感器光学系统的研制与性能测试[J]. 光学学报, 2013, 33(5): 0522005.

3 Sun Xiangyang, Zhang Guoyu, Duan Jie, *et al*.. Design of star charts simulator for high-precision star simulator [J]. Acta Optica Sinica, 2013, 32(5): 0523001.
孙向阳, 张国玉, 段　洁, 等. 高精度星模拟器目标标准源设计 [J]. 光学学报, 2012, 32(5): 0523001.

4 Wei Dan, Wang Fei, Fang Dan, *et al*.. Optical design of sunlight fiber coupling system [J]. Journal of Applied Optics, 2013, 34(2): 221-222.
魏　丹, 王　菲, 房　丹, 等. 太阳光光纤耦合光学系统设计 [J]. 应用光学, 2013, 34(2): 221-222.

5 Zhong Fengjin, Xu Shiwen, Zhao Liang, *et al*.. The calculation of effective illumination on optical fiber port in integrating sphere of star simulator [J]. Journal of Harbin Institute of Technology, 1998, 30(4): 113-115.
钟奉金, 许世文, 赵　亮, 等. 星模拟器中积分球光纤端面有效照度的计算 [J]. 哈尔滨工业大学学报, 1998, 30(4): 113-115.

6 Zhang Yimo. Application Optics [M]. Beijing: Electronic Industry Press,2008.
张以谟. 应用光学[M]. 北京: 电子工业出版社, 2008.

7 Sun Gaofei, Zhang Guoyu, Jiang Huilin, *et al*.. Design of star simulator and proposes a technique of correction method for the position of star [J]. Laser & Optoelectronics Progress, 2011, 48(9): 091201.
孙高飞, 张国玉, 姜会林, 等. 一种静态星模拟器的设计与星点位置修正方法 [J]. 激光与光电子学进展, 2011, 48(9): 091201.

8 Zhang Xiaojuan, Zhang Guoyu, Sun Gaofei, *et al*.. Spectral study for star simulator on hybrid light source [J]. Acta Photonica Sinica, 2014, 43(2): 022201.
张晓娟, 张国玉, 孙高飞, 等. 基于混合光源的星模拟器光谱研究 [J]. 光子学报, 2014, 43(2): 022201.

9 George S Kliros, Paraskevi C Divari. Coupling characteristics of laser diodes to high numerical aperture thermally expanded core fibers [J]. J Mater Sci: Master Electron, 2009, 20(10): s59-s62.

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