Analysis of structural features of a LED searchlight

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Abstract. We come up with the design of an illumination device with point light sources, which are arranged on three different-level surfaces. We rely upon the visualization and light flux analysis to identify reflective surface shapes and the number of point light sources (LEDs). With a view of optimizing the illuminator's design, we look into its ability to withstand deformations (rigidity) at different vibration frequencies. For the design with highest rigidity, we study the impact of reflective surface roughness on the illuminator's performance. We conduct the ray tracing for each optical surface with due account for its roughness, with the illuminator vibrating on an Eigenfrequency. Based on the ray tracing, we find the light flux intensity pattern from the illuminator. We argue that following the study stages proposed it is possible to:
- choose an optimal illuminator's design for specific service conditions;
- choose a fabrication procedure for the reflecting surfaces.

The results obtained will be useful when designing navigation lights, floodlights for tall building cranes, and aircraft landing lights.

1. Introduction

During their service life, quite a few optical systems are exposed to vibration strain. For instance, spaceborne computer vision systems \cite{1-2} and hyperspectral equipment for earth remote sensing \cite{3-4} are exposed to vibration while being launched into and moving along the orbit. Vibrations heavily affect the operation of lighting devices found in automobiles, railway cars, and airplanes \cite{5-7}, street lights \cite{7-8}, and dashboard lighting \cite{9}. Vibration may cause a structural damage of the optical device, deteriorating its performance. Lighting devices operate in a wide range of frequencies. Fabrication techniques utilized to synthesize an optical element \cite{10-14} produce some surface microroughness. All these factors affect the performance of the optical device.

In previous works \cite{15-16}, we proposed three-dimensional models of a railway headlamp which enabled us to improve its design. We also analyzed the capability of an illuminator's structure to withstand vibrations \cite{17-18}. The effects of vibrations and structural features on the illuminator's operating performance were investigated in Refs. \cite{18-19}. Note that the said analysis was based on the assumption of a single, ideally smooth light-flux generating surface. Meanwhile, many state-of-the-art illuminating devices are composed of an array of complex-shape reflecting surfaces. Surface roughness affects operating characteristics of the illuminator. Previously, we have not studied in which way vibrations affect the performance of the illuminators containing several reflecting elements and
disregarded surface roughness effects. We have been unable to find publications dealing with these topics.

These circumstances have prompted us to conduct a study of operating capabilities of an aircraft spotlight [5]. In doing so, we built a 3D model of a LED illuminator (spotlight), identifying reflecting surface deformations at different frequencies, including Eigenfrequencies of the structure. Using ray tracing, the light flux was numerically simulated for deformed reflecting surfaces with various microreliefs, on the assumption of point light sources.

Using the 3D model, the ability of a LED illuminator to withstand deformations (structural rigidity) was studied. The simulation results show that the design proposed may be utilized as an aircraft landing/taxiing headlamp, ship navigation lights, and a building crane spotlight (figure 1).

Objective of the paper: we seek to work out recommendations on the selection of (i) the design and (ii) techniques for fabrication of the reflecting surfaces of a LED illuminator. By following the recommendations, the vibration resistance of the illuminator will be enhanced and the spread of its performance parameters reduced.

Figure 1. Various-purpose illuminators: a- aircraft landing/taxiing lamp; b- aircraft take-off/landing lamp; c- ship’s navigation lamp; d- ship’s signal lamps; e- building incandescent spotlight; and f- building LED spotlight.

2. Problem statement
In Ref. [5], a design of an aircraft take-off/landing lamp was discussed. This lamp is exposed to high-amplitude vibrations in a wide range of frequencies.

Based on design solutions and the optical setup chosen, a 3D model of the spotlight was built. The size of the 3D model was adapted for an aircraft take-off/landing lamp. The choice of a particular model, BL-L513 LED, determined the number of point light sources and geometrical size of light-emitting surfaces (figures 2 and 3). Using geometric optics approach, we built a light flux generated by the lighting device (figure 4). We assumed the specular reflection of light off the reflecting surfaces and the reflecting surfaces perfectly matching the design shape. Point light sources were assumed to be used. The light flux was generated by seven LEDs on the first level, 19 LEDs – on the second level, and 21 LEDs on the third level. The light-emitting surface of each LED was assumed to be found in the focus of a paraboloid (figure 4).

The light-reflecting surfaces were supposed to be made of 0.75-mm sheets of an aluminum alloy 6063 EN 573-1: ENAW-6063. This alloy was chosen due to its high plasticity, enabling a complex-shaped light-reflecting surface to be fabricated. Two cases were analyzed:
- perfectly smooth reflecting surfaces;
- reflecting surfaces with roughness parameter $R_a = 0.16 \mu m$.

