An optical design and simulation of LED low-beam headlamps

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Abstract. The low-beam headlamp is an important component for the automobile safety. With the improvement of optical efficiency and heat dissipation technology of white LEDs, it becomes feasible to design low-beam headlamps with LEDs. The principle of B-spline surfaces is used to construct the free-form surface reflector meeting the requirement. First, the initial B-spline surface reflector is established on the basis of the light source structure, emitting features and capability of light distribution. Optical simulation is carried out according to the principle of ray tracing. And then the simulation results will be compared with the standard of photometric characteristics. The segmented surfaces fine-tuning method and the method of trial and error are used to trim the part that failed to meet requirements gradually. The vector groups of surfaces are obtained. Finally, the desired free-form surface reflector meeting the ECE regulations is got. The experimental results can meet the standard of photometric characteristics. The impact of the technique showed in this paper in the field of LED illumination design seems to be a very promising topic.

1. Introduction
The safety of car-driving relates to automotive headlamps’ quality. When we are driving at night, headlamps not only illuminate the road ahead to provide drivers with a bright and broad vision, but also avoid causing head-on car drivers glare. With the development of automobile technology, customers have increasingly high quality demands for headlamps.

LEDs (Light Emitting Diodes) have advantages of long service life, low power consumption, small packaging, very short switching time, and anti-vibration, compared with conventional light sources of headlamps [1,2]. In addition, LEDs have the mounting depth on the order of millimeter. It agrees with modern cars’ styling demands that car front is low and streamlined. A more usable space inside the car is obvious [3].

Early, manufacturers produced some vehicle lamps of low brightness with LED light sources, for example, CHMSLs (center high mount stop lamps), position lights, turn signals, and daytime running lights [4]. Thanks to the rapid increase in power in LEDs and the development of manufacturing technology, applications in headlamps can now also be possible. In the summer of 2008, Cadillac Escalade Platinum was the first high-volume vehicle in the world to be equipped with Hellas’s full-LED headlamps. Subsequently, new Audi A8 also used the LED headlamps.

As LEDs have unconventional structure and light emitting characteristics, use of only LEDs array is difficult to satisfy the illumination distribution in most cases. Therefore, using multiple LEDs in...
Combination with optical elements is necessary. One of the keys is the optical design of low-beam lights in the whole optical design process of LED headlamps.

There are three forms to design optical systems for low-beam lights, namely, refraction systems, reflection systems and hybrid systems. In 2008, André Domhardt etc. designed a projection-type low-beam lamp which satisfied the standard with VRS (virtual reflection or refraction of surface) technology [5]. Lexus LS600h equipped with a full headlamp system with all functions in LEDs. Three projection units and a reflection unit constituted its low-beam part. In China, Jilin Dongguang Group Corporation developed the LED-headlight sample at research funding of the 863 Program. Its low-beam light was composed of three projection units.

For low-beam headlamps using ordinary light sources, free-form segmented surfaces have been applied to design the reflector. Almost no paper introduced optical design methods of LED low-beam lamps within publishing literature, whose design theory and methods are not perfect. The studies are concerned with a new technique for designing LED-based automotive low-beam lamps. To solve the problems above, this article will introduce B-spline surfaces theory into optical design of LED low-beam headlamps. According to the simulation results, the beam pattern met the standard of photometric characteristics of headlamps. We expect to improve the efficiency of designing LED low-beam lamps.

2. ECE legal regulations for low-beam light distributions

The light performance of automotive headlamps is greatly related to driving safety. So there are many regulations and standards about light distributions. For example, there are more than 30 regulations which are directly related to vehicle lighting and signal lights. ECE regulations for low-beam light distributions are very strict. China’s standards about light distributions of automobile headlamps mainly refer to the ECE legal regulation. Figure 1 is the low-beam light distributions. André Domhardt etc. drew it in terms of ECE.

![Figure 1. Typical low-beam light distributions.](image)

There is the night sky on the top of the figure, and the road below. The red zones with high brightness, the hot spot, illuminate the road far ahead. A broad yellow distribution illuminating the road surface in front of the car has low illumination. Obviously, there is a blue dotted line in the figure 1. It is called the cut-off line to avoid glarring of the oncoming drivers. In the top of the horizontal portion of the dotted line, light intensity is strictly very weak. The fifteen degrees tilted line is on the right. It mainly provides better lighting for oneself.

