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Study of Digital High-Precision Multi-star Simulator for Multi-Magnitude Output

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Abstract

A new type of high precision digital star simulator was designed for the requirement of the application. The star simulator is a device used to test and correct the defect and spatial resolution. For this device, a compact structure of mechanical and electrical integration was designed for the optical system of the star simulator. The new-type white light X Lamp LED was used as the light source and the constant current source control system based on PWM was applied to control luminance of the light, which makes it possible for the digital subdivision control between the light intensity of 640~1.0 lux. Compared with the halogen lamp, the weaknesses of large volume, high heat leak and low precision is avoided by using LED light source. As shown in the test, the result indicated that the star simulator designed in this paper was compact, reasonable and easy to control. The simulated apparent magnitude can be reached between 0^m*~*7^m*, and the spectral range can cover the whole visible light and the control precision can reach* $\pm 0.1^m$*.*

Keywords*: star sensor, star simulator, optical system design, LED light source*

1. Introduction

As a kind of attitude control instrument with high precision, star sensor has gradually became the main trend of aerospace aircraft navigation with the deep exploration of space detection [1-6]. The attitude of the aircraft is determined by detecting the position of the fixed star through the star sensor and then given further adjustment; hence, the star sensor is crucial for the aircraft navigation [7]. In order to test and calibrate properties of the star sensor, the properties, such as the measurement ability and spatial resolution, should be tested and calibrated by applying star simulator that is able to simulate space infinite light source in space. As for the static star simulator, the real-time change of the star catalog is difficult to realize, so that the high calibration precision could not be reached. As for the dynamic star simulator, the position precision of the star simulator could only reach ±0.3 m, and the high roundness of the simulated star point is also difficult to be achieved [8-10]. Therefore, the study and development of a new type static simulator has become the focus in the field of star simulator.

At present, in traditional star simulator, xenon lamp and halogen lamp are mainly selected as light source. The shortcoming is that mounts of light source have to be added or the light emission intensity of single light source has to be enhanced to promote the

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dynamic range of simulated apparent magnitude. In reality, the working mode of the combination of multi-light source star simulator is usually adopted to cover the simulated spectrum range, which not only expands the volume of the simulator, but also increases the difficulty of control and expense [11-12].

2. Structure Development of the High Precision Simulator

2.1. Structure Design and Working Principle of Star Simulator

As an equipment of ground calibration, a new type of static star simulation system is designed in order to better simulate star map characteristics of the apparent magnitude and spectral properties. This device is mainly composed of a high precision parallel light pipe system, a LED light source system and a control system. The system structure diagram is shown in Figure 1.

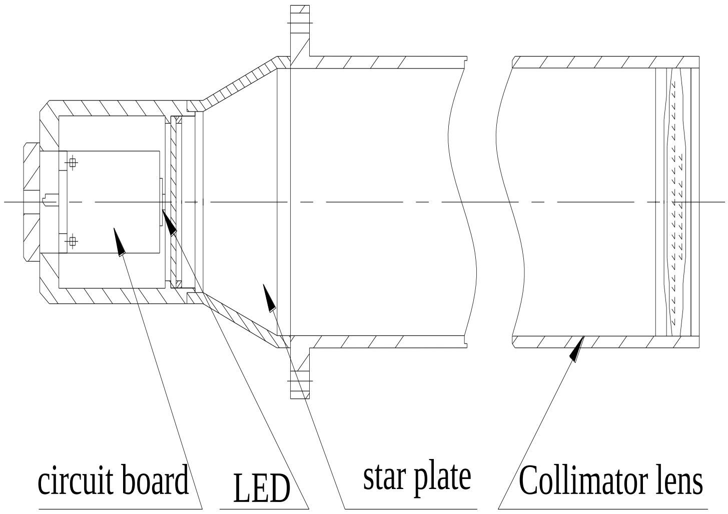

Figure 1. Structure of the Star Simulator

As the conventional star simulators using Xenon lamp and halogen lamp have the disadvantages of bad stability, low precision, narrow spectral of star simulation and heat radiation, the authors use a wide spectrum white light LED as the light source. The LED light source is placed in a chamber with its driving circuit in it so that the leakage of light and heat can be prevented. In order to have a better light source, the LED light source is installed at the end of its driving circuit board and the axis of the LED should be in accordance with the optical axis of the parallel light pipe.

