Rapid modeling method of LED free-form surface lens based on Scheme language

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Abstract: Multiple softwares were required in the traditional design process of LED free-form surface lens. It is obvious that this process is complicated and inefficient. Moreover, when the model was transferred from 3D modeling software to optical simulation software, the file format had to be changed to solve the problem of the software compatibility. Note that some subtle changes were inevitably introduced to the model by such an operation, such as the generation of cracks or tiny deformation which would seriously affect the light efficiency and the degree of illumination uniformity. A new design method was presented in this paper which was used to directly generate model in the optical simulation software by using Scheme language. In this paper, the method of mesh division was applied to design the LED free-form surface lens with rectangular lighting. After the corresponding surface configuration was obtained, 3D modeling software and the Scheme language programming were used to generate lens model respectively. With the help of optical simulation software, a light source with the size of 1 mm in diameter was used in experiment, in which total one million rays were computed. The simulated results could be acquired by both models. It can be seen that the model deformation problems caused by the process of the model transfer could be prevented by using Scheme language, and the degree of illumination uniformity was also increased from 67% to 93.5%. Meanwhile, only 5 seconds were needed in modeling process by Scheme language which was more efficient than 3D modeling software.

Key words: Scheme language; LED road lighting; rapid modeling; free-form surface; secondary optics
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Scheme 语言的 LED 自由曲面透镜快速建模方法

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摘　要: 传统的自由曲面透镜建模通常需要多个软件共同协作完成,其建模过程繁琐,且由于不同软件之间的不兼容会导致模型在导入光学仿真软件时出现微小形变。提出一种在光学仿真软件中利用

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Scheme 语言直接进行快速建模的 LED 自由曲面透镜建模方法。根据光源辐射特性和需要实现的照明面上的能量分布，采用划分网格法，利用 Snell 方程和能量守恒定律，沿经纬方向分别迭代求解，在得到自由曲面各节点坐标后，分别采用 3D 建模软件和 Scheme 语言编程构建透镜模型。通过光学仿真软件，模拟计算了 100 万条光线，直径 1mm 的光源在距离地面 10 m、面积为 40 m×10 m 的照明区域内的照度分布。结果表明：利用 Scheme 语言在光学仿真软件中直接快速建模避免了模型从 3D 软件导入光学仿真软件时产生的微小形变从而使光照均匀度由 67%提升到 93.5%。同时 Scheme 语言编程建模仅需 5 s，建模速度远高于 3D 建模软件。

关键词：Scheme 语言； LED 道路照明； 快速建模； 自由曲面透镜； 二次光学设计

0 Introduction

As a new type of solid light sources, light emitting diodes (LEDs) have many advantages comparing with the traditional light sources for road lighting, such as stable performance, energy saving, long work life, smaller size and safety[1]. Because the radiation pattern of LED is very similar to a point light source, which means that the direct output of an LED is normally a circle spot while the desired illumination in projector is always a rectangular form, a large energy loss and a poor longitudinal luminance uniformity which is described as a "zebra effect" will be introduced[2].

The secondary optical design belongs to the category of nonimaging optics design, which is different from the traditional imaging optical design. The nonimaging optics design is aimed at achieving maximize light energy utilization and obtaining the most reasonable distribution of light intensity[6].

The basic types of optical element designed on the basis of nonimaging optics theory mainly are reflective, refractive and catadioptric. The surface type includes spherical, aspherical and free-form surface. Among them, the free-form surface component is considered as the best one to obtain the desired illumination due to its good degree of freedom, small volume and accurate light control characteristic. There are two main methods of free-form lens design. One method is the trial and error method[7-8], which is time-consuming since it is essential for the designers to modify the parameters interactively until a satisfactory pattern is obtained. The other method is numerical solution [9-10], which includes the simultaneous multiple surface method, the Monge-ampere equation method and the Non-imaging tailoring method. These methods have lots of limitations, not only on the limit of forming the desired illumination, but also on the time consuming in the calculation. In this paper, the method of mesh division is used to set up the equation of LED free-form surface lens with rectangular lighting. On the premise of that the radiation characteristics of LED source and the required illumination distribution on the target surface are known, one can get the surface data of free-form surface by dividing the energy grid based on the edged-ray theory.

The traditional design process is given as follows. At first, we set up the surface equation to calculate surface data. Then, the obtained data is imported into a 3D modeling software for solid modeling. Finally, with the help of optical simulation software, we could analyze the model for obtaining the output light distribution. It is obvious that the above process is complicated and inefficient. Moreover, when the model is transferred from 3D modeling software to optical simulation software, one usually has to change the file format to solve the problem of the software compatibility. Note that such an operation would inevitably introduce some subtle changes to the model, such as the generation of cracks or tiny deformation which would seriously affect the light efficiency and the degree of illumination uniformity. To solve the above problems, we propose a new design method which could directly generate model in the optical simulation software by using Scheme language while the free-form surface data is calculated. Scheme is a functional programming language and one of the two main dialects of the programming language Lisp.

