

ELECTRONIC CONTROL OF LOCAL UNIFORMITY OF ILLUMINANCE FROM POWER LED

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Abstract: *It has been suggested to assess non-uniformity of illuminance by the coordinate distribution of its gradient. By the example of mathematical model, the possibility to form a desired illuminance gradient profile from a multicomponent module by means of electronic control of the LED lighting parameters.*

Keywords: *LED, multicomponent module, lighting unit, luminous intensity, lighting parameters*

INTRODUCTION

Sharing radiotechnical and lighted aids extends the functionality of navigation systems, improves safety during low visibility takeoff and landing of aircrafts. In the most critical stages of piloting an aircraft, the aerodrome lighting system is a reliable source of visual information. In connection with brisk development of pilotless aircraft worldwide, the components of aeronautical equipment operating in the infrared (IR) band of electromagnetic waves are particularly in-demand, as IR cameras, thermal imagers are an integral part of the payload of unmanned aerial vehicles. The current stage, the development of light signaling devices is focused on the use of solid-state semiconductor sources, which are more effective by many performance criteria in comparison with thermal radiation sources. Physical properties of semiconductor injection emission sources allow further improvement of airfield spotlights and markers (increase in lifetime, higher reliability, optimization of light distribution, etc.) via implementation of electronic control of lighting parameters.

1. ANALYSIS OF PUBLICATIONS

Over the past few years of the development of electronic instrument-making, the highest achievements are observed in the areas of optoelectronics and are associated with the development of high performance photodetectors, high-brightness LEDs and semiconductor lighting units of various designations (Gridin, Zaytsev, Ryzhikov, Shcherbakov, 2012). There occurs mass replacement of conventional light sources by semiconductor analogs. The introduction of LED (*light-emitting diode*) technology in the manufacture of airfield lighting equipment seems promising (Galakova, Lyalyutskaya, Galakova, 2016; Adakin, Irevlina, 2016; Zyryanov, Volkov, Dmitriyev, 2011; Holovenskiyi, Lisovenko, 2017; Holovenskiyi, 2018; Holovenskiyi, Andrusyevych, Lisovenko, 2017; Holovenskiyi, Bazyk, Lisovenko, 2018; Thesis work; Lisovenko, 2006; Anisimov, Budak, Zhukov, Kaloshin, Shishkin, 2016). New epitaxial technologies for heterostructures type Al-In-Ga-P, In-Ga-N, Ga N allow achieving almost 100% internal quantum efficiency of luminescence in different optical bands of the emission spectrum. The result is that LEDs have higher energy efficiency today as compared with gas discharge fluorescent lamp, and their luminous efficiency is expected to increase to 150 lm/W (Mills, 2003a; Mills, 2003b).

LED small size expands the range of geometric configurations for collecting them into modules, which in turn opens up possibilities for designing individual lighting technology models for special requirements that should be considered as early as at the model design stage. The objective is a general transition from manual calculations to computer modeling of the structural elements of individual LEDs and their modules, as well as their lighting characteristics. Calculations of parameters of the secondary optics and lighting characteristics of modules have been successfully developed for different

layout configurations of LEDs in lighting modules for planes of different spatial orientation (Udaltsov, Uvarova, 2010; Gorbunova, Korotaev, Peretyagin, Cherotov, 2013; Peretyagin, 2015; Sobolev, Poddenezhny, 2011; Sobolev, Poddenezhny, 2011). The main idea is to simulate the synthesis of the physical parameters of individual components into the integral lighting characteristics of a general lighting unit. It is important to establish the lighting parameters patterns of the LED lighting unit depending on the characteristics of its components and the geometry of their spatial arrangement. LEDs are commonly point sources with a predetermined directional diagram of the luminous intensity. Luminous intensity diagrams can be conditionally classified into three types of mathematical approximations that are originally based on the Lambertian emitter diagram:

- as a P -times magnified polar angle $\theta - \cos(P\theta)$;
- as a power function with a different arithmetic nature of degree $m - \cos^m(\theta)$;
- as algebraic functions of $\cos\theta$.

The pressing matter is the search for the most successful mathematical approximations of the empirical curves of luminous intensity of LED modules with different LED arrangement configurations.