As can be seen in figure 1, the desired low-beam light distribution is uneven and asymmetrical. To illuminate both sides of the road ahead, light distributions in horizontal directions need to have a certain expansion. So drivers can acquire a broad and secure view. On the left side of the vertical direction, light intensity above is weak, and the one below is strong. For illuminating distant road surface and traffic signs, the maximum light intensity is in the centre and weakens along the cut-off line of fifteen degrees. As LED light sources compared with traditional ones have small volume and very different optical characteristics, conventional methods for designing the optics of LED low-beam
headlamps are hardly practical. In order to meet requirements, new mathematical methods should be introduced.

3. Mathematical expressions of B-spline surfaces

3.1. B-spline curve and its derivative vector

B-spline surfaces are constructed from basic B-spline curves. It has some beneficial properties for designing surfaces: 1. local support; 2. differentiability; 3. convex hull properties. According to the theory of B-spline, B-spline curves can be expressed as:

\[ P(u) = \sum_{i=0}^{n} d_i N_{i,k}(u) \]  

(1)

Where \( d_i, i = 0,1, \cdots, n \) are the control points and \( N_{i,k}(u), i = 0,1, \cdots, n \) are the kth orders B-spline basis functions: \( U = [u_0, u_1, \cdots, u_{n+k+1}] \) is a knot vector which specifies the distribution of the parameter \( u \) on the curve.

There are many different equivalent definitions for B-spline basis functions. The following describes an algorithm and it is defined by

\[
N_{i,0}(u) = \begin{cases} 
1 & u_i \leq u \leq u_{i+1} \\
0 & u < u_i \ or \ u > u_{i+1} 
\end{cases}
\]

(2)

\[
N_{i,k}(u) = \frac{u-u_i}{u_{i+k}-u_i} N_{i,k-1}(u) + \frac{u_{i+k+1}-u}{u_{i+k+1}-u_{i+1}} N_{i+1,k-1}(u)
\]

In above formulas, we define \( 0^0 = 0 \).

According to the above definitions, we can determine the B-spline curves after having given control points and the parameter-interval \( u \). The de Boor algorithm is used to calculate the derivative vector of the B-spline curve. To solve normal vector groups of surfaces, we only introduce an algorithm for obtaining curves' first-order derivative vector (tangent vector). It can be calculated as

\[
\frac{\partial p(u, v_0)}{\partial u} \bigg|_{u=u_0} = \sum_{j=i-k+1}^{i} d_j^1 N_{j,k-1}(u), u \in [u_i, u_{i+1}]
\]

(3)

\[
d_j^1 = k \frac{d_j - d_{j-1}}{u_{j+k} - u_j}, \quad j = i - k + 1, \cdots, i
\]

(4)

3.2. Construction of B-spline surfaces

A B-spline surface in three-dimensional space is defined by

\[
P(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} d_{i,j} N_{i,k(u)} N_{j,L(v)}
\]

(5)

Where \( d_{i,j} , i = 0,1, \cdots, m; \ j = 0,1, \cdots, n \) are control points, and \( N_{i,k(u)} \) and \( N_{j,L(v)} \) are the Kth-degree and Lth-degree B-spline basis functions, respectively. Assume that we have all control points, the degree of parameters \( u \) and \( v \) and knot vectors. Then the B-spline surface can be defined.
The calculation for normal vectors of B-spline surfaces can refer to B-spline curves’ one. When a control point \( d_{i,j} \) in the definition domain is given, parameter values \((u,v)\) can be calculated. According to the calculation for normal vectors of B-spline curves, the normal vector of the point \( \frac{\partial p(u,v)}{\partial u} \bigg|_{u=u_0, v=v_0} \) can be similarly obtained.

4. Construction of free-form reflectors

4.1. Establishment of initial surfaces
In order to construct B-spline surfaces, control points \( d_{i,j} \), \( i = 0 \cdot \cdot \cdot m; j = 0 \cdot \cdot \cdot n \) firstly should be defined. Let us assume that there are \((m+1)\times(n+1)\) control points located on the paraboloid (see figure 2).

![Figure 2. Some controls points located on the paraboloid.](image)

The red line-group presents closed B-spline curves of \( u \) cluster, the other line segment group presents B-spline curves of \( v \) cluster. There are some control points distributed on curves. The density of control points are determined by the size of light sources, the initial reflector and desired light distributions. Control points are calculated according to parabolic equations.

After defining control points, we can fit a \( K \times L \)-order B-spline surface which is similar to paraboloid. As figure 3 shows, the center of LED array will be placed in the B-spline surface and longitudinal axis of the array and optical axis are made in a vertical.

