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*Stanisław Kosek**

Methods of estimation of colour rendition**

In this paper the object as well as the methods of estimation of the so-called colour rendition (which is a visual property of radiation) have been discussed, and the practical realization of the estimation procedure described. An improvement of the Mobar meter produced in Poland has been proposed.

1. Introduction

The proper colouring of objects is of a great importance in different aspects of production, work safety, handicraft, and art. For this reason a considerable attention is payed to right illumination and proper colour rendition, as well as to the methods of colour rendition estimation.

The colour rendition of the object is connected with spectrum distribution of the incident radiation. The coloured appearence of the objects depends on the said distribution as well as on the spectral luminance factor of the object, thus, on the colour properties of the object material. The same colours look differently at different spectral distributions of the incident light, as well as different colours look differently when illuminated in the same way.

In the methods of colour rendition estimation the chromaticity of the object under given illumination condition is referred to its chromaticity when illuminated by a reference illuminant. The colorimetric terminology used hereafter is specified in numerous publications of International Comission for Illumination CIE [1] and in a Polish monograph [2].

In the course of research on colour rendition two methods of its estimation have been elaborated [3–8]; they were next aproved by CIE and recommended for international use. Both methods are relative and refer the colour rendition estimation of a given radiation to a reference illuminant, but are based on different colorimetric relations. In the method of testing colours (indicators) actually recommended the above mentioned notion of chromaticity is used, while the historically earlier method of spectral bands employes the notion of relative distribution of radiation in the bands.

* Research and Development Center of Illumination Technique, Warsaw, Poland.

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2. Method of spectral bands

In this method the estimation of the colour rendition property consists in comparing the spectral distribution of the light flux (or luminance) from the examined light source within each of the spectral bands with the respective flux distribution (or luminance) of the reference source, provided that average values of ordinates of these spectral distributions are equated for both the sources.

The starting point for examination was an assumption that the relative flux of energy band is a measure of colour deformation. A consistency condition of this assumption is a colorimetric equivalence of these bands. The latter requires that the same changes of the flux in each of the bands be accompanied by the same colorimetric deformation. With these assumptions a unique choice of the band position and width is not possible, due to various proportions in the spectral density of the radiation flux from different sources. Therefore the choice must be made for definite types of sources. The development of the method was directed toward weighting the flux sources and dividing the spectrum into the bands, so that the best consistency with the visual method be obtained. The weighting of the radiation flux of the sources has been achieved by introducing a function weighting colour sensitivity of the eye to the spectral distribution of radiation. This method has been developed by Bouma [3], Kruithof [4], Barnes [5], Grawford [6] and Winch [7].

The method of consistency coefficients (i.e. sum of absolute values of differences in spectral distribution ordinates for examined and reference sources, calculated in equal wavelength distances along the whole visual spectrum) widely used in the U.S. was a precursory one of the spectral bands method, since the former does not take account of the colour sensitivity of the eye and its applicability is limited.

The method of testing colours elaborated by the CIE experts was based on a quite different principle [8]. The applicability of these two methods was compared by Ouweltjes [9] who took adventage of the modern techniques available in the Philips Laboratory. The author stated that the most complete and worth recommendation is the method of testing colours. This method has been suggested by CIE in 1965 for international use [8].

3. Method of test colours

Independent role played by the spectral characteristics of colour and the illuminating radiation distribution implies a solution of the colour rendition evaluation problem, by using a vector between the respective chromaticity points of the radiation incident on the viewed object, and the radiation reflected from the object. In the normal system of trichromatic coordinates $x\ y\ z$, recommended by the CIE in 1931 [10], the usage of this vector would not give, however, any reliable results, as the difference of the $x\ y\ z$ trichromatic coordinates of colours differing visibly depends strongly on the position of their chromaticity points in the colour triangle of the system. Therefore, it appeared reasonable to employ the so-called uniform system of trichromatic coordinates suggested by MacAdam [11], and recommended in 1959 by CIE for common use [12]. In the uniform system the perceptible difference is approximately the same for the whole colour diagram (triangle).

