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A METHOD FOR REDUNDANT MEASUREMENTS OF BRIGHTNESS

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Abstract: The paper considers some theoretical problems, concerned with automatic correction of systematic errors, occurring in determination of real values of brightness under a nonlinear transfer function of a photoelectric transducer. A version of a solution for the problem of linearization of a general transfer function of digital brightness meters is given. The paper describes a procedure of a linearization, based on the functional-algorithmic methods, grounded on application of quantities substitution formulas. The redundant measurements equations are derived. It is shown, that it is necessary to generate correcting physical quantities, homogeneous with a measured physical quantity, associated with it by a certain dependence and providing realization of the proposed redundant measurements method.
Keywords: brightness, redundant measurements, error correction

1 INTRODUCTION

One high-priority photometric problem consists in a metrologic provision, made for different methods and means, aimed at measurement both of photometric quantities (PhoQ) and characteristics of light. The problem, concerned with a highly-accurate brightness measurement, is among the most important photometric measurement problems. This point is associated with study of brightness, produced by light sources of different physical nature or by illuminated or light-scattering objects, as well as with various requirements, set forth by practical photometry.

The known brightness measurement methods are based on the proportional dependence, which is between ray beam brightness B_x and luminous flux F_x [1], i.e.

$$B_x = F_x / G \,, \tag{1}$$

where G is a value (geometric factor), constant for an applied optical system, through which a ray beam passes onto a light-sensitive surface of a photoelement (PE). The devices, used for beam brightness calculations and based on measurements of a luminous beam flux, are known to be the brightness meters, the main functional units of which are an optical system, a photoelectric transducer (PET), a millivoltmeter, or some other (analog or digital) measurement instrument.

2 BRIGHTNESS MEASUREMENT PROBLEMS: THEORY AND PRACTICE

The known brightness meters possess a linear transfer function (TF), which means to convert luminous fluxes into electric currents or into voltages, but this is done only within limited measurement ranges. This matter is due to the fact, that it is necessary to achieve a specified accuracy by way of narrowing of a measurement range and, therefore, to eliminate an error, caused by TF nonlinearity. In fact, in photodiodes (PD), under mean values of illuminance, a photocurrent value is linearly dependent on a value of a luminous flux, coming to a light-sensitive PD surface. However, when illuminance values are small or sufficiently large, this dependence becomes nonlinear [2].

Another drawback, possessed by semiconductor PEs of PETs, consists in the dependence of their parameters on a temperature and in an essential variations of characteristics from one specimen to another. The technological PE parameter variation may amount to (10-15)% even among elements of one manufactured batch [2]. For PDs, for example, a dependence of an initial section of a static PD resistance on a temperature is observed. The voltage-current characteristics of an illuminated PD, took under a constant temperature, are not parallel to each other. Only if thermocompensation circuits are applied [2], PD characteristics are stabilized under deviations of an environment temperature from a nominal one. In the general case, a TF of a PD may be approximated in the odd power function form:

$$U_{íx} = S_{nl}\, F_x^{\,3} + S_l\, F_x + \Delta U, \tag{2}$$

where $U_{íx}$ is a voltage drop, provided by a passage of a PD current through a loading register under a luminous flux F_x ; S_{nl} and S_l are constant coefficients, characterizing a PD sensitivity and depending on a semiconductor material type, on a concentration of various admixtures in a semiconductor and on a processing technology; F_x is a luminous flux of an unknown dimension; and ΔU is a zero drift of a PET, provided by a constant PD current component.

The said drawbacks of PEs with nonlinear characteristics, as well as deviations from normal conditions of operation with digital meters (DM), possessing PETs based on semiconductor PEs, lead to the result, that a TF of a PET (PET TF) differs from TF (2) of a PE and is described by the quantities equation

$$U_{íi} = S_í (1 + \gamma_í)(F_õ)^3 + S_ë (1 + \gamma_ë)F_õ + (\Delta U + \Delta_à) = S'_í (F_õ)^3 + S'_ë F_õ + \Delta U_í \,, \qquad (3)$$

where $S'_{nl} = S_{nl} (1+\gamma_{nl})$ and $S'_l = S_l (1+\gamma_l)$ are conversion conductances for a nonlinear component (NC) and a linear component (LC) of PET TFs under operation conditions, differing from normal conditions; $\gamma_{nl} = \Delta S_{nl} /S_{nl}$; $\gamma_l = \Delta S_l /S_l$; ΔU_{nl} - is a resulting shift of a real PET TF; Δ_a is an additive error component, provided by a long-time PET zero drift $\Delta_{mn} = \Delta S_{nl} (F_x)$ is an NC of a multiplicative error, provided by nonstability of an NC, existing for a PET TF; and $\Delta_{ml} =\Delta S_l Ô_x$ is an LC of a multiplicative error, provided by nonstability of an LC, existing for a PET TF.