**Figure 2.** Aircraft take-off/landing lamp: $a$-outside view; $b$-lamp cross-section.

**Figure 3.** Geometric measures of light-emitting surfaces of the spotlight:
- $a$-outside radii of the light-emitting surfaces and their relative shifts;
- $b$-measures of the light-emitting surface of the fourth, paraboloid-shaped surface.

**Figure 4.** Ray tracing for different light-emitting surfaces:
- $a$- the cross-section of the light-emitting surface of the second reflector;
- $b$- the cross-section of the light-emitting surface of the fourth reflector; and
- $c$-the overall cross-section of light-emitting surfaces of three reflectors.
The illuminator under study also contained the following materials: silicate glass, an organic-silicon rubber, and rigid plastics (polymethylmethacrylate).

We need to identify the eigenfrequencies of the illuminator’s structure for admissible operating conditions to be chosen. We assume that the performance of the illuminator needs to be analyzed under extreme conditions. The operating performance of a spotlight needs to be evaluated under maximum vibrations. For this purpose, their radiance pattern at different distances from the illuminator need to be calculated under highest possible deformations of the illuminator’s surface.

To study the influence of fabrication techniques on the spotlight performance, similar calculations were conducted with due regard for the optical surface roughness.

3. Ray tracing mathematical model

The searchlight’s construction consists of several types of surfaces, such as ellipsoidal, spherical and parabolic surfaces. Those surfaces are the second order surfaces. Therefore, to model the searchlight’s ray tracing, we were using exactly this type of surfaces. In general, such type of surfaces defines by following matrix equation:

\[
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
=
\begin{bmatrix}
    a_{11} & a_{12} & a_{13} & a_{14} \\
    a_{21} & a_{22} & a_{23} & a_{24} \\
    a_{31} & a_{32} & a_{33} & a_{34} \\
    a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    z \\
    1
\end{bmatrix}
= \mathbf{0}.
\]  

This is a quadratic form in which we can separate quadratic part from linear:

\[
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
= \begin{bmatrix}
    a_{11} & a_{12} & a_{13} \\
    a_{21} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
+ \begin{bmatrix}
    a_{14} & a_{24} & a_{34}
\end{bmatrix}^T
+ \begin{bmatrix}
    a_{41} & a_{42} & a_{43}
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
+ a_{44} = \mathbf{0}.
\]  

We introduce the notation:

\[
\begin{bmatrix}
    x \\
    y \\
    z
\end{bmatrix}
= \mathbf{\bar{r}},
\]

\[
\begin{bmatrix}
    a_{11} & a_{12} & a_{13} \\
    a_{21} & a_{22} & a_{23} \\
    a_{31} & a_{32} & a_{33}
\end{bmatrix}
= \mathbf{A},
\]

\[
\begin{bmatrix}
    a_{14} & a_{24} & a_{34}
\end{bmatrix}
= \mathbf{\bar{B}}.
\]

Finally, the equation (1) may be written in significantly compact form:

\[
\mathbf{\bar{r}}^T \mathbf{A} \mathbf{\bar{r}} + \mathbf{\bar{B}} \mathbf{\bar{r}} + a_{44} = \mathbf{0}
\]  

Using the formula (3), we can easily find an intersection point with the ray. Each ray was represented in parametric form

\[
\mathbf{\bar{r}} = \mathbf{\bar{r}_0} + t \mathbf{\bar{e}},
\]

where \(\mathbf{\bar{r}_0}\) - start point of ray, \(\mathbf{\bar{e}}\) - ray’s direction (\(\|\mathbf{\bar{e}}\|=1\)), \(t\) - intersection point parameter. Substituting fourth equation in to third we were obtained square equation relatively from parameter \(t\):

\[
(\mathbf{\bar{e}}^T, \mathbf{A} \mathbf{\bar{e}}) t^2 + (\mathbf{\bar{e}}^T, \mathbf{A} \mathbf{\bar{r}_0}) t + (\mathbf{\bar{B}}, \mathbf{\bar{e}}) + (\mathbf{\bar{r}_0}^T, \mathbf{A} \mathbf{\bar{e}}) + a_{44} = \mathbf{0}.
\]

Coordinates of each intersection point may be found by substitution solution (5) in to formula (4).