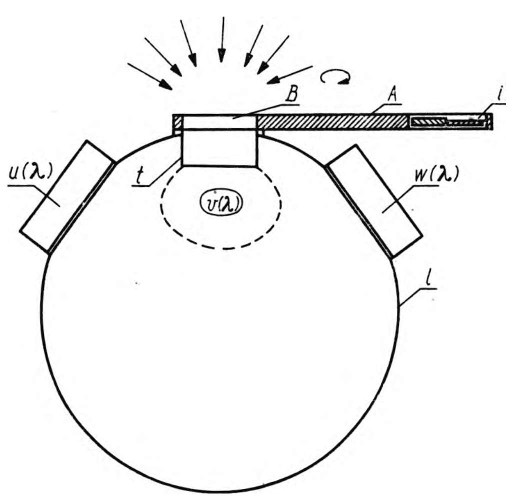

Fig. 1. Trichromatic colorimeter of the colour rendition meter Mobar

Notations: A — rotatable disk with ten apertures, B — an empty aperture, i — one of eight sets of filters installed in the disk, the spectral characteristics of transmission coefficient being close to spectral characteristics of luminance coefficients for recommended testing colours, l — lumenmeter, t — cylindric diaphragm conversing receptors $\bar{u}(\lambda)$, $\bar{v}(\lambda)$ and $\bar{w}(\lambda)$ before direct illumination with the measured beam

Due to this property the vector length (between the chromatic point of two colours) on the diagram (of uniform system of colours) is directly proportional to the perceptible differences of colours, thus it has a univocal meaning. The usage of the colorimetric deformation of one colour does not allow to determine properly the properties of colour rendition of each visible radiation from numerous contemporary light sources (the monochromatic radiation being excluded e.g. that of low-pressure sodium lamp).

For instance: the infrared radiation will approximately properly render the red colours, but green and blue colours will not be rightly percepted. For this reason, in order to determine the colour rendition properties in a way representative of the whole colour triangle, a set of fourteen colours defining fourteen indicators of colour rendition has been chosen. The arithmetic average of the first eight indicators gives a universal evaluation of colour rendition and is called a general indicator.

In order to express the colour rendition evaluation in a possibly simple and suggestive way the general indicator has been represented by a number included between 0 and 100, assuming two characteristic points: the number 100 at an ideal colour rendition assumed for the black body radiation or the reconstructed day radiation [13], and the number 50 for the warm-white fluorescent lamps. The assumption of the characteristic point of the scale equal to 100 implies such a form of the calculating formula, that for arbitrary thermal radiation or the reconstructed day radiation the term in the formula representing the colorimetric deformation of the testing colours for the measured and reference radiation be reduced to zero. The colorimetric deformation is defined as the difference of vectors between the chromaticity points for incident and reflected radiation. If spectral distribution and intensity of the measured radiation is identical with those of reference radiation, then difference of the vectors becomes zero. In the general case of an arbitrary radiation and an arbitrary colour the difference of vectors defined above takes a finite value, and the indicators of colour rendition defined by the formulae given below are smaller than 100.

$$\Delta E_i = [(U_{r,i}-U_{k,i})^2+(V_{r,i}-V_{k,i})^2+(W_{r,i}-W_{k,i})^2]^{1/2}, \tag{1a}$$

$$R_i = 100-4.6\,\Delta E_i, \tag{1b}$$

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i, \tag{1c}$$

where ΔE_i is a modulus of the difference of vectors U, V, W, calculated in the CIE 1964 uniform space of colours for the measured radiation (with index k) and the reference radiation (with index r), R_i and R_a being particular and general indicators of colour rendition, respectively. The black body radiation accepted in the temperature range of spectral distribution up to 5000 K or a reconstructed day radiation above this temperature range, has been accepted as a reference radiation (the so-called illuminants). The choice of reference illuminant for each case of measured radiation is the problem which should be discussed. The solution recommended by CIE in 1971 (in the Institute of Electrotechnics has been used since 1969, see formula (1) in report (14)) consists in finding a minimum of the expression.