As for the airfield lighting equipment, the importance of expanding the functionality of on-line change in the light field characteristics at different stages of the aircraft take-off and landing should be noted. Regulation of the directional diagram of lighting devices is dictated by the variability of the flight situation, providing the most comfortable visual perception of the outside world by the crew. The directional diagram in modern aeronautical signal spotlights is static or changes by mechanical deformation of the emitting module membrane, on which LEDs are placed. This method of controlling the spotlight parameters has significant drawbacks – various kinds of aberrations, a rigid connection between the radiant intensity and beamwidth, low operational reliability, the need for high-accuracy deformation of the membrane in the form of quadric surfaces, which is a rather complex. Aberrations are partially eliminated by changing the structure of emission unit – placing the LED emission sources on flexible segments, lamels, which change their curvature from concave to convex under the action of the control mechanism, whereby the light distribution solid takes different forms of surfaces (Patent. LED spotlight with regulated emission indicatrix). However, the above-mentioned issues remain. Since modern LED manufacturing is robotic and high precision, the solution of these problems is possible provided complete rejection of a mechanical control of spotlight lighting parameters by replacing it to the electronic control.

2. STUDY OBJECTIVE

To theoretically investigate the possibility and conditions for the formation of the predetermined illuminance profile from the multicomponent LED spotlight by means of electronic control of LED lighting parameters.

Basic material presentation

Let us consider a planar LED module with N LEDs with identically oriented principal optic axes and Cartesian coordinates (x_k, y_k) . Illumination from each of them on the plane perpendicular to the principal optic axes located at distance z from the module (LEDs are taken as the point sources) is expressed by the inverse square law (Epstein, 1975):

$$E_k(\theta_k, \varphi_k) = \frac{I_k(\theta_k, \varphi_k) \cdot \cos^3 \theta_k}{z^2} \quad (1)$$

where:

- $I_k(\theta_k, \varphi_k)$ – luminous intensity of the k LED;
- θ_k, φ_k – polar distance, longitude of spherical coordinates with pole at k LED.

For the majority of LED body designs and secondary optics I_k does not depend on angle φ_k , and the luminous intensity directional diagram can be represented as $I_k(\theta_k) = I_{ok} \cdot \cos(P_k \theta_k)$. Then, expression (1) will have the form:

$$E_k(\theta_k) = \frac{\cos(P_k \cdot \theta_k) \cos^3(\theta_k)}{z^2} \quad (2)$$

where:

- $\theta_k(x, y, z) = \arccos\left(\frac{z}{\sqrt{(x-x_k)^2 + (y-y_k)^2 + z^2}}\right)$;
- x, y, z – Cartesian coordinates of the point of observation;
- I_{ok} – luminous intensity of k LED in direction $\theta_k = 0$;
- $P_k = \frac{\pi}{3\alpha_k}$ – change factor parameter of k LED directional diagram with respect to Lambertian emitter [20];
- α_k – half-width of the k LED directional diagram.

The limiting value of argument $P_k \theta_k$ amounts to angle $\frac{\pi}{2}$. With known quantity α_k , which is presented in the LED nameplate data of with account of the ambiguity of function $\text{Arccos}\xi$, we have a range of θ_k : $\theta_k \in \left[-\frac{3}{2}\alpha_k; \frac{3}{2}\alpha_k\right]$.

As a result, the coordinate distribution of illumination from the module in the plane under consideration takes the form:

$$E_z(\theta_k) = \frac{1}{z^2} \sum_{k=1}^N I_{ok} \cdot \left[H\left(\theta_k + \frac{3}{2}\alpha_k\right) - H\left(\theta_k - \frac{3}{2}\alpha_k\right) \right] \cdot \cos\left(\frac{\pi}{3\alpha_k} \cdot \theta_k\right) \cdot \cos^3(\theta_k) \quad (3)$$

where $H(\theta)$ – asymmetric unit function (Heaviside).

Visual evaluation of illumination non-uniformity of the working surface is subjective, and may be difficult under low intensity conditions. For objective evaluations, we can use numerical characteristics of the spread of values $E_z(x, y)$ relative to the mean: dispersion, standard deviation, coefficient of variation. In lighting engineering, the illumination profile control is estimated by the average to minimum illuminance area ratio – E_{aver}/E_{min} (Knorring, Fadin, Sidorov, 1992). However, this ratio is not sufficiently integral to evaluate the illuminance non-uniformity between very close points of the surface.