To determine the influence of surface properties on the light flux, we were using diffuse reflectance. Such type of reflectance may be easily modeled, using normal’s distribution function in specific solid angle, instead discrete normal. Value of such angle depends from surface roughness. The dependence of solid angle from surface roughness, which were using in our model is:
where $\rho$ - is surface roughness amplitude in millimeters, $\vec{n}$ - is smooth surface normal. Let’s $\|\vec{n}\|=1$ mm, then dependence may be written as:

$$\Omega = \frac{1 - \sqrt{1 - \rho^2}}{2\|\vec{n}\|}.$$  

4. Results of the study

The Eigenfrequencies of the 3D model of a spotlight were identified using the software program ANSYS Workbench. The majority of structural Eigenfrequencies were found to be in the ultrasound range, which does not produce frame-damaging vibrations. Otherwise, this would have resulted in a structural failure of the vehicle or building equipment. A feasible vibration frequency coincident with the structural resonant frequency is 2043 Hz. A deformation pattern of the illuminator’s light-reflecting surfaces on the frequency of 2043 Hz is shown in figure 5.

![Figure 5](image)

**Figure 5.** Deformation of light-reflecting surfaces of a spotlight on the Eigenfrequency 2043 Hz.

Vibrations of an aircraft or ship frame on the frequency of 2043 Hz are indicative of an emergency situation preceding a structural failure of the vehicle. In this case, the operating performance of the illuminator ceases to be relevant. Hence, under normal operation conditions of building equipment or transport vehicles, the light-emitting surfaces of the spotlight under study are practically deformation-free. Intensity patterns in the planes found 5 and 10 m away from the spotlight are shown in figure 6. Note that the calculations were conducted without regard for the optical surface roughness using the software Zemax (educational version, Samara University). The grid of the spotlight model was composed of 33,000 triangles, with the 3D model presented in the format .stl. Figure 6 suggests that the spotlight structure under study with perfectly smooth optical surfaces generates a light flux with a divergence angle of $\approx 0.7^\circ$.

Figure 7 depicts variations in the angular size of the beam reflected off the surface roughness in the planes found 5 and 10 m away. The simulated roughness features were the same in size as real light-reflecting surface roughness, being equal to Ra= 0.16 $\mu$m. At first, the effect of microroughness of light-reflecting surfaces on the light flux was studied using the software Zemax. For a 3D spotlight model, the program was run in a nonsequential mode. However, the functional capabilities of Zemax proved to be insufficient for solving the problem. This prompted the development of the program in Matlab. With the newly developed program, it became possible to identify variations in the angular size of the
beam reflected off the rough surface. The incident beam was 2 µm in diameter. A 5x5 µm detector was used to measure the light flux reflected off the rough surface.

Analysis of Figs. 6 and 7 suggests that:
1. The proposed design of a spotlight offers required operating performance and high-quality radiation pattern. An axisymmetric distribution of the light flux intensity is generated in different cross-sections (figure 6).
2. Light-reflecting surface roughness introduces essential distortions in the light flux shape. The intensity distribution in different cross-sections is not axisymmetric.

![Figure 6](image)

**Figure 6.** Intensity patterns (calculated without regard for light-reflecting surface roughness) in the planes found at (a) 5 m and (b) 10 m from the spotlight.

![Figure 7](image)

**Figure 7.** Variations in the angular size of the beam reflected off surface roughness $Ra = 0.16 \mu m$ (the angles of incidence and reflection of light are $45^\circ$, the detector is 5x5 µm in size, the incident beam is 2 µm in diameter, the distance from the detector to the point of light incidence on the rough surface is (a) 5 m and (b) 10 m.

These circumstances suggest that reflector fabrication techniques essentially affect the operating performance of the lighting device. In the authors' opinion, an optimal choice of the process of reflector fabrication and the spotlight scatterer shape will enhance its operating performance.

We also think that the proposed design of a lighting device is well suited for the operation under vibrations.

5. Conclusions
The study we have conducted has shown that:
- when transport vehicles and building equipment are used in normal operation conditions, a LED spotlight practically experiences no deformation on its Eigenfrequencies;
- on a vibration frequency critical for transport vehicles and building equipment, which corresponds to the spotlight Eigenfrequency (2043 Hz), only the first light-reflecting surface of
the illuminator is deformed. This drawback can be overcome by using a thicker aluminum sheet when fabricating the optical surface;

- roughness affects the intensity distribution of the light flux. An optimal choice of a technique for illuminator fabrication will enhance the illuminator's performance capabilities;
- the spotlight design studied can be recommended for use as aviation take-off/landing lights, ship signal lights, and at tall building cranes.

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