Due to this circumstance, the solution of the brightness measurement accuracy enhancement problem should be oriented, first of all, to decrease and even elimination of the systematic error components ($\Delta_à$, Δ_{ml} and Δ_{mn}), including an NC, and also to elimination of an influence of absolute values of the PET TF parameters S_{nl} and S_l, , exerted onto a brightness measurement result. The latter case makes it possible to provide interchangeability of PEs in PETs, when their operation term is expired or when proceeding from results of checking of respective DMs.

Consider the essence of the proposed method of linearization of a general transfer function (GTF), possessed by DMs, as well as of the redundant brightness measurements method, providing automatic correction of systematic errors.

3 GTF LINEARIZATION. DERIVATION OF EQUATIONS FOR REDUNDANT BRIGHTNESS MEASUREMENTS

To solve the stated problem, the paper proposes to apply the functional-algorithmic (FAL) method [3], used to linearize GTFs of DMs, possessing nonlinear PETs [3]. The proposed FAL method is based on application of the formulas, concerned with substitution of input and output quantities, and this is done in order to derive a system of linear equations for transformed quantities. As for the solved problem, the FAL method is the one, which is also based on application of PET TFs with a known nonlinear equation of association between input and output quantities, but with unknown TF parameters, on determination of essential TF features and of specific TF graph points, as well as on selection and introduction of quantities, transformed by quantities substitution formulas. In addition, the same method means to construct a system of coherent equations for transformed quantities and to solve them in order to derive a linear equation of associations between transformed quantities. In this case, the additional equations are derived under or not under a specified reference PET TF graph point, which corresponds to a PhoQ ΔF_x of a small size {ΔF_x }, or to a PhoQ , having a size, differing from a size of a controllable PhoQ k_l times, while this number is known ($k_l \neq 1$). In this case, a numerical value of k_l should be selected as such one, which is close, but not equal to one, i.e.: k_l = 0,8…0,99, or k_l = 1,01…1,2, and it should be also such one, that a deviation of X_2 from X_1 (or of x_2 from x_1) is a small value, but, at the same time, a meter should be able to make out this value [4,5].

The analysis of TF (3) shows, that the linearization problem can be solved with the use of the FAL method under reference to some PET PE graph point A, which corresponds to PhoQ $Ô_1$ with a size, differing from a size of a controllable PhoQ k_l times, while this number is known ($k_l \neq 1$), i.e. the equality { F_1 } = k_l {F_x } takes place here.

Introduce the new variables in accordance with the quantities substitution formulas

$$Y_i = (U_{íi} – U_{í1}) / F_x \,, \qquad (4)$$

and

$$X_i = F_x \,. \qquad (5)$$

In this case, Y_i and X_i are transformed quantities and F_x, U_{nlx} and ΔU_{nl} are initial or transformable quantities.

The PET output voltage, corresponding to the PhoQ F_x, is calculated according to the additional quantities equation

$$U_{nl1} = S'_{nl}(k_l F_x)^3 + S'_l k_l F_x + \Delta U_{nl} . \tag{6}$$

Determine the difference of equations (3) and (6) and divide both sides of the new equation by F_x. With respect to expressions (4) and (5), the result is that the transformed quantities equation has the form:

$$Y_i = S'_{nl} X_i^2 (k_l^3 - 1) + S'_l (k_l - 1) . \tag{7}$$

The derived quantities equation does not contain an LC and has the power exponent value, from which one is subtracted. This circumstance means, that such transformations provide a partial GTF linearization. The parameters S'_{nl} and S'_l in equation (7) remain unknown. To calculate them, write additionally two coherent equations for transformed quantities, obtained from equation (7) under the quantities X_1 and X_2 of a specified small size. Denote the small quantities by ΔX_0 and $k_l \Delta X_0$, i.e. $X_1 = \Delta X_0$ and $X_2 = k_l \Delta X_0$, the sizes of which differ from each other $k_l = \{X_2\} / \{X_1\}$ times. Then,

