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Mixed reflection modeling based on a superposition of specular reflections

***Abstract**. The article proposes an alternative to the currently used method for calculations of the lighting effect (luminance distribution) derived from the flat surface of the reflector with mixed reflection (with features of both specular and diffuse reflection). The calculations used the ability to replace the mixed reflection as a superposition of specular reflections. Individual specular reflections are derived from the same reflection surface, but taking into account the specific deviation of the reflected beam from the specular reflection law direction, and using the specified weighting factor.*

***Streszczenie.** W artykule zaproponowano alternatywną, do obecnie stosowanych, metodę, pozwalającą na obliczenie efektu oświetleniowego (rozkładu luminancji) pochodzącego od płaskiej powierzchni odbłyśnika o odbiciu kierunkowo-rozproszonym (o cechach zarówno odbicia kierunkowego jak i rozproszonego). W obliczeniach wykorzystana jest możliwość zastąpienia odbicia kierunkowo-rozproszonego superpozycją odbić kierunkowych. Poszczególne odbicia kierunkowe pochodzą od tej samej powierzchni odbłyśnika, ale z uwzględnieniem określonego odchylenia wiązki odbitej od kierunku zgodnego z prawem odbicia kierunkowego, a także zastosowaniem określonego współczynnika skalującego. (**Modelowanie odbicia kierunkowo-rozproszonego na podstawie superpozycji odbić kierunkowych**).*

Keywords: lighting technology, luminaire calculations, mixed reflection
Słowa kluczowe: technika świetlna, obliczenia opraw oświetleniowych, odbicie kierunkowo-rozproszone

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Introducton

In the process of computer design of luminaires calculations are performed, as a result of which we want to obtain the lighting effect that will be visible in real circumstances, but having it only in the computer memory [1]. Lighting effect may be determined in various ways, e.g., as an illuminance distribution on the illuminated plane. If the resulting lighting effect is not suitable, we can make appropriate modifications to the optical system and re-check the results. Such a design process does not require building an expensive physical model, which is replaced by a mathematical model. In order to get the results sufficiently close to reality, we need to use a suitable mathematical model of a light source, reflective elements (reflectors), the light emission phenomenon and its interaction with the elements of the optical system [2].

The basic kind of reflection of light from a material, treating it at the macro scale are the specular reflection and the diffuse reflection [3, 6]. Both reflections are opposites. Specular reflection preserves the geometric features of the incident beam, such as divergence and photometric characteristics, i.e. luminous flux, luminous intensity and luminance are only reduced by reflectance. In contrast, diffuse reflection changes the geometric and photometric characteristics of the incident beam. It causes directing reflected light towards all directions available from the point of reflection within hemisphere [3]. Both types of reflection are described in an analytical way, which allows for their ease of use. Problems arise when we want to model the reflection of light encounter in the real materials because it has features of both basic reflections with different intensity, which are characteristic for a given material. There are different attempts of reflectance description, both real and feasible to implement in simulation tools [4, 5, 7, 8].

Generally speaking, a description of the nature of the reflection of luminous flux on the real materials (mixed reflection) is divided into two ways: discrete and continuous.

The discrete way comprises of a set of values in the form of an array, describing the relationship between the photometrics in the direction of observation and the direction of the incident light. This description is a result of measurements on a physical model and applies only to specific directions, for which measurements were performed. Other values are obtained as a result of interpolation. An example of a discrete description is indicatrix (relative luminance curve) relating luminance in the direction of observation to its value for a normal direction of observation, for a particular angle of incidence of illumination beam [3, 4, 5, 6]. This description is typical for calculations in lighting technology, where we are dealing with a particular material from which the resulting lighting effect we want to determine.

A continuous way, however, is a description based on an analytical function that links as in discrete way, photometrics in the direction of observation and the direction of the incident light. An example of this approach is the BRDF function (bi-directional reflectance distribution function). It combines the surrounded luminance of the point on the material surface viewed from any direction to the surrounded illuminance of the point in the light source direction [7, 8]. The description in the form of BRDF function is commonly used in computer graphics, which is primarily related to its analytical parameterized form, which allows for easy manipulation of the nature of reflection and thus visual effects. The BRDF may also be derived from measurements and have the form of an array (discrete).

In the simulation calculations, regardless of the method used, it is necessary to describe the conversion of the incident light beam on the material for the reflected beam. Function that allows such a conversion is described above indicatrix or BRDF. If the form of this function is discrete, then multiple calculations are required to solve the value of the function by interpolation from neighboring values [4]. In contrast, the continuous form of the function each time requires the substitution of data for analytical function and to solve it. An alternative method for the calculation may be to simulate the specular reflection and, on the basis of its results, obtain the effect for mixed reflection. Such an approach has already been proposed, but for the diffuse reflection and not mixed reflection [9].