As shown in Figure 1, due to the system working in a large field and full spectrum band range and considering the practical installation, the transmission optical structure was adopted in order to eliminate the off-axis aberration of the system. In addition, this paper finds a method to reduce the interference, which installs an LED drive circuit of the light source to the closed chamber of the parallel light pipe. The star board is placed in the focal plane of parallel light pipe and the distance from the star board to the LED light source installed in front of the drive circuit can be modified by the nut bolt. The starboard has a good roundness so that its appearance has a better accordance with the fixed star simulated. The light emitted from the light source is adjusted to be parallel after going through the collimator optical system and arrives at the star simulator to accomplish the simulation of star atlas at infinity. During the working process, current output has been well controlled by the control system to obtain the required duty circle using the control mode of PWM constant current source. And in this way, the apparent magnitude simulated by light source is finally precisely controlled with the control accuracy of $\pm 0.1^m$.

2.2. Optical Design of the System

The navigation equipment accomplishes the attitude determination based on the center of the light power of the fixed star, which calls for the steep demand of the optical system. The optical system for this device is not only a simple telescope system but also a high-quality aberrations-corrected system that requires for a certain field of view.

As a kind of general of test equipment of the navigation, it is required for the star simulator to be easier to be fixed, debugged and transformed during the process of the design. This device is desired to have the advantages of miniaturization and lightweight.

As a high precise ground calibration equipment of star sensor, the optical system of the star simulator is first required to guarantee high position precision of the star points. In addition, the exit pupil of the star simulator should overlap with the entrance pupil of the star sensor, in order to ensure no waste of the total light flux. According to the technical indicators, the wave band of this system covers the whole visible light band, namely 400 nm~800 nm, and the system aperture is 92 mm, which leads to the heavy effect on the imaging quality caused by the distortion, curvature field and color difference. Therefore, the consideration of eliminating distortion, curvature field and color difference should be taken seriously in the system design.

The focal length of the optical system can be calculated by equation (1).

$$f' = \frac{L}{2\tan\frac{q}{2}} \quad (1)$$

Where f' ——Focal length of optical system

L—The size of the star point, 10 μm

θ—Effective field of view of the parallel light tube, 0.001°

According to the equation, the effective focal length of the parallel light tube system can be obtained, which is 550 mm and the optical system is shown in Figure 2.

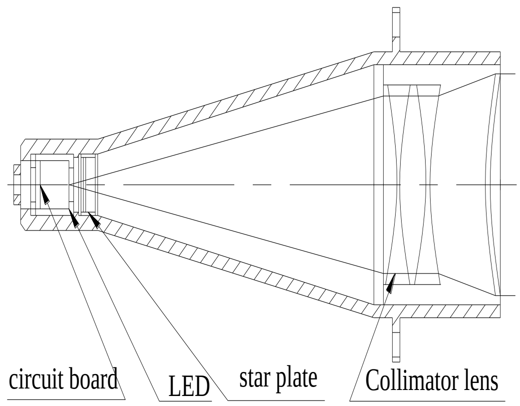

Figure 2. Structure of the Optical System

2.3. Modeling and Optimization of Optical System

In order to fully verify the imaging quality of the optical system presented in this paper, the modulation transfer function curves of the optical system and spot diagram are shown in Figure 3 and Figure 4.