$$Y_1 = S'_{nl} \Delta X_0^2 (k_l^3 - 1) + S'_l (k_l - 1) , \tag{8}$$

and

$$Y_2 = S'_{nl} k_l^2 \Delta X_0^2 (k_l^3 - 1) + S'_l (k_l - 1) . \tag{9}$$

Define the parameter S'_{nl} as the result of the solution as for the difference of the right and left sides of equations (8) and (9) with respect to S'_{nl}, , i.e.:

$$S'_{nl} = (Y_2 - Y_1) \big/ \Delta X_0^2 (k_l^2 - 1)(k_l^3 - 1) . \tag{10}$$

Determine the second unknown parameter S'_l by way of substitution of expression (10) into equation (9):

$$S'_l = \left[Y_2 - (Y_2 - Y_1)\, k_l^2 \big/ (k_l^2 - 1) \right] \big/ (k_l - 1) . \tag{11}$$

Take expressions (10) and (11) into account, and quantities equation (7) is now

$$Y_i = X_i^2 \frac{Y_2 - Y_1}{\Delta X_0^2 (k_l^2 - 1)} + \left[Y_2 - (Y_2 - Y_1) \frac{k_l^2}{k_l^2 - 1} \right] . \tag{12}$$

To make the power of equation (15) decreased further on and to obtain a linear dependence, introduce the new variable

$$\Delta Y = Y_3 - Y_4 , \tag{13}$$

where Y_3 and Y_4 are those transformed quantities, which are derived after substitution of two other quantities X_3 and X_4 into expression (12), and the sizes $\{X_3\} = \{X_i\} + \{\Delta X_i\}$ and $\{X_4\} = \{X_i\} - \{\Delta X_i\}$ of the latter quantities differ from the size of the quantity X_1 by the known value $\{\Delta X_0\}$, i.e.:

$$Y_3 = (X_i + \Delta X_0)^2 \frac{Y_2 - Y_1}{\Delta X_0^2 (k_l^2 - 1)} + \left[Y_2 - (Y_2 - Y_1) \frac{k_l^2}{k_l^2 - 1} \right] \tag{14}$$

and

$$Y_4 = (X_i - \Delta X_0)^2 \frac{Y_2 - Y_1}{\Delta X_0^2 (k_l^2 - 1)} + \left[Y_2 - (Y_2 - Y_1) \frac{k_l^2}{k_l^2 - 1} \right]. \quad (15)$$

under $X_3 = X_i + \Delta X_0$ and $X_4 = X_i - \Delta X_0$. Substitute expressions (14) and (15) into expression (13), and the following linear transformed quantities equation

$$\Delta Y = (Y_3 - Y_4) = 4X_i \frac{Y_2 - Y_1}{\Delta X_0 (k_l^2 - 1)} \quad (16)$$

is obtained, which describes the linearization procedure (the algorithm). On the basis of this procedure, it may be concluded, that, to solve the stated problem, the PhoQs $F_1 ... F_8$ with the sizes $\{F_1\} = k_l \{F_x\}$, $\{F_2\} = \{\Delta F_0\}$, $\{F_3\} = k_l \{\Delta F_0\}$, $\{F_4\} = (k_l)^2 \{\Delta F_0\}$, $\{F_5\} = \{F_x\} + \{\Delta F_0\}$, $\{F_6\} = k_l (\{F_x\} + \{\Delta F_0\})$, $\{F_7\} = \{F_x\} - \{\Delta F_0\}$ and $\{F_8\} = k_l (\{F_x\} - \{\Delta F_0\})$ are to be formed and measured.

Take equation (16) into account, and the linear equation of transformed quantities is

$$X_i = \Delta X_0 (k_l^2 - 1)(Y_3 - Y_4) \big/ 4(Y_2 - Y_1). \quad (17)$$

If the circumstance, that

$$Y_1 = (U_{nl\,3} - U_{nl\,2})/\Delta F_0 , \quad (18)$$

$$Y_2 = (U_{nl\,4} - U_{nl\,3})/k_l \, \Delta F_0 , \quad (19)$$

$$Y_3 = (U_{nl\,6} - U_{nl\,5})/(F_x + \Delta F_0) , \quad (20)$$

and

$$Y_4 = (U_{nl\,8} - U_{nl\,7})/(F_x - \Delta F_0) , \quad (21)$$

where

$$U_{nl\,2} = S'_{nl} (\Delta F_0)^3 + S'_l \, \Delta F_0 + \Delta U_{nl},, \quad (22)$$