Unlike Common Lisp, the other main dialect, Scheme follows a minimalist design philosophy specifying a small standard core with powerful tools for language extension. Scheme is a very simple language, and is much easier to implement than any other languages of comparable expressive power. This ease is attributable to the use of lambda calculus to derive much of the syntax of the language from more primitive forms[11].

1 Design idea of LED free-form lens

In our research, the energy loss is assumed to be ignored. According to the law of energy conservation, the output power of the source is equal to the flux incident in the target plane. The light source and the energy intensity of target plane are divided into several small squares. Then, one of the output rays from the light source is selected as the initial line of free-form surface lens. By combining the energy division results of light source with that of target plane, we use the method of iteration solution to acquire all the coordinates and normal vectors of discrete points of lens surface.

1.1 Design method

To simplify the design, the incidence plane of free-form lens is assumed to be a half spherical surface and the LED can be seen as a point source. The LED is put in the center of hemisphere so that the rays′ direction would not change after passing through the incidence plane[12]. The outside surface of lens is free-form surface, which is also the output surface of rays.

The LED spatial coordinate is shown in Fig.1. In the theoretical model, the center of LED source is assumed to be located at the origin of an orthogonal coordinate system. As shown in Fig.1, φ is the angle between the ray and the y axis, θ is the angle between the z axis and the plane determined by the ray and the y axis. Meanwhile, the intensity distribution of the LED source is:

$$I=I_0\cos\theta\sin\varphi \quad (1)$$

Where I_0 is the luminous intensity in the z axis; I is luminous intensity of the ray i.

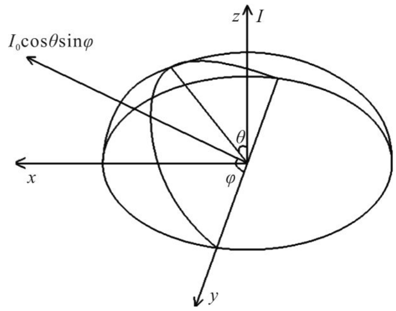

Fig.1 LED spatial coordinate

The target lighting area is rectangle, whose length and width are a and b, respectively. The distance between the target lighting area and the LED light source is h. A rectangular coordinate system can be established in target lighting surface, while the original point is located in the center of the rectangle, as shown in Fig.2[13]. The total luminous flux of LED is Φ, the average illuminance of target plane is constant EV ($EV=\Phi/(a*b)$), and the center light intensity is $I_0=\Phi/\pi$. The length a is divided into m copies at the length of k in the x axis, the length b is divided into n copies at the length of k in the y axis.

Then the array $x(m)$ and $y(n)$ are obtained. Thus the lighting area is composed of $m\times n$ square grids with the same area. Accordingly, after calculating the energy of each grid, we discretize the emergent light intensity. The angle θ is divided into m copies, and the angle φ is divided into n copies.

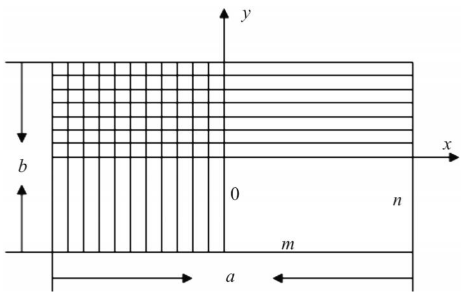

Fig.2 Target lighting area grid

In the x axis of target plane, the luminous energy of each square grid is:

$$E(\Delta x)=E_v \cdot k \cdot b \tag{2}$$

An initial ray i_{00} (θ_0,φ_0) is chosen from the light source, and its corresponding step length $\Delta\theta_1$ can be calculated as follows:

Within the scope of radiation $\Delta\theta_1$, the energy of LED, $E(\Delta\theta_1)$, is:

$$E(\Delta\theta_1)=\int_{\theta_0}^{\theta_1}\int_0^{\pi} I_0\cos\theta\sin^2\varphi \mathrm{d}\theta\,\mathrm{d}\varphi \tag{3}$$

According to the law of energy conservation [13], have:

$$\int_{\theta_0}^{\theta_1}\int_0^{\pi} I_0\cos\theta\sin^2\varphi \mathrm{d}\theta\,\mathrm{d}\varphi=E(\Delta x) \tag{4}$$