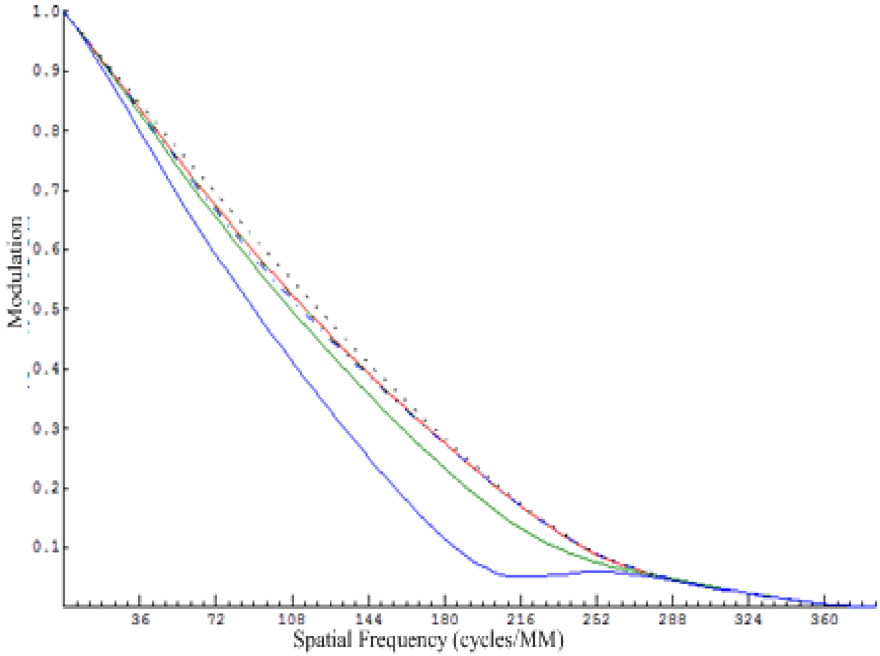

Figure 3. MTF of the Optical System

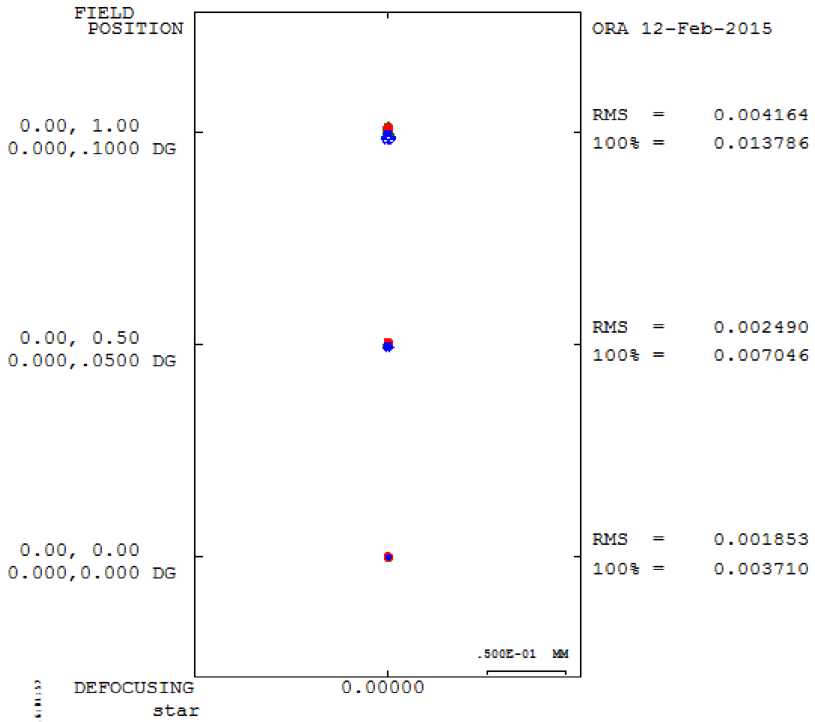

Figure 4. Spot Diagram of the Optical System

As shown in Figures 3 and 4, we can find that the transfer function of the optical system is close to the diffraction limit and the transfer function of optical system can reach as high as 0.9 at 25l p and 0.8 at 50l p. The RMS value of the image spot diagram formed by light sources under different field of view after the optical system is below 0.005, obtained good imaging quality and thus the structure design is reasonable.