This article has proposed modeling mixed reflection as a superposition of a finite number of specular reflections. Studies conducted by the author have shown that the mixed reflection may be presented with a certain approximation, using the superposition of a finite number of specular reflections, except that each of these reflections have a certain deviation of direction with respect to the specular direction law resulting from equal angles of incidence and reflection, and scaling with the weighting factor.

The research method

Researches were carried out on the basis of author's calculations tool for determining the profile of a trough-shaped reflector based on the MS Excel environment [10]. It allows to calculate the luminance distribution resulting from the light source and the reflector on the illuminated object along the characteristic line, which is the vertical axis of symmetry of the generated light spot. The input data for the calculations are luminance distributions on the light source surface registered from directions contained in the calculation plane. Moreover, the input data includes luminance distributions produced by the light source on the perpendicular screen to the plane of the calculations. The reflector part is defined as a flat mirror surface of a certain size and position relative to the light source, which is the zone of the trough–shaped reflector.

Using these computing tool, the author made a series of calculations of lighting effects resulting from the zone of reflector with specular reflection. The first calculation has the reflected beam geometric parameters of the incident beam at the reflector, according to the specular reflection law. Subsequent calculations differed only in the deliberate introduction of an appropriate deviation of the reflected beam with respect to the reflection law. In this way, a set of luminance distributions was obtained along analyzed line within the light spot. Finally the obtained set of luminance distributions was scaled using empirically determined weighting factors and the resulting distribution was averaged. The averaged obtained luminance distribution sought to conduct properties for mixed reflection beam.

Model justification

Reflector's materials are described in theoretical way by means of two models of light reflection – specular reflection and diffuse reflection (Fig. 1). For this reason, they are present only in theory, but as practice shows, scattering of luminous flux in the range of up to 5° shows that the material can be treated as specular [5].

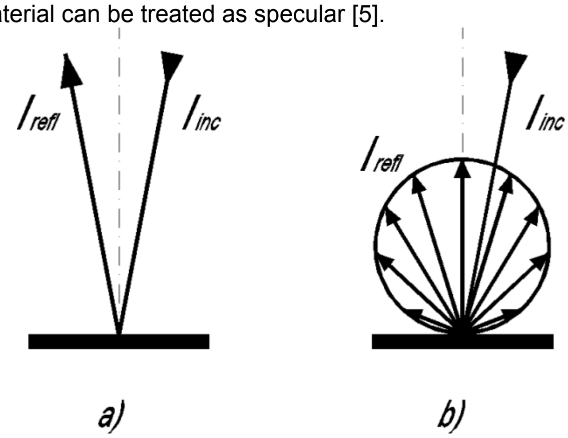

Fig.1. Luminous intensity distributions of luminous flux reflected from surface a) specular, b) diffuse (I_{inc} – incidence luminous intensity, I_{refl} - reflected luminous intensity)

The materials that the real reflectors are made from are the combination of both types of reflections (specular and diffuse) with proportion characteristic of the material used. Thus, the real materials have to be described using the mixed reflection model (Fig. 2).

Analyzing the equations to calculate the reflected luminous flux, assuming the rotational symmetry of luminous intensity distributions, for specular reflection (1) and mixed reflection (2), we can realize a certain property. If the integration range marked from 0 to π in the formula for mixed reflection (2) is split into smaller ranges (3), the mixed reflection becomes a superposition of specular reflections.

(1) $$\phi_{rs} = 2\pi I_{r\gamma} \int_0^{\gamma} sin\gamma d\gamma$$

(2) $$\phi_{rm} = 2\pi \int_0^{\pi} I_{r\gamma} sin\gamma d\gamma$$

(3) $$\phi_{rm} = 2\pi I_{r\gamma_1} \int_0^{\gamma_1} sin\gamma d\gamma + \cdots + 2\pi I_{r\gamma_n} \int_{\gamma_n}^{\pi} sin\gamma d\gamma$$

where: ϕ_{rs} - luminous flux (ϕ) reflected (r) under specular reflection (s), ϕ_{rm} - reflected luminous flux under mixed reflection (m), γ - angle determining divergence of reflected beam, $I_{r\gamma}$ - luminous intensity (I) of reflected beam under direction angle γ.

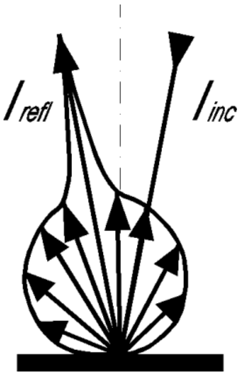

Fig.2. Luminous intensity distributions of luminous flux reflected from mixed surface (I_{inc} – incidence luminous intensity, I_{refl} - reflected luminous intensity)

Referring to equation (2) for the mixed reflection, the following substitutions can be made:

(4) $$I_{r\gamma} = I_{r0} I_{rw}$$

where: I_{r0}- luminous intensity of reflected beam under surface normal direction, I_{rw} is an indicatrix, which determines what part of the axial luminous intensity states luminous intensity in the direction of the reflected beam γ.