$$\Delta C = [(u_r - u_k)^2 - (v_r - v_k)^2]^{1/2}, \qquad (2)$$

where which u_k, u_r and v_k, v_r are the trichromatic uniform coordinates for examined and reference radiation, respectively. Thus such an illuminant should be chosen within the set of possible reference illuminants that its chromaticity point in the uniform diagram be the nearest to the chromaticity point of the radiation measured. In 1967 JUDD suggested the so-called flattery indicator of colour rendition [15] derived from the general CIE colour rendition by adding to the CIE formula an additional term characterizing the tested samples when illuminated with the refeence source. The applicability of this indicator is now being discussed [16] and [17]. Other propositions of the colour rendering index formula were also published [18–20].

4. Practical realization of the method

The majority of users employ the relative spectrum distribution determined photometrically to evaluate the colour rendition properties. In the method of bands first the radiation content in the bands is measured or calculated, by taking account of the eye sensitivity distribution, and next the same is done for the sum of differences in radiation flux content in the bands with respect to the reference illuminant. In the testing colours method the trichromatic coordinates of the examined radiation, as well as those transformed by the testing colours, are calculated from the radiation distribution, and next the colorimetrical deformation is evaluated from (1a) using successively the known trichromatic coordinates of the reference illuminants, particular indicators (1b) and finally a general indicator averaged over first eight of the latter (1c). The calculations are complex (for instance, the finding of a right reference illuminant, and taking account of the chromatic adaptation, which is practiced recently) and realized on the computers, according to more or less complex programmes depending on the required accuracy and efficiency.

Alternatively, in the method of testing colours we may immediately measure the trichromatic colorimetric coordinates of the mentioned radiations. On this basis a colour rendition meter called Mobar was built at the Institute of Electrotechnics in 1970 [21]. This meter allows to measure the uniform coordinates of the examined and reference radiations, as well as the coordinates of both radiations when filtered through the sets of colour optical filters, equivalent to those recommended for colour tests. The results of uniform coordinate measurement allow to calculate: the colorimetric deformations (the examined radiation against reference radiation), first eight of fourteen particular indicators, and the general indicator evaluated as an average value of the first eight particular indicators; in the latter chromatic adaptation can eventually be taken into account [22].

The colorimeter built in the meter is an Ulbricht photometric sphere equipped with three receptors of the uniform trichromatic coordinate system u, v, w [23], which are located symmetrically around the input aperture and directed toward the inside. These receptors are the selenium cells produced by B. Lange firm and corrected with the sets of Schott glass filters. The sphere assures an equal illumination of all the receptors, as they receive light scattered inside the sphere not that falling directly. A disk fastened above the entrance aperture has one empty hole and the other eight filled with a set of filters equivalent to those recommended for Munsell testing colours. The diaphragming of the entrance aperture in the sphere is realized by rotating the disk. In the design solutions the rotational symmetry of the photometric apertures has been assured and corrective filters in the form of circular zone sets have been applied. In this way a simple construction and high sensitivity are achieved. The transmission characteristics of the sets of filters — because of their shape — are independent of the circle radius. This property is especially useful in designing the devices with the sources of compact filaments, or rounded surface of the radiating filament, and cylindrical surfaces shaping the transmitted light beam.

5. Application of Mobar device

Mobar may be used to perform a wide variety of photometric and colorimetric measurements, e.g.:

1. Illumination intensity as well-corrected luxmeter.

2. Total transmission coefficient of colour optical filters by using a standard as an adjustable illuminant. In both the types of measurements the receptor $\bar{v}(\lambda)$ of the spectral sensitivity is identical with the relative spectral efficiency $V(\lambda)$.

3. Uniform trichromatic coordinates of various radiations coming for instance from signalling lamps.

Moreover, if associated with a monochromator the Mobar meter may be employed to determine:

4. Spectral sensitivity distributions of cells and the average value of spectral characteristics of cells joined parallely, and also deviations of the spectral sensitivity distributions of cells joined in a push-pull system.

