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DETERMINATION OF THE DIFFERENTIATED PHOTOMETRIC BODY SYSTEM RADIATORS

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ABSTRACT

This paper proposes a method for calculating the light distribution of a system of multi-oriented LED emitters, based on the combination of coordinates systems associated with these light sources. The algorithm is based on combining own coordinate systems of various ICs with the help of turns described in a matrix form, transition to a common spherical coordinate system as well as the addition of the forces of light corresponding to the same values of the angular coordinates. Unlike other well-known approaches, this method can be applied to emitters whose light distribution have an arbitrary symmetry or does not have it at all.

1. INTRODUCTION

Several years ago, in scientific publications [1, 2, 4, 7-9], there was a certain interest in the idea of designing lighting devices (OP) assembled from several LEDs (LEDs) or LED modules (LED modules) with secondary optics with different orientations in space. This approach has two advantages. First, it allows creating a photometric body (PB) of any complexity using secondary optics with simple geometry. Secondly, by ensuring in the OP design the ability to rotate individual LEDs (LED modules), it is possible to optimize its light distribution, considering the specifics of the lighting conditions. It is worth noting that over the last decade, the range of secondary optics for street lighting has significantly expanded so that the application of this approach to the development of this category of lamps turned out to be economically unjustified; however, attempts were made. In our opinion, it remains relevant to apply this approach, firstly, to the development of transom lamps designed to illuminate railway transport facilities, as well as for industrial premises, architectural lighting of buildings and structures. Secondly, it can be used to design lighting devices implementing the "flat beam" lighting technology [10], allowing for more efficient use of light energy and eliminating "light pollution", not dazzling vehicle drivers when illuminating the roadway [11], and more effectively providing architectural lighting. In this regard, research on the solution of the problem of finding the total angular distribution of the luminous intensity of a system of multi-oriented light sources with PBs is still relevant.

A method developed by Ashurkov and Bartsev [2] is currently known to solve this problem for round-symmetrical initial PB. Further, in the paper, a method for solving the problem is proposed, but without this limitation, that is, for asymmetric source PBs.

2. PROBLEM STATEMENT

As known, the light distribution of a point source is described by the indicatrix of the luminous intensity − a function determining the dependence of the luminous intensity $I(\vec{e})$ in the chosen direction. In turn, the direction can be determined by two angles in one of the systems (A, α), (B, β) or (C, γ) [3]. From the point of view of mathematics, the structure of the indicatrix of luminous intensity is an image of the surface in a spherical coordinate system, where I plays the role of a radius, and the angular coordinates depend on the choice of the photometric system.

As a rule, the indicatrix of luminous intensity is found from measurements on a goniophotometer. The result of such experiments is presented in IESNA format [10] - in fact, in the form of a table listing the values of each of the angles with a certain step and presenting the values of the luminous intensity corresponding to each pair of such values.

Denoted by Θ, Φ angular coordinates in some spherical system (Figure 1), $\Theta \in [0°; 180°]$, $\Phi \in [0°; 360°]$

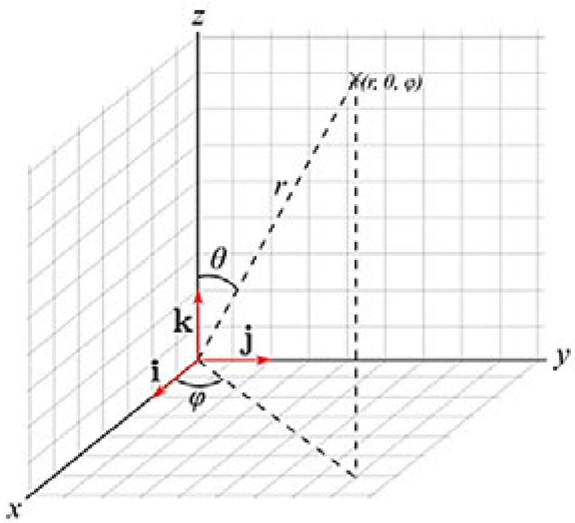

Figure 1: Angular coordinates in a spherical system

Let the measurements are made in increments $\Delta\Theta$ on the first and $\Delta\Phi$ — on the second corner, designating:

$$\Theta_k = k\Delta\Theta, \Phi_l = l\Delta\Phi \quad (1).$$

It is recognized that the values are known as

$$i_{kl} = I(\Theta_k, \Phi_l), \quad (2),$$

where $k = 0 \ldots N_\Theta$, $l = 0 \ldots N_\Phi$, and $N_\Theta = 180/\Delta\,\Theta$, $N_\Phi = 360/\Delta\,\Phi$.