![Figure 3. The rudiment of optical system.](image)

The size of LED array is slightly smaller than the one of the reflector, so it can not be simplified as point light sources. We need to describe near-field photometric data of LED array. Good manufacturers will provide accurate LEDs’ parameters used for modeling and analysis.

4.2. A method for fine-tuning segmented surfaces
As figure 4 shows, the basic reflector is divided into fifteen segmented surfaces. The beam pattern can be got from the contribution of all segments of the reflector. A1, A2, B1, B2, C1 and C2 are part of reflector, respectively. A1 and A2 are mainly used to illuminate central zones. C1 and C2 are provided for forming the level expansion of light distribution. B1 and B2 are for the transition of light beam. Shallow gray area is used to form the cut-off line. Dark gray area is aimed to strengthen the effect of the tilted part of the cut-off line.
The fifteen segmented surfaces will be more segmented in the detailed design process to obtain more B-spline segmented surfaces, and then fine-tune them. The function of each segmented surface must refer to the corresponding area on the basis reflector, especially in the center of each segmented surface.

Figure 5 shows the illuminated area corresponding with reflected area on the light-match screen.

With near-field photometric data of light sources, we can adjust the normal vector of B-spline surfaces by the ray-tracing theory. The principle is shown in figure 6.
Figure 6. The schematic diagram of fine-tuning.

We choose any intersection of B-spline curves, \( d_{i,j} \), in field A1 of reflector, and name the bin with the center of \( d_{i,j} \), M. We divide the extended light source into several pieces. Each small piece of light source emits light to the bin M. With received luminous flux of the bin M and position of each piece, we can assume that all rays illuminating the bin M come from a reference point which is obtained by weighting method. The incident ray I is from the reference point to the center \( d_{i,j} \) of the bin M. After obtaining the incident ray I, the ray intersection point \( d_{i,j} \) and the normal vector \( \frac{\partial p(u,v)}{\partial u} \) of the bin M, it is easy to calculate reflected ray \( II \) by the ray-tracing theory. Because the above reflector is only the initial surface, the reflected ray \( II \) obtained by ray tracing may be diverse on the light-match screen. For example, the intersection point of the reflected ray \( II \) may be located on the left of the desired light distribution, and may also be located on the right. To adjust surfaces, we can assume that the reflected ray \( II \) deviates from the center region and illuminates field B1. The position of the ideal reflected ray \( II' \) is marked in the figure 6. Finally, the required normal vector \( n' \) can be easily obtained.

The light distributions are uneven and asymmetrical, so the entire fine-tuning process is relatively complicated. The requirements of light distributions and light intensity are strictly prescribed. The marginal area of the reflector, A1 and A2, and the middle regions, C1 and C2, are key areas, we must subtly divide them. More and complete desired normal vectors \( n' \) are obtained by calculating. For transitional area, B1 and B2, we can adopt an approach of dividing large region, and then gain less normal vectors. To obtain a vector grid, all normal vectors are arranged by the position of control points. New B-spline surfaces are built according to the position of control points and normal vector groups, \([n']\). We use optical software for ray tracing. According to simulation results, we must adopt amendment until the results are consistent with the standard by above design idea. However, it is very difficult to manufacture some of surfaces in the engineering process, and then we need to do re-calculation and simulation to acquire new positions of control points, \( d_{i,j} \).

5. Optical simulation of LED low-beam headlamps

We select three LED light sources whose total luminous flux meets the requirements of the low beam lamp. The luminous flux of single LED is 425 lumens. For complete product specifications, please see table 1.

| Part Number | Form Factor | Min.LuminousFlux @1A | Typical Vf @1A | Typical CCT |
|-------------|-------------|-----------------------|-----------------|-------------|
| LAFL-C2*-0425 | 1x2 | 425 lm | 7.0 | 5600K |

The initial reflector of B-spline surfaces is established based on the design method above, the structure of LEDs and photometric characteristics. Figures 7 and 8 show the section diagram of the model in adjusting process.
According to the desired light distributions and the ray-tracing theory, we repeatedly adjust the model. Finally, the distribution curve flux is gained (see figure 9).

As can be seen in figure 9, the low-beam light distributions can well fit the regulation. If LEDs can be coupled with lens, light distributions would be better.

6. Conclusion
In this paper, we introduced B-spline surfaces and designed an optical system of LED low-beam headlamps. Finally, the optics satisfying the regulations was obtained. The simulation results show that the method is feasible. In recent work, we will apply this method to design a LED low-beam headlamp for a kind of car. The method can solve optical design of LED low-beam lightings, but the calculation amount is large. We still need further improvement in theory.

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