3. Design and Test Results of the Simulator

The star simulator is used for simulating the fixed star infinity against the sky background. Except for the collimation of the light effused from the parallel pipe, the spectral rang and the apparent magnitude should all be considered, which is decided by the light source.

Considering the strength of high brightness and longevity of the high-powered LED, the LED is applied as the light source of the star simulator. Besides, the LED light source has the advantages of high drive current and good stability of light spectrum.

3.1. Spectral Modulation of LED Light Source

The relationship between different apparent magnitude is shown in equation (2).

$$m = -\sqrt[5]{100}\log_{E_0} E \tag{2}$$

Where E—The illumination of the star

E_0—The illumination of the 0 apparent magnitude

M—The apparent magnitude

The difference of illumination between two adjacent integral apparent magnitudes is 2.15 times.

Except for the requirement of luminous intensity from apparent magnitude 0 to 7, it is important for the light source to have a wide spectral range, because the spectral range and the center wavelength are different for different type of fixed star, as shown in Table 1.

Table 1. Navigation Stellar Spectra

Spectral type of stars	Spectrum (μm)	Center wavelength (μm)
A_2~A_9	0.30~0.40	0.35
F_0~F_9	0.35~0.60	0.45
G_0~G_9	0.48~0.68	0.56
K_2~K_9	0.56~0.82	0.64
M_0~M_8	0.71~1.10	0.85

According to the Hertzsprung-Russel diagram shown in Figure 5, the spectral types of stars have a certain relationship with the luminosity. When the luminosity of the main sequence star is 0^m~7^m apparent magnitude, the spectral type is F, G, K, covering the whole spectral band of visible light. As a result, the spectral range of the LED light source used in this system is the whole visible light.

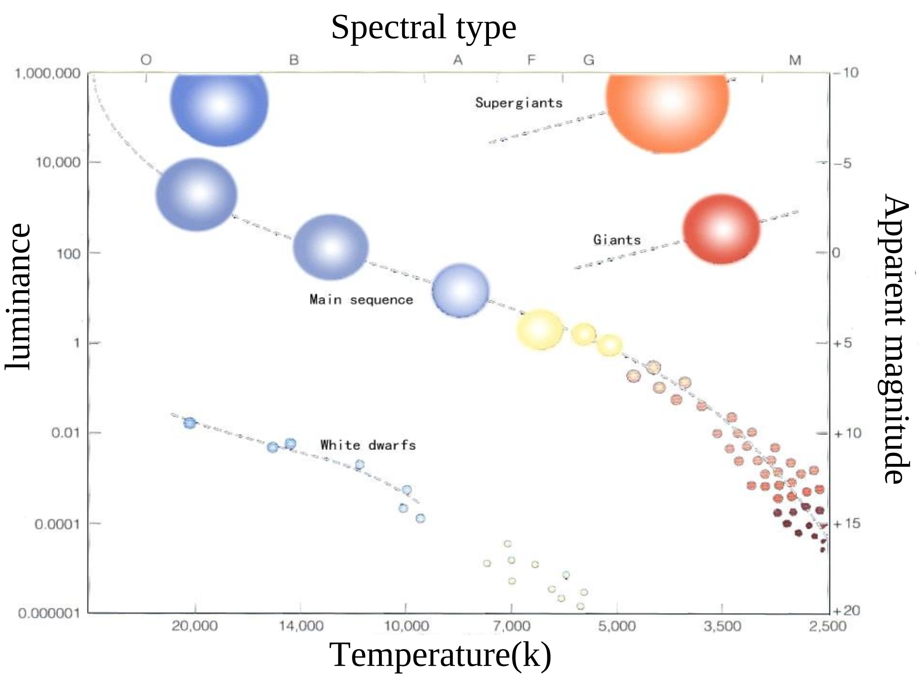

Figure 5. Hertzsprung-Russel Diagram

3.2. Calculation of the Luminous flux of LED Light Source

In order to meet the requirement of the apparent magnitude changing range of the star simulator, the maximum luminous flux that the light source required needs to be known. Due to the absorption and reflection of the light source, certain loss will be caused when the light goes through the optical system. The transmission efficiency of the optical system is assumed to be η. And when the apparent magnitude of output light is m, the equation of the luminous flux of the star point is;