5. Receptor spectral distributions, i.e. measurements of cells with corrective filters.

The measurements mentioned in items 4 and 5 are performed with an own Mobar system standard as an adjustable illuminant.

6. Spectral distributions of the transmission coefficient of one to eight (in one experiment) optical filters. However, after diaphragming the empty aperture with a glass plate we obtain immediatelly the value of the internal transmission coefficient of measured filters. The read-out (in promilles) is made on a digidial of the precise potentiometer, which makes the measurement quick and eliminates the erroneous read-outs [21]. The compensator system of Mobar may be adjusted for mass measurements, so that each coordinate be read on the digidial of a separate precision potentiometer. If radiations are similar the manipulation is reduced to small rotating of the potentiometers, which results in reduction of the time of trichromatic coordinates [24].

5.1. The forseen development of Mobar

The most dramatic restriction in measurement accuracy of trichromatic coordinates in Mobar colorimeter is in instability of the selenium photoelectric cell as the radiation receiver. Nowadays, it is possible to apply more stable silicon cells, which may be corrected as receptors of uniform trichromatic coordinates, as indicated e.g. in [25]. Separate correction of parts of the receptors u and w with layer filter stocks and electrical photocurrent sumation can also be considered. An improvement of receptor stability would reduce the random errors, while the betterment of correction accuracy leads to diminishing of the systematic errors. It is worth noting, that the accuracy of trichromatic coordinate measurements of the to-day's Mobar device does not deviate from that of other trichromatic colorimeters (error of order of 1%) but is generally too small, because the complex form of the formula (1) for the general indicator R_a leads to an excessive resultant error of its value

$$\delta R_a = \sum_{i=1}^{8} \left[\sum_{x_j=u,v,w} \frac{\delta R_a}{\delta x_j} \middle| \Delta x_j \right]_i \tag{3}$$

of order of 10 units i.e. 10% of the indicator value.

The Mobar standard contains a source of radiation on continuously adjustable colour temperature for producing an illuminant simulating the filament type illumination, as well as different phases of daylight illumination. The actual adjustment of colour temperature by changing the feeding of the filament lamp is accompanied by extraordinary rapid changes of emitted and used light fluxes. The flux changes are compensated by a considerable change in position of the electric bulb with respect to the colorimeter objective, which makes the calibration very tedious. Besides, the BG34 Schott optical filters, used in the actual construction to raise the temperature of spectral distribution, introduce additional systematic errors in the part of the range of higher colour temperatures. These errors differ from those obtained without the filters in the lower colour temperature range.

Because of a reserve of light flux existing in the Mobar standard the temperature of the spectral distribution can be raised continuously in one way, i.e. by applying a BG34 filter of variable thickness (a wedge shifted with respect to a slit). Moreover, the improvement in standard source correction can be signalized by coupling the wedge with properly chosen colour filters and a profiled diaphragm, e.g. according to [26]. The application of such a regulation of the standards allows to simplify both the operation principle and the design, to restrict the measurement manipulation, and to reduce the errors. This principle of compensator in the improved form has been realized and proved in [27] and [28], the photoelectric current transformer build in Poland [29] can also be applied.

Since the method of test colours, which was incorporated in Mobar and is used in numerous papers (Jerome [30], Wyszecki [31], Koedam and Opstelten [32], Ouweltjes [33], Walter [34], Thoronton [17] and [18], the latter presenting also other methods consisting in using the colour contrast) has been recommended once more by CIE, and the Polish Illumination Committee also recommends this method for this country, therefore it seemed to be advantageous to modernize the principle of the Polish solution of the meter as suggested in this paper, and in the case of success to automise the device to create a set of colorimetric meters based on universal principle of Mobar.

Методы оценки отображения цветов

Описан предмет и методы оценки свойства видимого излучения, называемого отображением цветов, а также способы практической реализации метода оценки. Предложено усовершенствование созданного в Польше измерителя отображения цветов „Мобар".

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