Prediction of LED luminaire spectral power distribution using a mathematical model developed based on the interpolation method

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Abstract—LED luminaires with controllable luminous flux are increasingly used, mainly due to the need to reduce electricity consumption, which is the equivalent of improving the energy efficiency of a lighting installation. Changing the dimming level changes the spectral power distribution of the luminaire or light source.The knowledge of dimming characteristics including spectral power distribution relationships provides the opportunity to optimize control algorithms and predict the impact of lighting parameters on the work surface. The paper presents a mathematical model to calculate the spectral power distribution of an LED luminaire for any level of dimming. Two interpolation methods were used to develop the model, fitted by polynomial functions and spline functions. The validation of the model was performed for two values of control voltage-dimming levels.

LED luminaires with controlled luminous flux (active power) are now widely used in both indoor lighting and road lighting. The main goal of the control is, of course, to reduce electricity consumption, which is the equivalent of improving energy efficiency. Reducing electricity consumption also reduces greenhouse gas and other pollutants emitted into the atmosphere during the electricity generation process [1–2].

For a significant part of LED luminaires available on the market, manufacturers do not provide dimming characteristics. By dimming characteristics it is meant the dependence of electrical, photometric, and colorimetric parameters as a function of dimming. The knowledge of these characteristics makes it possible to estimate both the impact on the mains of a luminaire operating at a given dimming level and also to calculate the lighting parameters on the work surface. Moreover, knowing the dependence of the spectral power distribution (SPD), it is possible to predict the photobiological impact. In addition, from the point of view of optimizing control algorithms, it is important to know as many dimming characteristics of photometric, colorimetric, and electrical quantities as possible.

In this article, a model will be presented to determine the SPD of a dimmable LED luminaire for the entire dimming range. The model was developed for an LED luminaire used in road lighting with a power rating of 32W. The luminaire is equipped with a power supply with analog control input made standard 1–10 V. The SPD was measured with a GL Spectis Touch 5.0 spectroscope from GL Optics. The SPD was measured for the entire available dimming range in 1V increments. The used spectroradiometer allowed measurements with a resolution of 1nm. The dependence of SPD as a function of the dimming of the tested LED luminaire is shown in Fig. 1.

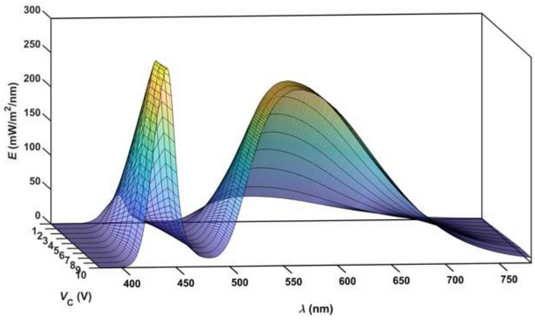


Fig. 1. The SPD of the LED luminaire in the 1–10V dimming range.

In the case of the tested luminaire, it was found that in the range of 8V to 10V, the luminaire lit with full luminous flux. However, it was decided that the mathematical model would be developed for the entire dimming range and not for the limited 1–8V range.

The linear regression method was used to develop the model. It is a relatively simple method that also provides the required accuracy [3–5]. The accuracy measure of the fit is the root mean square error R^2. Two methods were chosen to develop the model: interpolation by polynomial and spline functions. The first method is a parametric method that results in an interpolating polynomial with specific coefficients. The form of such a polynomial interpolating the SPD for a given wavelength λ can be written as follows:

$$E_\lambda(V_C) = \sum_{i=0}^{m} a_i V_{C,i}, \tag{1}$$

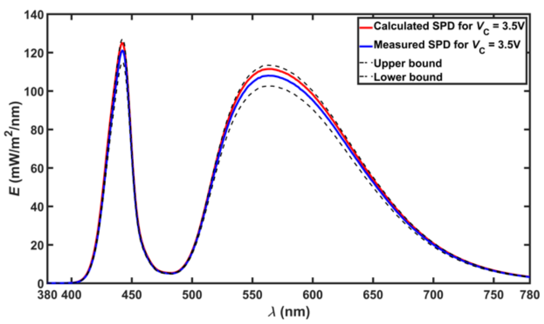
where the coefficients a_i are the parameters of the polynomial.

