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RESEARCH ARTICLE

Analysis of flash lamp structure using Monte Carlo photon tracing method

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Abstract By analyzing the flash lamp structure, better illumination distributions in the lamp's field of view can be obtained. Instead of geometrical optical approaches, the Monte Carlo photon tracing method was used here to trace the photon tracks in a three-dimensional space. The models of elemental structures in a camera flash lamp, such as the flash tube, reflector and focus lens, were set up by introducing the cosinusoidal random number and other mathematical methods. Initially, the single photon was traced in the flash lamp by using the Monte Carlo method to simulate various photon tracks. A large sum of photons was then generated to simulate the real situation in the flash lamp. Finally, a group of structural parameters was applied to verify the simulative computer program. The output light intensity distributions at different angles of view in the orthogonal directions meet the ISO standards and are very close to the measured ones. Hence, the Monte Carlo photon tracing method in the design of flash lamps has been proven to be applicable and useful.

Keywords luminescence, photon tracing, Monte Carlo method, flash lamp, model

1 Introduction

Multifocal flash lamps are generally used in middle- and high-end cameras. The multifocal characteristic is realized by moving the focus lens in the flash lamp to change the distance between the flash tube and the lamp. As a result, different illuminating angles, and hence different illuminating areas in the object plane, can be achieved to satisfy different photographic requirements. According to the ISO 2827/1230 standards, the effective illuminating angles of a flash lamp are defined as the half angles between the center line and the margin lines, the luminous intensities of which are half of the central one. The angles are measured in orthogonal directions. Effective illuminating angles should be larger than the angles from the view of the camera lens. Generally, there are four illuminating angles—Tele, Std, Wide1, and Wide2—which correspond to four focuses: 85, 50, 35, and 28 mm [1].

The radiated output energy is determined by the circuit system of the flash lamp, and the spatial distribution of the energy is defined by the optical system. Currently, hardly any research reports about designing flash lamps are available. The authors' laboratory, however, has studied this issue for a long time with great effort. We proposed the dimension reduction method, which studies the luminous intensities in the two orthogonal two-dimensional spaces, instead of the real three-dimensional space, to simplify the analysis. Results obtained by this method fit with actual situations well [1–3]. But there exists some limitations in that method, which would affect the results. Reference [1] used the dimensionality reduction method, simulated the projected rays, and calculated the effective illuminating angles in two orthogonal two-dimensional planes. However, it cannot be applied to complex and unsymmetrical structures. Reference [2] used the ray tracing method in the real three-dimensional space, but the light source model was incorrect. The radiated energy distribution of the light source was also different from the distribution of a real flash tube, and the attenuation of rays when they pass through the flash tube was not considered.

As the rays emitted from the flash lamp are incoherent, the Monte Carlo simulation method, which has been used in various areas [4,5], can be applied in the analysis of the flash lamp structure. This method treats the rays as photons. By tracing the tracks of the photons, the method can calculate the radiated energy distribution without the limitations in the above references, and the results are very close to the real situation. It has been used in the simulation and design of the LEDs [6–10], the lasers [11–13], the structure of new materials [14–16], and so on.

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2 Analysis of flash lamp structure

The schematics of a typical camera flash lamp structure are shown in Fig. 1. To comprehend the geometrical structure of the reflectors, two orthogonal sectional views, which are defined in the *x*-*z* (horizontal) and *y*-*z* (vertical) planes, are plotted in Figs. 1(b) and 1(c). The width of the exit plane of the reflector is D_1 in the *x*-*z* plane and D_2 in the *y*-*z* plane. The width of the bottom of the reflector is D_3, the height of the reflector is h_2, and the inclined angle of the two side planes is α. The length of the flash tube is L, the diameter of this tube is r_1, and the distance between the central axis of the tube and the bottom of the reflector is h_1. The distance between the Fresnel lens and the reflector is Δ.