$$\Phi_1^{(m)} = \frac{E^m A_1}{\eta_1} \tag{3}$$

Where E^m—Output of the parallel light tube

m—The output of the illumination of m apparent magnitude

A_1—Area of exit pupil of the parallel light tube

In addition, because of a certain distance R between the LED light source and the star point hole, there exists an unavoidable loss of the radiation flux of the LED light source that cannot be fully used. When output apparent magnitude is m, equation of luminous flux of the LED light source is

$$\Phi_2^{(m)} = \frac{\Phi_1^{(m)} \times A_3}{A_2} \tag{4}$$

Where A_3—The whole irradiated surface of the LED, $A_3 = \frac{2\pi R^2}{1 - \cos\frac{\theta}{2}}$

θ—Irradiation space cone angle of the LED

From (3) and (4), we can get equation (5)

$$\Phi_2^{(m)} = \frac{E^{(m)} \times A_1 A_3}{\eta_1 A_2} \quad (5)$$

According to the requirement of the technical indicator, the system design of the collimator aperture diameter of the parallel light pipe φ is 50 mm and the diameter of the star point hole is 50 μm. The vertical distance R between the LED light source and the star point hole is 2 mm. And when the output apparent magnitude is 2, the maximum luminous flux needed by the LED light source is 13 lm.

Based on the analysis above, the system selects the XLamp@XP-E LED produced by CREE company as light source whose spectral range is 400 nm~800 nm, covering the whole visible spectrum. The maximum luminous flux is up to 100 lm. Its typical color temperature is 3700 K~5000 K. The LED has met the requirements of the spectrum range and large dynamic range of the apparent magnitude designed in the system.

3.3. Control of the Light Source

The CPU named STM32F103UET6-LQFP100 of the core controller of the star simulator can generate ten paths of PWM signal. The LED of the system is driven by PT4115 and the control of the apparent magnitude from 0 to 7 is realized by adapting PWM control technology. The LED light source and the drive circuit are installed in the closed light chamber of the parallel light pipe, communicating with the controller in a very long distance. In order to ensure the collection accuracy of the signal, the PWM signal has been differentially transformed before conveyed. And at the receiving terminal, the differential signal is returned to the original form of PWM signal. Meanwhile, the apparent magnitude controller of the star simulator possesses the communication interface and the upper computer control system for the convenience of application. The principle structure of the apparent magnitude controller of the star simulator is shown in Figure 6.

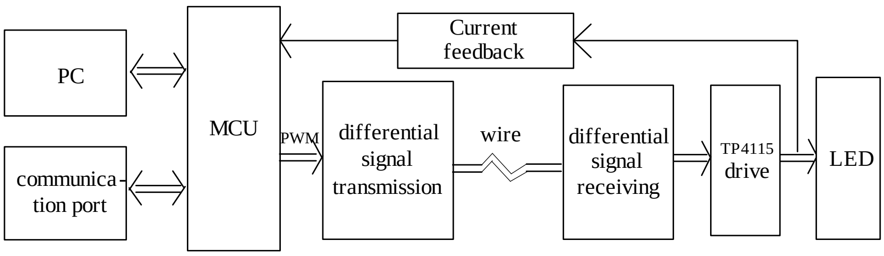

Figure 6. Structure of the Light Source for Star Simulator

As shown in Figure 6, in the working process, the upper computer conveys the commands to the controller via serial port, and the controller will guide the working cell via the wire cable to perform the relevant requirements from the upper computer after receiving the commands. To guarantee the accuracy of the control commands, a multi-bit data transmission is adopted and the command format is in sequence of the start bit, the equipment code, the channel address, the data and the check bit.