Consider now several light sources (IC) located at one point. The indicatrix of the light intensity for each of them is separately known and is given by equations of the form (1), (2). Moreover, all indicatrices are described in the same photometric system, for example, (C, γ), in which the role of the corner Θ plays γ, and the role of the corner Φ is as C. It is also logical to assume that when measured, the steps of changing angles $\Delta\Theta$ and $\Delta\Phi$ are common to all light sources, although this assumption is not critical.

Sources are multi-oriented: the light distribution of each of them is described in its own coordinates system, rigidly connected with this particular source. In this case, the mutual arrangement of the IC is known, i.e. the known sequence of turns, allowing combining their coordinate systems by themselves.

The task is to find the total light distribution of the point sources described above.

Due to the non-coincidence of the coordinate systems, the directly added values i_{kl} of different sources in the corresponding grid nodes are impossible. It is required to preselect a certain common coordinate system, recalculate the functions for each source in it, and only then perform the addition. To reduce computation, you can choose your own coordinate system of one of the ICs as a general system. The method for solving the problem will be described below, as well as the experimental setup, which prepared the input data to verify the theoretical calculations, and the comparison of the methods.

3. CALCULATION OF LIGHT DISTRIBUTION IN SPACE

ASC is a function of two variables in the three-dimensional case: $I = I(\theta, \varphi)$. Corners $\theta \in [0°; 180°]$ and $\varphi \in [0°; 360°]$ set the direction in a spherical coordinates system, whose beginning is combined with the IP, where I acts as a distance (Figure 1).
The transition from spherical to Cartesian coordinates is described by the equations:

$$x = I\cos(\varphi)\sin(\theta), y = I\sin(\varphi)\sin(\theta), z = I\cos(\theta), \quad (3)$$

and the reverse transition - formulas

$$I = \sqrt{x^2 + y^2 + z^2}, \theta = arccos\left(\frac{z}{I}\right), \varphi = \begin{cases} \varphi^*, y \geqslant 0, \\ 360° - \varphi^*, y < 0, \end{cases} \quad (4)$$

where the auxiliary angle φ_0 is determined by the equation:

$$\varphi^* = \arccos\left(\frac{x}{\sqrt{x^2+y^2}}\right) \quad (5)$$

This approach allows to correctly determine all the values of φ from the segment $[0, 360°]$. However, it is impossible to do without considering additional conditions in the last of the formulas (4), since the range of values of any of the functions "arcsin", "arccos" and "arctan" is equal to $180°$. For x = y = 0, we can assume $\varphi = 0°$.

Note that in the photometry system (C, γ), the value of C corresponds to the angle φ, and γ

(after being replaced with $360° - \gamma$) — corner θ.

As in the two-dimensional case, to add together the forces of light emitted by ICs located at one-point O, it is required to combine the own coordinate systems of these ICs by turning around O. For example, these transformations can be specified with Euler angles. In the present study, sequential rotations around the axes are used to align the coordinate systems of Ox, Oy, Oz on some angles α_x, α_y, α_z.

Let the basis in space be formed by vectors $\overrightarrow{e_1} = \{1; 0; 0\}$, $\overrightarrow{e_2} = \{0; 1; 0\}$ and $\overrightarrow{e_3} = \{0; 0; 1\}$. After transformation, they will be transferred to other vectors of $\overrightarrow{f_1}$, $\overrightarrow{f_2}$, $\overrightarrow{f_3}$. The coordinates of these "new" vectors in the "old" basis are contained in the columns of the transition matrix M, thus fully describing the studied transformation.

If the coordinates of the same vector $\vec{r}$ in the "old" and "new" basis are contained in the columns X and Y, respectively, they are related by

$$X = MY \tag{6}$$

For rotations around the coordinate axes of the transition matrix in the Cartesian rectangular coordinate system, they have the form as below:

$$M_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_x & -\sin\alpha_x \\ 0 & \sin\alpha_x & \cos\alpha_x \end{bmatrix}, \quad M_y = \begin{bmatrix} \cos\alpha_y & 0 & -\sin\alpha_y \\ 0 & 1 & 0 \\ \sin\alpha_y & 0 & \cos\alpha_y \end{bmatrix},$$
$$M_z = \begin{bmatrix} \cos\alpha_z & -\sin\alpha_z & 0 \\ \sin\alpha_z & \cos\alpha_z & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{7}$$