$$U_{nl\,3} = S'_{nl} (k_{\ddot{e}l} F_0)^3 + S'_l \, k_l \, \Delta F_0 + \Delta U_{nl} , \quad (23)$$

$$U_{nl\,4} = S'_{nl} [(k_l)^2 \Delta F_0)]^3 + S'_l \, (k_l)^2 \Delta F_0 + \Delta U_{nl} , \quad (24)$$

$$U_{nl\,5} = S'_{nl} (F_x + \Delta F_0)^3 + S'_l \, (\hat{O}_x + \Delta F_0) + \Delta U_{nl} , \quad (25)$$

$$U_{nl\,6} = S'_{nl} [k_l (F_x + \Delta F_0)]^3 + S'_l \, [k_l (F_x + \Delta F_0)] + \Delta U_{nl} , \quad (26)$$

$$U_{nl\,7} = S'_{nl} (F_x - \Delta F_0)^3 + S'_l \, (F_x - \Delta F_0) + \Delta U_{nl} , \quad (27)$$

and

$$U_{nl8} = S'_{nl} [k_l (F_x - \Delta F_0)]^3 + S'_l \, [k_l (F_x - \Delta F_0)] + \Delta U_{nl} \quad (28)$$

are the equations of coherence between input and output PET quantities under PET TF parameter deviations from nominal values, is taken into account in accordance with quantities substitution formulas (4) and (5), then, when proceeding from the initial quantities, equation (17) is written as

$$B_x = \frac{F_x}{G} = \frac{\Delta F_0 (k_l^2 - 1)}{4G} \left[\left(\frac{U_{nl6} - U_{nl\,5}}{F_x + \Delta F_0} - \frac{U_{nl8} - U_{nl\,7}}{F_x - \Delta F_0} \right) \Bigg/ \left(\frac{U_{nl4} - U_{nl3}}{k_l \Delta F_0} - \frac{U_{nl\,3} - U_{nl\,2}}{\Delta F_0} \right) \right]. \quad (29)$$

Expression (29) is the redundant measurements equation, which, according to quantities equations (22) … (28) (see also the expressions for $U_{nl\ 1}$ ... $U_{nl\ 8}$), characterizes: natural nonlinear coherent relations of the input and output PET quantities with each other and with brightness B_x : a sequence of transformations of the PhoQs ΔF_0 , $k_l\ \Delta F_0$, $(k_l)^2\Delta F_0$, $F_x+\Delta F_0$, $k_l(F_x+\Delta F_0)$, $F_x-\Delta F_0$ and $k_l(F_x-\Delta F_0)$ of known and specified sizes (see indices 2, 3, 4, 5, 6, 7 and 8); and a sequence of elementary arithmetic operations on quantities.

4 ANALYSIS OF A METHODOLOGICAL ERROR UNDER REDUNDANT BRIGHTNESS MEASUREMENTS

Within the considered method, a methodological error is caused by the error Δ_F of regeneration of an additional PhoQs F_2 … F_8 . Besides this, a methodological error feels the contribution, made into it also by the error Δ_{Sd} , associated with calculation and regeneration of values of A_{D2} , A_{D3} and A_{D4}, which are diaphragm hole areas, existing for corresponding measurement steps. The influence of the latter error may be reduced to $\Delta_{kl\ 1}$, which is the error of specification of the value of $k_{l\ 1}$, i.e. of the linearization coefficient. Therefore, instead of the PhoQs F_2 ,..., F_8 having, respectively, the sizes $\{\Delta F_0\}$, $k_l\ \{\Delta F_0\}$, $(k_l)^2\{\Delta F_0\}$, $\{F_x\}+\{\Delta F_0\}$, $k_l\ (\{F_x\}+\{\Delta F_0\})$, $\{F_x\}-\{\Delta F_0\}$and $k_l\ (\{F_x\}-\{\Delta F_0\})$, the PhoQs F'_2 ,..., F'_8 having, respectively, the sizes $\{F'_2\} = \{\Delta F_0\}+\{\Delta_{F0}\}$, $\{F'_3\} = (k_l+\Delta_{kl})\{\Delta F_0\}+\{\Delta_{F0}\}$, $\{F'_4\} = (k_l+\Delta_{kl})^2(\{\Delta F_0\}+\{\Delta_{F0}\})$, $\{F'_5\} = \{F_i\}+(\{\Delta F_0\}+\{\Delta_{F0}\})$, $\{F'_6\} = (k_l+\Delta_{kl})(\{F_x\}+\{\Delta F_0\}+\{\Delta_{F0}\})$, $\{F'_7\} = \{F_x\} - (\{\Delta F_0\}+\{\Delta_{F0}\})$ and $\{F'_8\} = (k_l+\Delta_{kl})(\{F_x\} - \{\Delta F_0\}-\{\Delta_{F0}\})$ are regenerated. In this case, equation (29) has the form