The flash tube in the bottom of the flash lamp is generally a straight long xenon pipe injected with xenon. The pressure in the tube is lower than standard atmospheric pressure. That xenon flash tube can produce a high intensity light of very short duration. When the electrodes of the flash tube are added with voltage higher than the breakdown voltage, the xenon atoms will be ionized, and then discharged with light [17]. Every xenon atom can be regarded as a point light source; hence the flash tube can be treated as a cylindrical combination of point light sources. From the above assumption, it can be shown that

$$y^2+(z-h_1)^2=r_1{}^2 \quad (|x|\leqslant L/2). \tag{1}$$

The conical surface of the reflector is a paraboloid mirror in most real situations. The two inclined surfaces are plane silver-gilt aluminous mirrors with a reflection factor ρ larger than 90%.

From Figs. 1(b) and 1(c), the analytical expression of the conical surface can be written as

$$y^2=2pz \quad (0\leqslant z\leqslant h_2, \quad z\tan\alpha-(x-(D_3/2))>0, \quad z\tan\alpha+(x+(D_3/2))>0). \tag{2}$$

The analytical expressions of the two inclined surfaces can be written as

$$z\tan\alpha+(x+(D_3/2))=0 \quad \left(0\leqslant z\leqslant h_2,\ y^2<2pz\right), \tag{3}$$

$$z\tan\alpha-(x-(D_3/2))=0 \quad \left(0\leqslant z\leqslant h_2,\ y^2<2pz\right). \tag{4}$$

The above three formulas can be used to determine whether a given photon has hit one of the three surfaces.

A focus lens is a kind of circular symmetrical Fresnel lens, which is shown in Fig. 2. One surface of the Fresnel lens, which is serrated, consists of concentric spherical rings, while the opposite surface is plane. The weight and volume of this lens are both reduced by keeping the curvature of the planoconvex lens but wiping off the unwanted intermediary materials.

Theoretically, the focal length of the Fresnel lens can be changed to an arbitrary value along the axial direction. But considering the processing techniques, the Fresnel lens is usually designed to have two or three regions, each with a specified focal length. The focal length of the planoconvex lens f is related to the radius r_2 and the refractive index n of the spherical surface:

$$f=r_2/(n-1). \tag{5}$$

Thus, for a desired focal length, the radius of the spherical arcs in the sawtooth in one region of the Fresnel lens can be determined by the above formula.

If the thickness of the Fresnel lens is negligible, the Fresnel lens plane can be expressed as

$$z=h_2+\Delta \quad (|x|\leqslant D_1/2, \quad y\leqslant D_2/2). \tag{6}$$

Meanwhile, the exit plane of the reflector can be written similarly as

$$z=h_2 \quad (|x|\leqslant D_1/2, \quad y\leqslant D_2/2). \tag{7}$$

The shell of the flash lamp is generally black engineering plastic. The photons will be totally absorbed in that area, hence one can regard it as the black area of photons. Those photons penetrate the exit plane of the reflector but do not pass through the Fresnel lens plane.

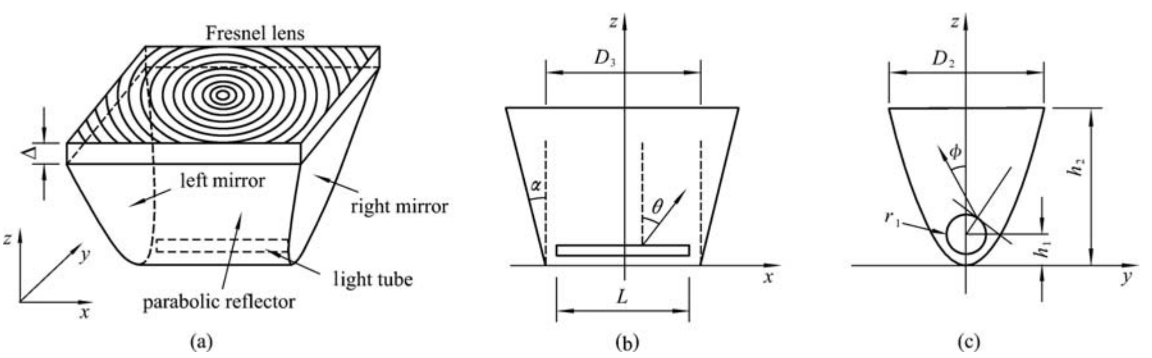

Fig. 1 Schematics of a typical flash lamp structure. (a) Perspective; (b) *x*-*z* sectional view; (c) *y*-*z* sectional view