Planar distribution $E_z(x, y)$ from the viewpoint of classical concepts is defined by distribution of the normal component of the Pointing vector and represents a stationary, planar, scalar field, the change of which in any fixed point (x, y) can be characterized by a derivative in the chosen direction \vec{l} or by illumination gradient. The gradient vector direction points to the maximum rate of increase $E_z(x, y)$ in any point of the surface. Planar distribution of the gradient module value:

$$|\text{grad}E_z(x, y)| = \sqrt{\left(\frac{\partial E_z(x, y)}{\partial x}\right)^2 + \left(\frac{\partial E_z(x, y)}{\partial y}\right)^2} \quad (4)$$

characterizes the field of maximum rates of changes in illuminance and may be a local characteristic of the degree of illuminance non-uniformity. The plane sites or individual points (x, y) , where $|\text{grad}E_z(x, y)| = 0$ correspond to mathematically uniform illuminance $E_z(x, y) = \text{Const}$.

If coordinate y is presented as function of x in formulas (2), (3), (4), we can get distribution profiles $E_z(x)$ and $|\text{grad}E_z(x)|$ on the curve of prespecified form $y = f(x)$.

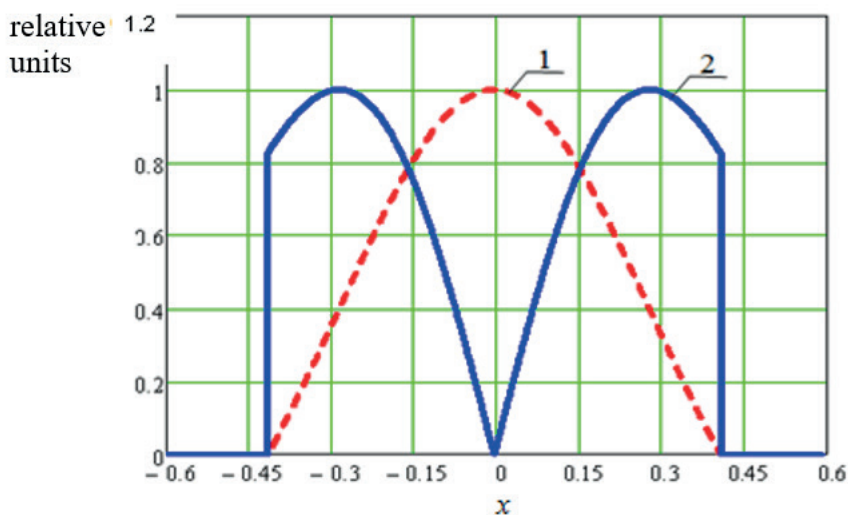


Fig. 1. Coordinate distribution of the illuminance normalized values (curve 1) and plane illuminance gradient module (curve 2) from an isolated LED with parameters:

$$x_1 = 0; y_1 = 0; I_1 = 1; \alpha_1 = \frac{\pi}{12}; z = 1$$

Source: Own elaboration

Figure 2 shows the illuminance distribution and the absolute value of its gradient in the plane which is at a distance $z = 3$ from the module consisting of 36 LEDs. The vector-matrices of the parameters, which are presented in the chosen system of physical quantities and take the form:

$$\begin{aligned} (x_k) &:= (0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 0 \ 2 \ 4 \ 6 \ 8 \ 10 \ 0 \ 2 \ 4 \ 6 \ 8 \ 10)^T; \\ (y_k) &:= (0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 2 \ 2 \ 2 \ 2 \ 2 \ 2 \ 4 \ 4 \ 4 \ 4 \ 4 \ 4 \ 6 \ 6 \ 6 \ 6 \ 6 \ 6 \ 8 \ 8 \ 8 \ 8 \ 8 \ 8 \ 10 \ 10 \ 10 \ 10 \ 10)^T; \\ (I_{0k}) &:= (5 \ 5 \ 15 \ 5 \ 5 \ 5 \ 5 \ 5 \ 9 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 10 \ 5 \ 5 \ 5 \ 10 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 3 \ 5 \ 5 \ 5 \ 5 \ 5 \ 8)^T; \\ (\alpha_k) &:= \left(\frac{\pi}{18} \ \frac{\pi}{18} \ \frac{\pi}{18} \ \frac{\pi}{18} \ \frac{\pi}{6} \ \frac{\pi}{18} \ \frac{\pi}{6} \right)^T \end{aligned}$$