The model developed by the method using interpolation with spline functions is a non-parametric method, that is, the interpolating relationship is not obtained explicitly.

The range of visible radiation from 380 nm to 780 nm was selected for analysis. In the first stage, 401 vectors containing the measured values of luminaire SPD for the analyzed dimming range were generated. Each vector for a given wavelength λ contains 10 radiant power values corresponding to given dimming levels. The same number of models was then developed for the two linear regression methods mentioned earlier. It was assumed that the accuracy of the fit could not be less than $R^2 = 0.95$. For the method using spline functions, R^2 error values are equal to 1. For the method using polynomial functions, interpolation using a linear function (1-degree polynomial) was sufficient to ensure the required fitting accuracy. Only for a wavelength of 380 nm was a 4th degree polynomial determined. Grade 3 interpolating polynomials were obtained for the following wavelengths from 381 nm to 386 nm, 388 nm to 396 nm, and for λ = 401 nm. All calculations were performed in the Matlab environment using the Curve Fitting Toolbox.

For purpose of verifying the accuracy of the developed model, a comparison was made between the SPD calculated using the model and the measured values. Verification was performed for two control voltage values V_C = 3.5 V and V_C = 6.5 V. Figures 2a and 2b show a comparison of measured and calculated SPD with a marked confidence level of 0.95 for the method using polynomial interpolation and the method using spline functions for V_C = 3.5 V, respectively. In addition, to verify the validity of the model, selected CIE 1931 parameters were calculated and compared with measured values (Table 1). Figure 3 shows the calculated fitting errors for each wavelength.

a)



b)

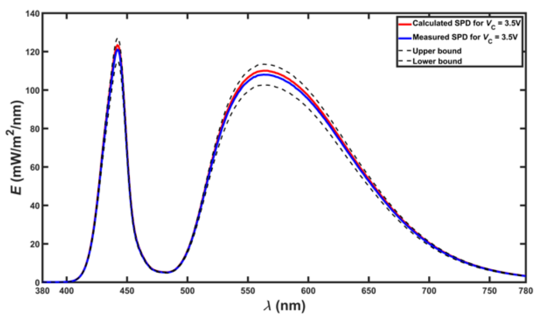


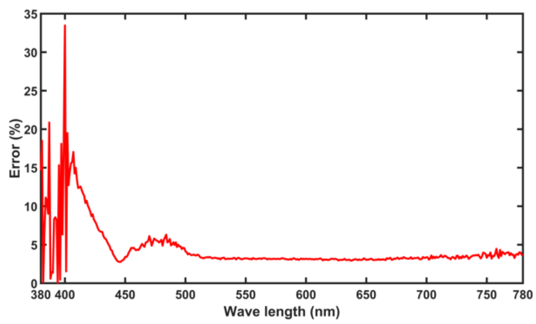
Fig. 2. Comparison of the SPD of the tested luminaire measured and calculated for V_C = 3.5V and (a) by the method using polynomial functions (b) by the method using spline functions.

Table 1. Comparison of selected CIE 1931 measured and calculated parameters for V_C = 3.5 V.

Parameter	Measured quantity	Calculated quantity - polynomial	Calculated quantity - spline functions	ΔE_p (%)	ΔE_s (%)
x	0.3887	0.3878	0.3885	0.23	0.05
y	0.3925	0.3911	0.3921	0.36	0.10
u'	0.2243	0.2211	0.2243	1.43	0.00
v'	0.5095	0.5088	0.5093	0.14	0.04
CCT (K)	3900	3909.9	3899.2	0.25	0.02

ΔE_p – relative error for method using polynomial functions
ΔE_s – relative error for method using spline functions

a)



b)

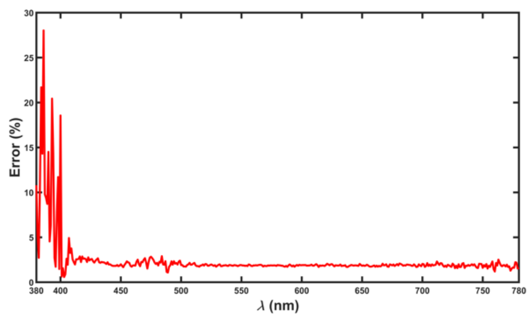
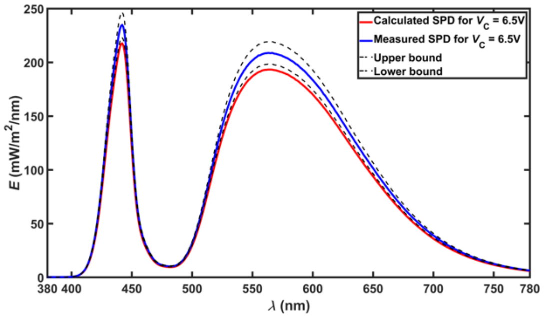


Fig. 3. Fitting error calculated for V_C = 3.5 V: a) the method using polynomial functions, b) the method using spline functions.