Due to the diode volt-ampere characteristics of the LED light source, voltage and current of the LED are supposed to be controlled under stable voltage with the method of constant-current control in every star point. PWM dimming method is used in this system to maintain the stability of the color temperature of the LED. The luminance can be changed by adjusting the pulse width, which largely improves the control accuracy. In the working process, the LED is controlled by different duty cycle PWM signal generated by the single chip connected with the upper computer. The signal is output after it goes through the power drive conversion. In order to promote the accuracy of the output current, close loop control system is formed, and the core controller that generates the PWM signal is a 16-bit system. The digital subdivision of PWM signal is 2^{16}, which is 65536 numbers of the signal pulse when the duty cycle is 100%, making the illumination ratio of the LED achieve more than 155:1 and finally realizing fine adjustment. Experiments show that the control accuracy of the PWM control system reach ±0.1%, which has lived up to the accuracy requirements $\pm 0.1^m$ of the $0^m \sim 7^m$ apparent magnitude dynamics and star simulator. The material object of the whole system is shown in Figure 7.

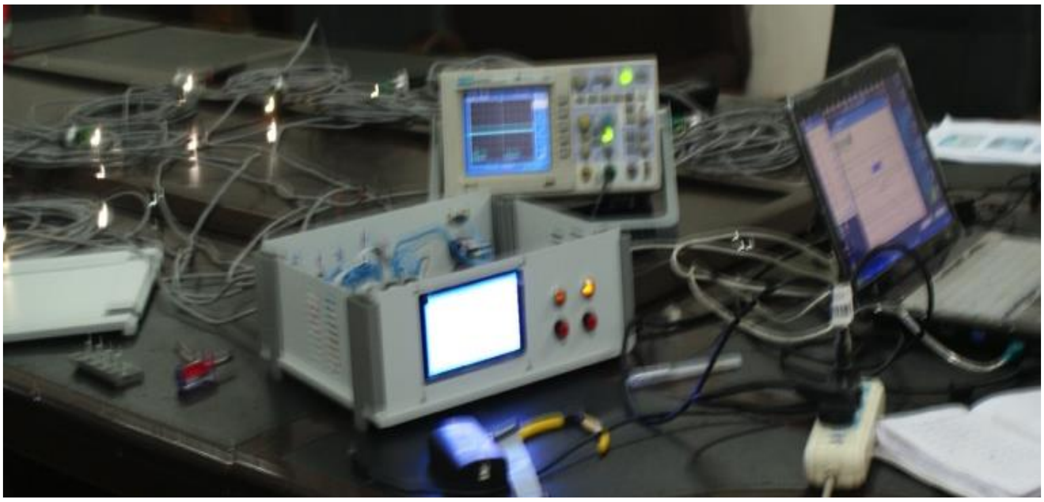

Figure 7. Material Object of Star Simulator

3.4. Determination of Size and Position of the Star Point Hole

The size of the star point hole determines the size of the picture point of the simulated star images on the image surface of the navigation device. The small star point hole would benefit for the simulation of the radiation angle to the earth from the simulated fixed star, but its disadvantage is the high requirements of processing technology and system energy. While, considering that the star simulator is used for the dynamic test to the aircraft, the stable testing condition requires that the size of the image of star point on the CCD target surface should be larger than 2×2 pixels. Hence, it is unseasonable for the star point hole being too small. Considering all these practical affecting factors, the size of the star point hole is set to be 1 mm.

The position of the star point hole determines the collimation of the beam emitted by adjusting the position of the LED and user in the distance.

3.5. Test Results of Star Simulator

In order to verify the star simulator, this paper selects to test it in the dark room and a μ2000 light level illumination meter is adopted. When the star simulator works, the luminance meter is placed in the outlet of the parallel light pipe to detect the illumination of the LED light source. And furthermore, the number of PWM signal pulse needed under different apparent magnitudes has been correspondingly counted. As depicted in Table 2, the relationship curve of the simulated apparent magnitudes and the pulse number is shown in Figure 8.