Figure 2 indicates that value $|gradE_z(x, y)|$ is very sensitive to changes in illuminance. In practice, not visually registered non-uniformity of illuminance can be detected by registration of $|gradE_z(x, y)|$, that is a large non-uniformity $E_z(x)$ corresponds to the larger value in the vicinity of the point of interest. Registration of distributions $E_z(x)$ and $|gradE_z(x, y)|$ gives a fairly comprehensive information of the degree of illumination non-uniformity.

The above model makes it possible to analyze the effects of a single LED characteristics on the formation of the module lighting parameters. Independent control of each LED characteristics such as I_{ok} , α_k and their arrangement geometry produces

the desired illuminance distribution profile. For circular symmetrical arrangement of the LEDs, it is more convenient to represent the LED coordinates in the polar coordinate system, then:

$$\theta_k(x, y, z, \rho_k, \varphi_k) = \text{Arccos} \left(\frac{z}{\sqrt{x^2 + y^2 - 2\rho_k(x \cdot \cos \varphi_k + y \cdot \sin \varphi_k) + z^2 + \rho_k^2}} \right) \quad (5)$$

where: ρ_k, φ_k – radius-vector and polar angle of k LED, respectively.

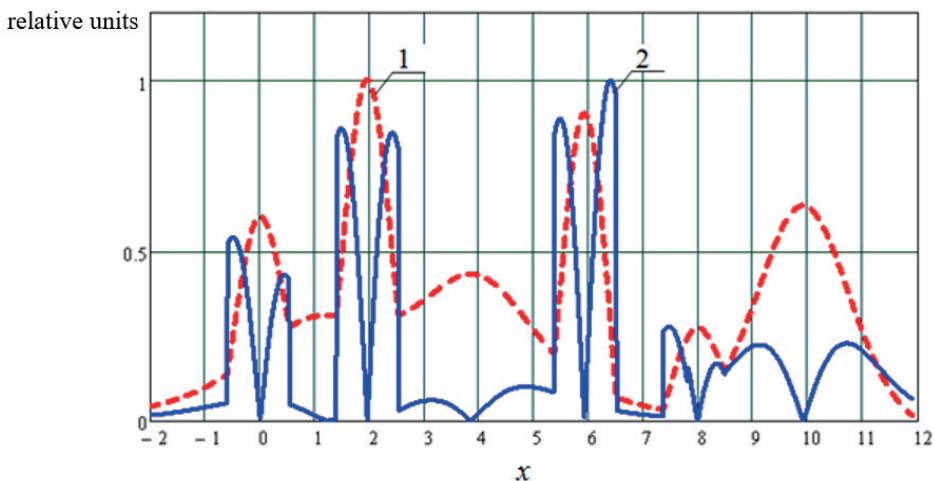


Fig. 2. Profiles distribution on diagonal $y(x) = x$ of the illuminated place:
 curve 1 – illuminance $E(x,y)$;
 curve 2 – illuminance gradient module $|\text{grad}E(x,y)|$
 Source: Own elaboration

Figure 3 shows the graphs of coordinate distributions of the site illuminance and illuminance gradient module for a spotlight of 25 LEDs arranged circularly symmetrically with polar coordinates:

$$(\rho_k) := (0 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 2 \ 2 \ 2 \ 2 \ 2 \ 2 \ 2 \ 2 \ 2 \ 3 \ 3 \ 3 \ 3 \ 3 \ 3 \ 3)^T$$

$$(\varphi_k) := \left(0 \ 0 \ 0.785 \ \frac{\pi}{2} \ \frac{3}{4}\pi \ \pi \ \frac{5}{4}\pi \ \frac{\pi-3}{2} \ \frac{\pi-7}{4} \ 0.393 \ 1.178 \ 1.963 \ 2.75 \ 3.534 \ 4.319 \ 5.105 \ 5.89 \ 0 \ 0.785 \ \frac{\pi}{2} \ \frac{3}{4}\pi \ \pi \ \frac{5}{4}\pi \ \frac{3\pi}{2} \ \frac{7}{4}\pi \right)^T$$