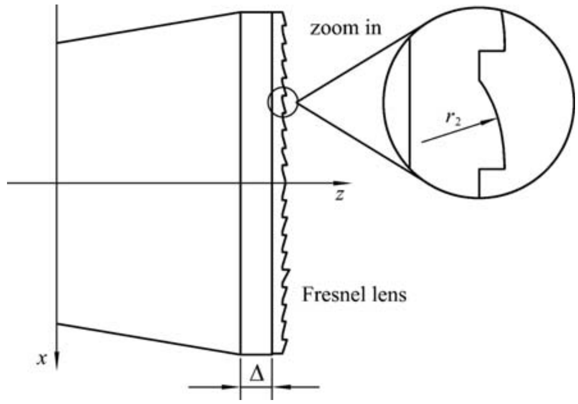

Fig. 2 Structure of a Fresnel lens

3 Implementation of Monte Carlo photon tracing method

The basic step in the Monte Carlo photon tracing method is to trace the tracks of a single photon. The states and tracks of a single photon should be determined by random numbers when it hits the boundary surfaces. Secondly, a large sum of photons will be generated to simulate the real situation. Generally speaking, the more photons used in the simulation, the more reliable the results obtained. But when the photon number is already large enough, increasing the photons will not affect the reliability of the results. Hence, there is no need to pursue an infinite number of photons, and the results in this paper are simulated by 1×10^6 photons.

First, let's introduce the photon state parameter I_{live}: when it is 1, the photon lives; and when it is 0, the photon dies. The initial state is defined as $I_{\text{live}} = 1$.

When the photon is generated in the flash tube at the bottom of the flash lamp, the possible position can be determined by Figs. 1(b) and 1(c). When the electrodes of the flash tube are added with voltage higher than the breakdown voltage, all of the xenon atoms will be ionized gradually within a very short time period (τ). After that time, the ionized xenon atoms, i.e., the point light, will fill the flash lamp uniformly. Although the distribution of the ionized xenon atoms at a special moment in that time (τ) cannot be determined, they are of no concern because the radiated energy distribution of the flash lamp, which is our focus, is the integrated results in the flash duration. τ is negligible as it is much shorter than the flash duration. Thus, the flash tube can be considered as a cylindrical light source in the simulation [1,3], and it is a uniform line light source in the x-z plane and a circular light source in the y-z plane. The photons are always generated on the cylindrical tube surface, and the initial points of the photons are simulated by the uniform random number.

The initial positional vector and directional vector in the Cartesian coordinate can be written as

$$\boldsymbol{R}_0 = \boldsymbol{x}x_0 + \boldsymbol{y}y_0 + \boldsymbol{z}z_0, \tag{8}$$

$$\boldsymbol{V} = \boldsymbol{x}\sin\theta\cos\phi + \boldsymbol{y}\sin\theta\sin\phi + \boldsymbol{z}\cos\theta. \tag{9}$$

$\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$ are unit directional vectors, x_0, y_0 and z_0 are scalar values of initial position, θ is the angle related to the azimuth, and ϕ is the angle related to the elevation. If the angle θ in the x-z plane is projected, it will produce a projected angle θ_x. Correspondingly, the projection will produce a projected angle θ_y in the y-z plane. As the line light source can be regarded as a cosinusoidal radiator, θ_x obeys the cosinusoidal distribution in the interval $[-\pi/2, \pi/2]$, and θ_y is the sum of a cosinusoidal random angle and the angle of the normal line vector [18].