Table 2. Number of PWM Pulse and the Corresponding Illuminance and Apparent Magnitude

Test point	1	2	3	4	5	6	7
Experimental value of PWM	26108	10394	4139	1644	657	263	103
Theoretical value of PWM	26088	10385	4134	1645	655	260	103
Intensity of illumination ($\times 10^{-3}$ lux)	1011	403	160	64	25	10.1	—
Magnitude (m)	1^m	2^m	3^m	4^m	5^m	6^m	7^m

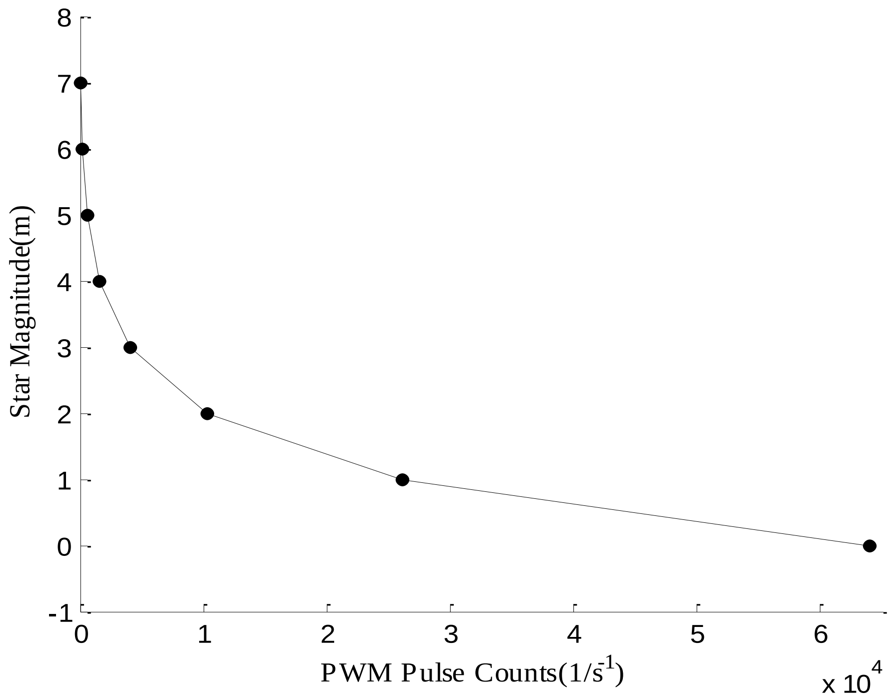

Figure 8. Relation of Simulated Apparent Magnitudes and PWM Pulse Counters

Because the illuminometer can only detect the light of 10^{-8} lux, which just equals to illumination of the 6^m apparent magnitude, the measurement method of illumination comparison has been adopted for the detection of the 7^m apparent magnitude. First, the LED illumination and PWM pulse number of 0^m to 6^m are measured respectively by 0^m~6^m. The PWM pulse number needed by the 7^m apparent magnitude can be simulated by multiplying 2.512 to decay the PWM number.

Analyzing the test results from the test above, the authors can obtain that simulated apparent magnitudes and distribution of the PWM pulse signal accord with 2.512 time relationship. The relationship of the apparent magnitude illumination and the pulse duty cycle is linear. When the star point hole is less than 1 mm, the result can reach 2.63 lx~2650 lx, maintaining well the accuracy less than ±0.1% and ensuring the stability of the system.

4. Conclusion

This paper has developed a high precision and multiple outputs digital star simulator. Detail design process of the optical system is described at length. The light source and the control system are analyzed as well. And finally, the test is performed in dark condition. The result shows that the system design of the high precision simulator is reasonable and satisfies all requirements of design and usage with compact structure and simple control. Meanwhile, the simulated range of the apparent magnitude is up to 0^m to 7^m , the spectral range is 400 nm~800 nm and the control accuracy is up to $\pm 0.1^m$. The star simulator designed in this paper not only can solve the test and calibration problems of the star sensor but also greatly meets the calibration and correction requirements of the aerospace detection system, making the star simulator more practically valuable.

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