Figure 4 shows a comparison of the SPD of the tested LED luminaire obtained from measurements and calculated with a marked confidence level of 0.95 for the method using polynomial interpolation and the method using glued functions for V_C = 6.5 V, respectively. Similarly, Table 2 compares measured and calculated CIE 1931 quantities along with calculated relative error values.

a)



b)

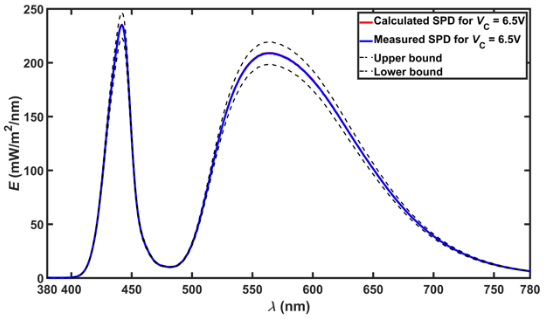
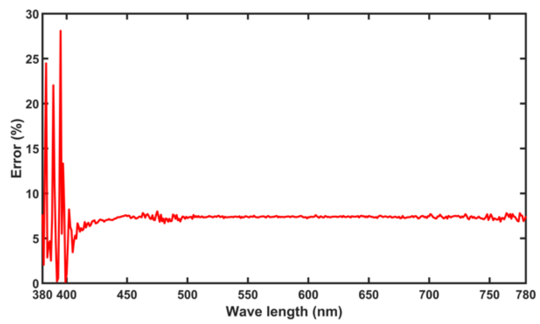


Fig. 4. Comparison of the SPD of the tested luminaire measured and calculated for V_C = 6.5V and (a) by the method using polynomial functions (b) by the method using spline functions.

Table 2. Comparison of selected CIE 1931 measured and calculated parameters for VC = 6.5 V.

Parameter	Measured quantity	Calculated quantity - polynomial	Calculated quantity- spline functions	ΔE_p (%)	ΔE_s (%)
x	0.3867	0.3864	0.3865	0.08	0.05
y	0.3896	0.3892	0.3893	0.10	0.08
u’	0.2241	0.2241	0.2241	0.00	0.00
v’	0.508	0.5078	0.5079	0.04	0.02
CCT (K)	3931	3930.4	3929.2	0.02	0.05

a)



b)

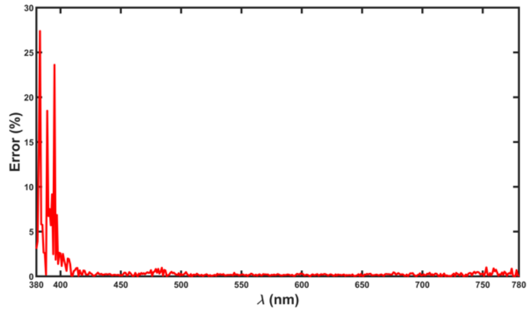


Fig. 3. Fitting error calculated for V_C = 6.5 V a) the method using polynomial functions b) the method using spline functions.

The matching error has the largest values for the wavelength range of 380–400 nm. This is due to the small level of the useful signal with the simultaneous presence of measurement noise. The high value of the error in this range of wavelengths does not noticeably affect the obtained results, since the share of LED luminaire radiation in this range compared to the entire analyzed spectrum is small. Thus, the relatively large values of fitting errors that occur in this wavelength range do not significantly affect the accuracy of the model.

In summary, the developed model allows us to predict, with assumed accuracy the SPD of a dimmable LED luminaire used in road lighting over the entire dimming range. Using the model, the SPD can be calculated over the entire range of visible radiation as well as the radiation power determined for a given wavelength. The presented method of model development can be used for any dimmable luminaire or light source.

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