After determining the state parameter I_{live}, the positional vector $\boldsymbol{R}_0$ and directional vector $\boldsymbol{V}$ of a generated photon, the tracks of the photon can be traced in the flash lamp. Any new position in the tracks of the photon can be expressed as

$$\boldsymbol{R} = \boldsymbol{V}t + \boldsymbol{R}_0 \quad (t \geqslant 0). \tag{10}$$

$\boldsymbol{R} = (r_x, r_y, r_z)$ is the new position of the photon, and $\boldsymbol{R}_0 = (r_{x0}, r_{y0}, r_{z0})$ is the start position. $\boldsymbol{V} = (v_x, v_y, v_z)$ is the directional vector, $\|\boldsymbol{V}\| = 1$, and t is a time parameter which is always positive. When the photon hits the boundary surfaces, such as the flash tube, the reflector, the Fresnel lens, and the dark area, it will be reflected, refracted or absorbed. For each hit, the state of the photon should be determined first: if $I_{\text{live}} = 0$, the photon dies. On the contrary, the new start positional vector and new directional vector should be calculated by Eq. (10), and the photon starts its new journey until it dies or emits the flash lamp.

There are two situations that should be considered to determine the parameter of I_{live}. If the photon penetrates the flash tube in the nth track at the length of travel l_n, the attenuation ($A_n = \exp(-a_n l_n)$) should be calculated, and a uniform distributed random number at interval [0, 1] will be generated and compared with the A_n. If the photon hits the reflector with the reflective index of which, ρ is in the nth track, a random number should be generated by the same method to compare with ρ. The results will determine the photon state parameter I_{live}:

$$I_{\text{live}} = \begin{cases} 1 & (\text{If } R_{\text{rand}} \leqslant [A_n, \rho], \text{ photon alive}), \\ 0 & (\text{If } R_{\text{rand}} > [A_n, \rho], \text{ photon absorbed}). \end{cases} \tag{11}$$

For simplicity, the above two formulas combine two different conditions, and the brackets are indicated by taking one condition at a time. If the photon penetrates the light tube, the attenuation A_n is taken; if the photon reflects in the boundary surface, the reflective index ρ is taken. By using Eqs. (2)–(4) in Sect. 2, one can determine which surface is hit by the photon and calculate the new positional vector $\boldsymbol{R}$ if the photon is not absorbed. Meanwhile, based on Eq. (10), the catadioptric model can be derived, and hence the new directional vector can be determined:

$$\begin{aligned} \boldsymbol{A}' &= \boldsymbol{A} + p\boldsymbol{N}, \\ p &= \sqrt{n'^2 - n^2 + (\boldsymbol{N}\cdot\boldsymbol{A})^2} - \boldsymbol{N}\cdot\boldsymbol{A}, \end{aligned} \tag{12}$$

$$\boldsymbol{A}'' = \boldsymbol{A} - 2\boldsymbol{N}(\boldsymbol{N}\cdot\boldsymbol{A}). \tag{13}$$

$\boldsymbol{A}$, $\boldsymbol{A}'$ and $\boldsymbol{A}''$ represent the incident directional vector with length n, the refractive directional vector with length n' and the reflective directional vector with length n'', respectively; $\boldsymbol{N}$ is the unit vector along the normal line direction from the incident medium to the refractive medium. If the photon is reflected at the boundary surface, the new directional vector will be determined by Eq. (12). If the photon is refracted at the boundary surface, the new directional vector will be determined by Eq. (13).

The flow chart of Monte Carlo simulation is illustrated in Fig. 3. The first step in a real simulation should be determining whether the photon penetrates the flash tube or not. If yes, then the state parameter I_{live} is calculated. If $I_{\text{live}} = 0$, the photon dies, the loop is ended, and a new photon will be generated. If $I_{\text{live}} = 1$, the new positional vector and directional vector should be calculated. If the photon does not penetrate the flash tube or still lives after the penetration, one should determine whether the photon hit the Fresnel lens or not. If yes, then the directional vector of the emitted photon is calculated after two refractions in the Fresnel lens, the illuminating angles in the two orthogonal planes can be calculated, the loop is ended and a new photon will be generated. If the photon does not hit the Fresnel lens, we should consider the next set of conditions, which includes the photon hitting the black area and the reflector. If the photon hits the above surfaces, then the state parameter I_{live} is calculated. If $I_{\text{live}} = 1$, the new start positional vector and directional vector should be calculated, and the loop should continue until the photon dies or emits the flash lamp. If $I_{\text{live}} = 0$, the photon is absorbed, the loop is ended, and a new photon should be generated.