The photometric parameters I_{OK} and α_k are artificially selected so as to obtain a square site with high illuminance uniformity:

$$(I_{\text{OK}}) := (9 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 7 \ 7 \ 7 \ 7 \ 7 \ 7 \ 7 \ 50 \ 50 \ 50 \ 50 \ 50 \ 50 \ 50)^T,$$

$$(\alpha_k) := \left(\frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{6} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \ \frac{\pi}{3} \right)^T$$

It is easily seen that in plane which is at a distance of $z = 3$ from the LED module, there is a circular symmetrical site (radius ~ 1) with the most uniform illuminance; within its boundaries $\max |grad E_z(x, y)| \leq 0,1$, which is significantly less compared to other sites.

In practice, the plane illuminance distribution can be changed by switching individual groups of LEDs with different directional diagrams and specifically placed on the module. With a large number of LEDs, such electronic switching enable dynamic formation of the required set of the spotlight directional diagrams, which is an important need when used in lighting equipment (Holovenskyi, Lisovenko, Huliak, 2018; Holovenskyi, Lisovenko, 2017).

relative units

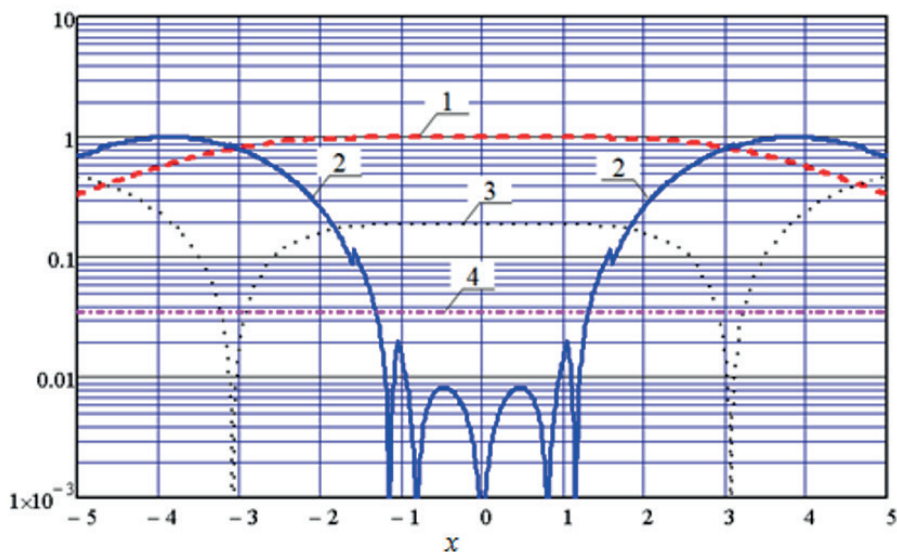


Fig. 3. Distribution profiles: *curve 1* – illuminance; *curve 2* – illumination gradient module; *curve 3* – quadratic deviation of illuminance from the mean value; *curve 4* – illuminance dispersion

Source: Own elaboration

The results obtained by the example of the LED model of multicomponent module are fully valid for module with semiconductor IR diode emitters. IR spotlights with electronically controlled focusing can be an important component of the payload of unmanned aircraft systems, and an additional means of aerial navigation in the form airfield based IR markers.

CONCLUSIONS

1. Plane illumination gradient and its module are highly sensitive characteristics of the plane illumination non-uniformity.

2. The method for switching individual LEDs with different lighting parameters allows the synthesis of the directional diagram of the spotlight luminous intensity of the required configurations and achieving illumination of the predetermined characteristics of uniformity on the work surfaces.
3. If the algorithm base for transition from individual characteristics of LEDs to the parameters of the integrated module is available, it is possible to switch to the dynamic programmable electronic control of all lighting parameters of aeronautic spotlights and markers.

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