Then $\Delta\theta_1$ can be expressed as:

$$\Delta\theta_1=E(\Delta x)/\cos\theta_0\int_0^{\pi}\sin^2\varphi \mathrm{d}\varphi \tag{5}$$

$$\theta_1=\theta_0+\Delta\theta_1,\ x_1=x_0+\Delta x \tag{6}$$

From equations above, we can get $\Delta\theta_2$, $\Delta\theta_3$, $\Delta\theta_4$ $\cdots$ $\Delta\theta_m$, and θ_2, θ_3, θ_4 $\cdots$ θ_m. According to the law of energy conservation, can be acquire the following relations:

$$\int_{\theta_0}^{\theta_1}\int_{\varphi_0}^{\varphi_1} I_0\cos\theta\sin^2\varphi \mathrm{d}\theta\,\mathrm{d}\varphi=E_v k^2 \tag{7}$$

$$\Delta\varphi_1=E(\Delta x,\Delta y)/\left(I_0\int_{\theta_0}^{\theta_1}\cos\theta\sin^2\varphi_0\right) \tag{8}$$

$$\varphi_1=\varphi_0+\Delta\varphi_1,\ y_1+y_0+\Delta y \tag{9}$$

From Eqs.(7), (8) and (9), the values of $\Delta\varphi_1$, $\Delta\varphi_2$, $\Delta\varphi_3$ $\cdots$ $\Delta\varphi_n$, and φ_1, φ_2, φ_3 $\cdots$ φ_n are obtained.

1.2 Establishment of free-form surface model

First, a vertical curve on the surface of the lens can be determined. According to the corresponding relationship between light source and illumination plane, $\theta(\varphi_0)=f(x_{y0})$, an initial ray i_{00} (θ_0,φ_0) is chosen from the light source, which corresponds to an initial position P_{00} (x_0,y_0) in illumination plane. After choosing an initial point on the ray i_{00} as the starting point of the free-form surface, from Eq. (10), we can get the direction vector of the light emergent from point S_{00}:

$$O_{00}=P_{00}-S_{00} \tag{10}$$

Then, according to the Snell's Law [14], the normal vector N_{00} can be calculated.

$$[1+n^2-2n(O_{00}I_{00})]^{1/2}N_{00}=O-nI \tag{11}$$

According to the corresponding relationship between the light source and target illumination plane, the second emergent ray i_{10} (θ_1,φ_0) is chosen, which corresponds to a position P_{10} (x_1,y_0) in illumination plane. As the surface normal vector N_{00} of point S_{00} is known, we can get the tangent plane T_{00}. The point of intersection S_{10} can be gotten. By following the method mentioned above, we can obtain a series of discrete data points S_{00}, S_{10}, S_{20}, $\cdots$, S_{m0} and their corresponding normal vector N_{00}, N_{10}, N_{20}, $\cdots$, N_{m0}. Then a vertical curve on the surface of the lens can be determined. Similarly the other curves of free-form surface can be calculated, and the solution introduction is shown in Fig.3.

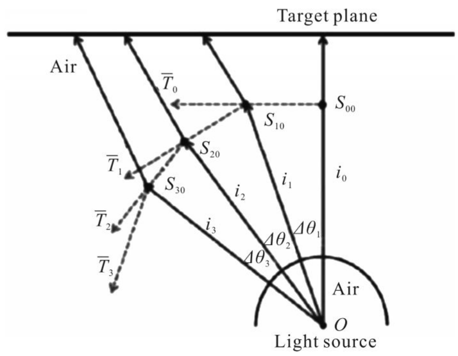

Fig.3 Solution introduction of a vertical curve on the free-form surface

The height of road lamp is set as 10 m, illumination target plane length is set as 40 m, and its width is set as 10 m. Since the free-form lens is symmetric about the x axis and y axis, we just need to calculate a quarter of the lens surface data.

2 Scheme language rapid modeling

Instead of importing the data into 3D modeling software for solid modeling and analyzing the model in optical simulation software for light tracing, this paper proposes an innovative method of directly generating model in the optical simulation software by using Scheme language while the free-form surface data is obtained. The lens horizontal contour line can be defined by define function, then the values of the coordinates of the lens horizontal contour line are listed in the list function [15]. Thus a complete contour line is defined. Many contour lines of the lens can be defined by using define function and list function. The more contour lines we get, the more smooth of the free-form lens surface is.

After the definition completed, a surface can be established after rotation and transformation the contour lines that we have already achieved. The entire modeling process time is about 5 seconds, the time used in programming is not included. The model established by Scheme language is shown in Fig.4.