The authors' lab has designed a flash lamp for a Singaporean company, whose initial parameters are $D_1 = 36.5$ mm, $D_2 = 23.0$ mm, $L = 26$ mm, $\alpha = 20^\circ$, $\rho = 0.95$, $\Delta_{\text{Tele}} = 21$ mm, $\Delta_{\text{Std}} = 14$ mm, $\Delta_{\text{Wide1}} = 8$ mm, $\Delta_{\text{Wide2}} = 4$ mm. The Fresnel lens has three regions, and each has a different focal length as listed below

$$f = \begin{cases} 70\ \text{mm} & (D \leqslant 20\ \text{mm}), \\ 90\ \text{mm} & (20\ \text{mm} < D \leqslant 24\ \text{mm}), \\ 110\ \text{mm} & (D > 24\ \text{mm}). \end{cases}$$

The above data is input in the simulation, and the projected angle distributions of the emitted directional vectors of the photons in the two orthogonal planes, the x-z and y-z planes, at the level of Wide2 will be obtained. The standard at that level requires the illuminating half angles arriving at 32° at the horizontal plane and at 23° at the vertical plane. The distributions in the orthogonal directions, which are shown in Fig. 4, agree with the design requirements as well as the measured data very well.

4 Conclusions

The Monte Carlo simulation method is a versatile tool applied in many scientific and technological areas. It is able to trace the photon tracks in the flash lamp with higher accuracy and is more quantitive than other methods. By introducing a cosinusoidal random number, the flash tube model is set up. The analysis of the two surfaces

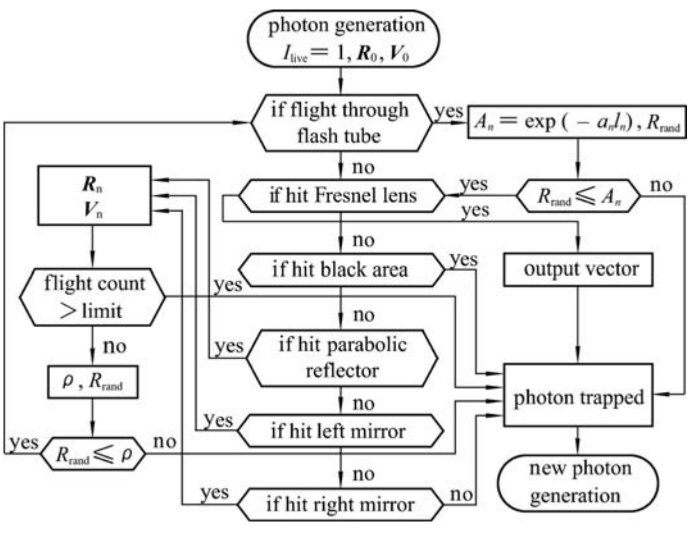

Fig. 3 Flow chart of Monte Carlo simulation for a single photon

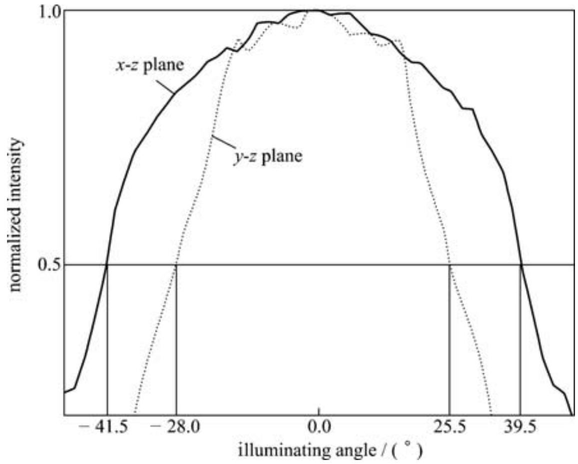

Fig. 4 Illuminant angles in orthogonal planes at standard of Wide2

of the Fresnel lens and the model of the photon penetrating through the Fresnel lens with two refractions are also set up. The final computer program traces the tracks of a large sum of photons in the flash lamp and derives the distribution of the projected illuminating angles in orthogonal directions. The simulation above can be used to design the flash lamp reflector by varying structural parameters to obtain various distributions of illuminating half angles.

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