If all three rotations are performed, then the final transformation will be described by a matrix.

$$M = M_x M_y M_z. \tag{8}$$

Equations (6)-(8) are valid in the Cartesian rectangular coordinates system; nevertheless, the luminous intensities of various ICs are determined by the angular coordinates in a spherical system. To combine both approaches and calculate the total light distribution of n multi-oriented sources located at the same point, the following algorithm can be used:

Describe the PB of all light sources by specifying functions of $I_k(\Theta, \Phi)$ in its own coordinate systems. Here $k = \overline{1, n}$ is the source number, but Θ, Φ represents angular coordinates in its system.

Choose a common coordinate system making the addition of light occur. Further, the angular coordinates in the general system are denoted by θ, φ.

For each IC, describe the angles of $\alpha_x(k), \alpha_y(k), \alpha_z(k)$, with the help of which there will be a combination of one's own system with common matrices corresponding to them and find the transition matrix $M(k) = M_x(k) \cdot M_y(k) \cdot M_z(k)$.

For all ICs, find the connection between θ, φ, and Θ, Φ. To this end, a formal unit vector is introduced as $\vec{e}$, the coordinates of which in the "new" (common) system are entered in the column $Y = colon(\cos\varphi \sin\theta, \sin\varphi \sin\theta, \cos\theta)$. In the "old" (own) system, its coordinates are listed in the column $X = colon(x, y, z)$, with some other kind and already depending on variables Θ, Φ. Insofar as $M(k)$ – this is the transition matrix from its own Cartesian coordinate system to the general one, then the connection between $X(\Theta, \Phi)$ and $Y(\theta, \varphi)$ will be set based on the formula (6): $X = M(k)Y$. Through calculating $M(k)Y(\theta, \varphi)$ and finding x, y, z, you can go from Cartesian coordinates to spherical coordinates in your own system using formula (4). Thus, the desired connection will be found

$$\Theta = T_k(\theta, \varphi), \Phi = F_k(\theta, \varphi). \quad (9).$$

To simplify the calculations in (4) you can immediately consider $I = 1$.

Given the Equation (9), the desired light distribution is obtained by the function

$$I(\theta, \varphi) = I_1\big(T_1(\theta, \varphi), F_1(\theta, \varphi)\big) + \cdots + I_n\big(T_n(\theta, \varphi), F_n(\theta, \varphi)\big) \quad (10)$$

In the two-dimensional case, the combination of its own and common coordinate systems is obtained by simply replacing Φ with $\varphi - \varphi_0$, where φ_0 is the angle at which your own system turns. In this regard, the question arises, "Is it possible to find such angles θ_0 and φ_0, dependent on α_x, α_y, α_z? What are angular variables Θ, Φ and θ, φ that will be connected by the same ratios $\varphi = \Phi - \varphi_0$, $\theta = \Theta - \theta_0$ for any values of Θ, Φ? As shown in [1], the answer to this question is negative. Therefore, it is necessary to find (10) after the additional interpolation stage [5].

4. EVALUATION OF THE CORRECTNESS OF THE METHOD WORK

The specified algorithm was implemented in a free package for mathematical calculations Octave. To record commands and expressions in GNU Octave, a functional high-level language similar to MatLab is used.

The real data necessary for assessing the correctness of the method was obtained during a goniophotometric experiment. In Figure 2, the LED ICs participating in the experiment is shown. The first source (IC 1) is the kososvet, made based on a Feron 3602 LB-24 MR16 LED lamp. The second source (IC 2) is a comparable in power LED accent lamp with round symmetrical light distribution.

The distribution of luminous intensity was measured under normal conditions by means of the goniophotometric complex GO2000A [12], including:

- Goniometer GO2000A (the range of rotation in the horizontal and vertical planes: ±180°, the accuracy of setting the rotation angle: 0.1°);
- Photometer ID-1000 based on silicon photodiode, corrected for the function V(λ), accuracy class L;
- Power supply DPS1060.

All photometric data used in further calculations represent the arithmetic average of the results of five measurements.

Figure 2: Light sources used in the photometric experiment: 1 - kososvet, 2 - LED lamp

Photometry was carried out in the Cγ system. The measurement step was conducted for plane C was 2.5°, and for the plane γ - 1°. The experimental PB of each IC is shown in Figure 3.