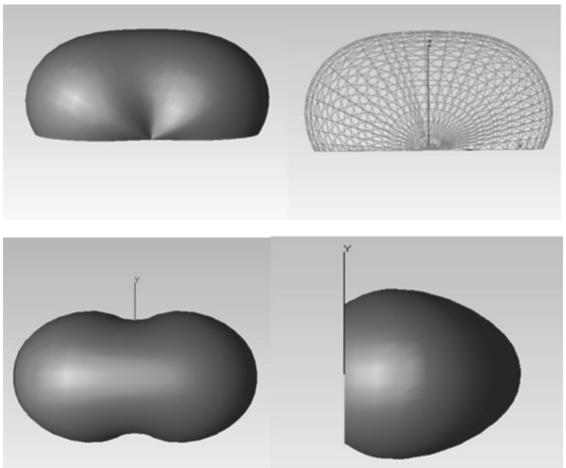

Fig.4 Free-form lens established by rapid modeling

And its illuminance diagram and photomatric data are shown in Fig.5.

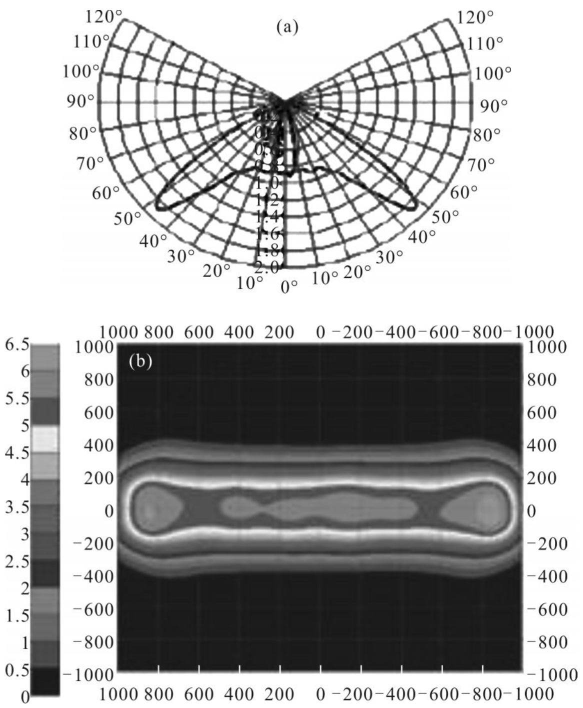

Fig.5 Photomatric data and illuminance diagram of free-form lens

We also generate another model in 3D modeling software with the same free-form surface data, Through the steps such as curve lofting and surface suture, a free-form surface lens model can be got. The entire modeling process time is about half an hour, which takes more time than the process of Scheme language rapid modeling. Its illuminance diagram and photomatric data are shown in Fig.6.

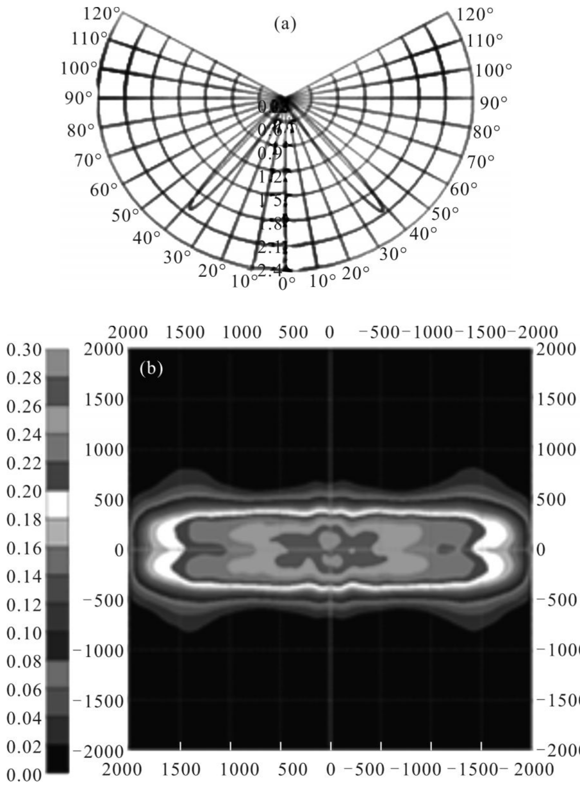

Fig.6 Photomatric data and illuminance diagram of free-form lens generated by 3D modeling software

Comparing the results of Fig.5 with that of Fig.6, the illuminance diagrams show that the intensity of illumination uniformity has decreased from 93.5% to 67%, and photomatric data diagrams show that the angle of beam divergence has decreased from nearly 100 degrees to nearly 80 degrees.

3 Conclusion

The rapid modeling method based on Scheme language is proposed in this paper. It can be applied to construct a freeform lens for uniform illumination provided that the characters of the source and the desired illumination are known. With this method, less time will be cost in the process of free –form lens design. Meanwhile, the tiny deformation could also be eliminated when the solid model is transferred from 3D modeling software to the optical simulation software since the Scheme language can directly generate lens model in the optical simulation software. In all, as an alternative for the modeling of surface, our method is more efficient and concise than the dual software collaborative modeling method, and many other kinds of free–form surface lens can be generated by using this Scheme language program.

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