Sample calculations results

As mentioned above, the luminance distribution along the axis of a light spot (named on figures 3, 4, 5, 6 as position along analyzed line) derived from the flat mirror with mixed reflection properties can be obtained by performing a series of calculations for specular reflection, but for those calculations we need to introduce a beam deviation and a weighting factor. After summing and averaging we can obtain a luminance distribution for mixed reflection, that we are looking for.

To apply this method we need a reference luminance distribution derived from the reflected luminous flux with a mixed reflection registered in optical system that belongs to the set of optical systems intended for further calculations. Such reference distribution can be achieved in two ways - first in the form of laboratory measurements using matrix luminance meter and the other in the form of a computer simulation.

When we have such a reference distribution, we can carry out the selection of the weighting factors and the deviation of the reflected beam. We do this based on the modeling of the same optical system that was used to capture a reference distribution, but using our calculation tool. First we calculate the luminance distribution derived from the analyzed reflector using specular reflection. Then we compare it with the reference distribution, which is derived from mixed reflection on the same optical system. We can see that the distributions are different, since the reference distribution comes from mixed reflection and the calculated distribution comes from specular reflection. So, we choose the weighting factor ε, to scale calculated distribution to fit the reference distribution (we calibrate the luminance). Then again, we calculate the luminance distribution, but with deviation angle α of the reflected beam and scaling by a ε factor of weight, so that if we add a two calculated distributions strive to "fill" reference distribution (with mixed reflection) by a set of specular reflections. In the same way we proceed with further calculations of specular reflections, by matching the deviation of the reflected beam and the weighting factor of scaling the distributions, so as to approach as closely as possible the distribution derived from the sum of the calculated distributions of specular reflections to the reference distribution with mixed reflection. In this work a selection of the angles α and weighting factors ε were applied as successive approximations based on visual assessment of obtained distributions. This does not preclude the use of other methods of selection. The individual components of the described procedure are shown in Figure 3. It consists of the base distributions, which are derived from the same optical system with specular reflection but have different positions, because of applied deliberate deviation of the reflected beam by an angle α from the direction according to specular reflection law. For such distributions we introduce weighting factors ε to "fill" the reference distribution, and thus form the scaled distribution. Finally we have an approximation of the reference distribution. However, Figure 3 shows a special case when the individual distributions do not overlap each other. This eliminates the need to average the distribution, which is the sum of the base distributions, which greatly facilitates the understanding of the method.

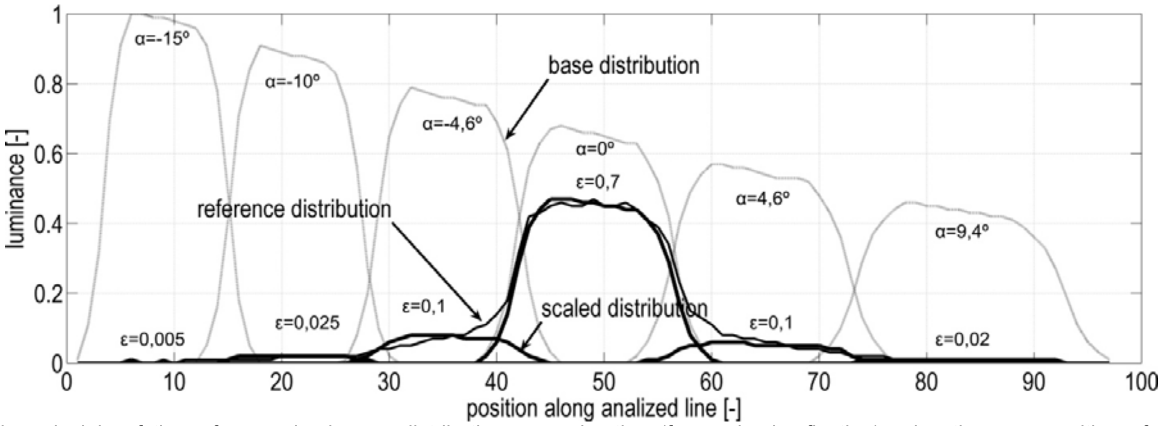

Fig.3. The principle of the reference luminance distribution approximation (from mixed reflection) using the superposition of specular distributions