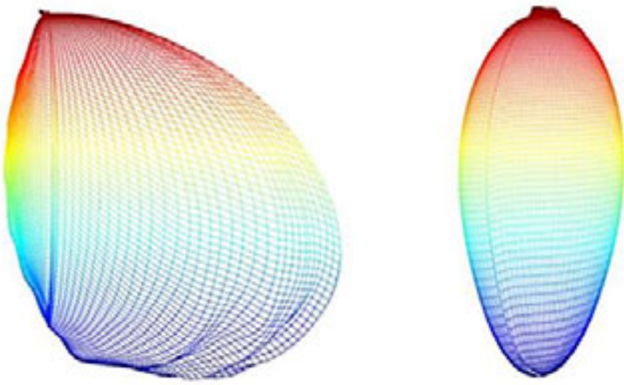

Figure 3: Photometric bodies of sources 1 and 2, obtained from the measurements

IC 1 was installed to measure the total light distribution of these sources, so that its geometrical axis was parallel to the photometric axis, and the orientation for IC 2 was determined by a sequence of rotations of its geometrical axis: around the Ox axis by 46°, then around the Oz axis by 190°. The overall coordinate system was associated with the IC 1. Of course, the angles are arbitrary. Total PB obtained as a result of measurements is shown in Figure 4.

Subsequently, the total light distribution was calculated. The photometric body of IC 2 was rotated about the axis Ox by 46°, then around the axis Oz by 190°. The overall coordinate system was associated with the IC 1. The total PB obtained from the calculation is shown in Figure 5.

The accuracy criterion was the relative error in calculating the total luminous intensity from the two integrated circuits, compared with its experimental values of I_{pq}. The calculated and experimental data were compared only in the area where $I_{pq} = I_{\max}/2$.

Here, $I_{\max}$ represents the highest intensity of the measured total luminous. Such a restriction allows us not to consider regions not actually covered by IP. On the other hand, these areas are not of interest from a technical point of view and the relative error can increase dramatically due to the smallness of the measured value.

In the selected area, the maximum error when using piecewise linear interpolation is about 6.5%.

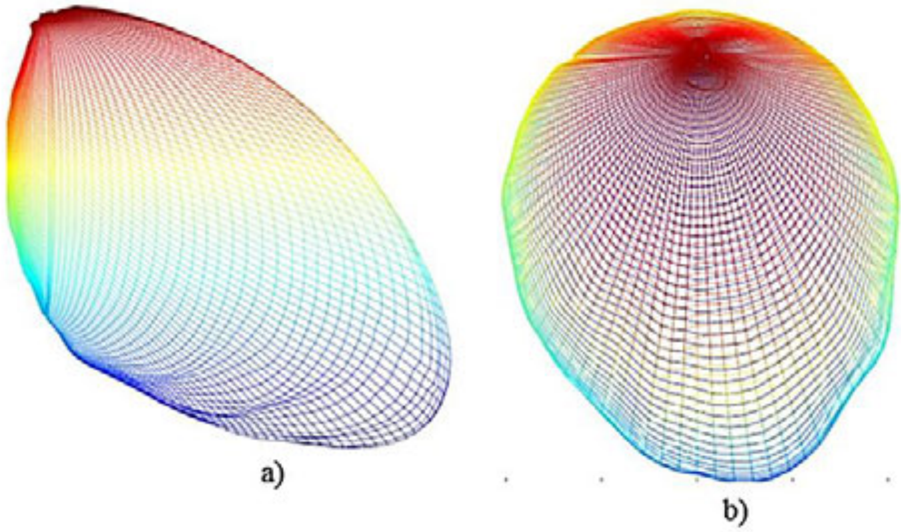

Figure 5: The estimated PB of a system of two differently oriented radiators: a) in a vertical plane C90-270; b) in the horizontal plane

5. CONCLUSION

Thus, this paper presents a method for calculating the total light distribution of several ICs located at the same point; however, with a different orientation in space. The algorithm is based on combining own coordinate systems of various ICs with the help of turns described in a matrix form, transition to a common spherical coordinate system as well as the addition of the forces of light corresponding to the same values of the angular coordinates.

The method contains no restrictions in terms of photometric IP bodies. It can be the basis of numerical algorithms for calculating the total light distribution in cases where the PB of the original ICs are described not analytically, but approximately - based on measurement results.

6. AVAILABILITY OF DATA AND MATERIAL

Data can be made available by contacting the corresponding authors

7. CONFLICT OF INTEREST

The authors confirm that the presented data does not contain any conflict of interest.

8. ACKNOWLEDGMENT

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