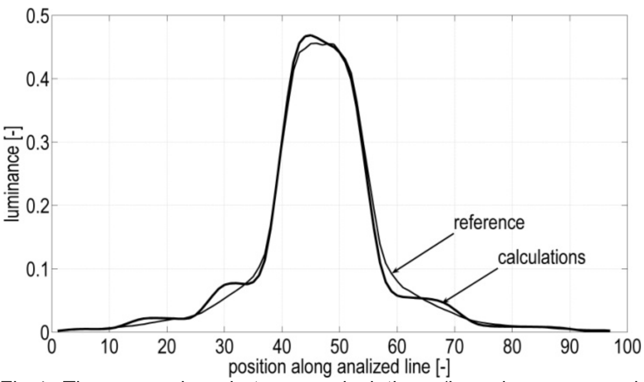

Fig.4. The comparison between calculations (based on proposed method) and the reference distribution of luminance

Figure 4 allows to evaluate the results of superposition of the individually scaled distributions (calculations), by comparing it with the reference distribution. Therefore the reference distribution was estimated with calculated distributions, which was the goal of the task.

As a check of the usefulness and accuracy of the proposed method, calculations must be made using pre-designated deviation angles α and weighting factors ε for the other dimensions and aiming of the reflector with the same kind of reflection of light. The following figures (Fig. 5 and 6) contain comparison of the calculated luminance distributions with distributions obtained using a computer simulation program, which was used to determine the reference luminance distribution, which lead to designate the angles α and weighting factor ε. Figure 5 was made in respect to previous calculated zone of reflector, but with a 10° change in aiming. In Figure 6 the changes are even greater and in relation to Figure 5 concern: aiming change of 2º, reducing the size of the reflector in the plane of the analysis from 20 to 10 mm and changing the position of the lower edge of 4.5 mm.

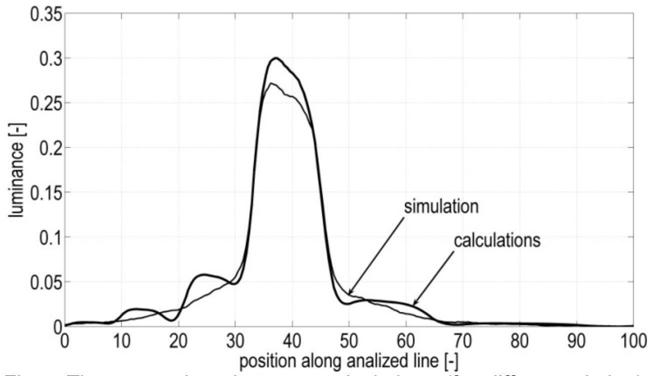

Fig.5. The comparison between calculations (for different aiming) and the reference distribution as simulation

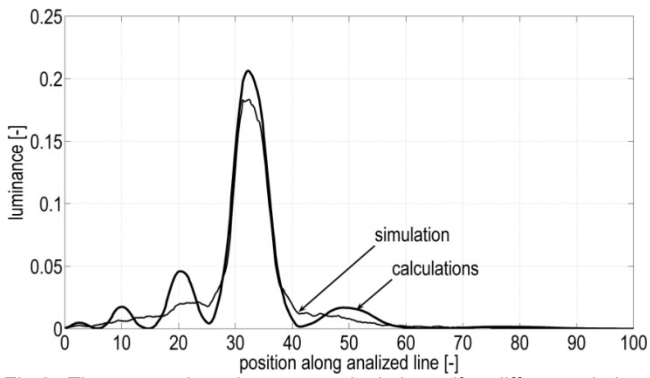

Fig.6. The comparison between calculations (for different aiming and different size of reflector facet) and the reference distribution as simulation

Comparison of distributions on Figures 5 and 6 shows the convergence of the simulated geometries which differ from those for which α and ε were designate, but with the same material of reflector. However, there is a need for averaging the results. Averaging the results was not necessary in Figure 4, where both reference and calculated luminance distributions relate to the same optical system. In Figures 5 and 6, the optical system has been modified, but the angles α and weights ε are nevertheless correct, although the angles of light incidence on a material have changed in the nature of the observed reflections. With increasing angle of incidence the specular reflection properties are enhanced [8].

Conclusions

The presented method and the results show an alternative way to simulate mixed reflection, which is not described analytically as it is in the case of specular and diffuse reflection. For this reason, there are many more or less accurate models of such reflections.

The presented results of the work have been so far an unused way of mixed reflection calculations, by means of a set of specular reflections with different weights and deviation, selected in the calibration process.

The advantage of the presented method is the ability to take into account the calculations of mixed reflection using the tool for specular reflection calculations. Only minor modifications are required to the algorithm and the process of choosing the weights and angles of deviation from the exemplary lighting effect (luminance distribution), which was measured or calculated in another program and originated from reflection of the luminous flux from the material.

The overall benefit is to allow calculations of optical systems with real materials which have characteristics of both specular and diffuse reflection.

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