$$B'_x = \frac{F'_x}{G'} = \frac{\Delta F_0(k_l^2-1)}{4(G+\Delta_G)} \frac{\dfrac{U'_{nl6}-U'_{nl5}}{(F_x+\Delta_{\mathrm{F}\tilde{o}})+(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})} - \dfrac{U'_{nl8}-U'_{nl7}}{(F_x+\Delta_{\mathrm{F}\tilde{o}})-(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})}}{\dfrac{U'_{nl4}-U'_{nl3}}{(k_l+\Delta_k)(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})} - \dfrac{U'_{nl3}-U'_{nl2}}{(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})}}, \tag{30}$$

where Δ_{Fx} is an error of calculation of a real value of F_x ; Δ_G is an error of determination of a geometric factor G'; Δ_{F0} is an error of regeneration of ΔF_0 ; Δ_k is an error of specification of a value of k_l ; and F'_x is a luminous flux, dealt with when an error of regeneration of ΔF_0 and k_l are taken into account.

A relative methodological error, associated with calculation of a real value of brightness B_x, is determined under the real PET TF by $\delta_{Bm} = (B'_x/B_x)-1$, where B'_x and B_x are those PhoQs, which, in their turn, are associated with initial and transformed quantities in accordance with redundant measurements equation (29), or those ones, the sizes of which are determined with and without consideration of the above-mentioned methodological errors under real PET TF (3).

To analyze the structures of the errors, represent redundant measurements equation (29) with respect to the initial quantities. Then, take quantities equations (6) and (22)…(28) into account, and here is the following expression:

$$B'_x = \frac{1}{4(G+\Delta_G)}\cdot\frac{\Delta F_0}{\Delta F_0+\Delta_{\mathrm{F\hat{i}}}}\cdot\frac{k_l^2-1}{(k_l+\Delta_k)^2-1}\left\langle \frac{\left[\dfrac{F_{\tilde{o}}^2}{\Delta F_0+\Delta_{\hat{\mathrm{O}}\hat{\mathrm{i}}}}+2F_{\tilde{o}}+(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})\right]+\dfrac{S'_l}{S'_{nl}}\dfrac{(k_l+\Delta_k)-1}{(k_l+\Delta_k)^3-1}}{1+\Delta_{\mathrm{F}x}/[F_x+(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})]} - \right.$$

$$\left. -\frac{\left[\dfrac{F_{\tilde{o}}^2}{\Delta F_0+\Delta_{\mathrm{F\hat{i}}}}-2F_{\tilde{o}}+(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})\right]+\dfrac{S'_l}{S'_{nl}}\dfrac{(k_l+\Delta_k)-1}{(k_l+\Delta_k)^3-1}}{1+\Delta_{\hat{\mathrm{O}}x}/[F_x-(\Delta F_0+\Delta_{\mathrm{F\hat{i}}})]}\right\rangle. \tag{31}$$

If not real, but certificate values of PET TF parameters are substituted into expression (31), then such a redundant measurements equation is obtained, which contains only the methodological errors of regeneration of the quantities Δ_{Fx} and k_l If this equation is substituted into the expression $\delta_{Bm} = (B'_x/B_x)-1$, then the purely methodological error of redundant measurements is yielded.

As it is seen from redundant measurements equation (31), the relative methodological error δ_{Bm} can be decreased, when the error Δ_{Fx} is decreased. Under $\Delta_{Fx} \approx 0$, the equation for the relative methodological error is

$$d'_{Bm} \approx \frac{\Delta F_0}{\Delta F_0 + \Delta_{F\hat{\imath}}} \cdot \frac{k_l^2 - 1}{(k_l + \Delta_k)^2 - 1} - 1. \quad (32)$$

According to expression (32), the relative methodological error feels no influence, exerted onto it by the error Δ_G , associated with calculation of a value of the geometric factor *G*, but the errors Δ_{F0} and Δ_k exert their influence onto the former error. Usually, the specified size $\{\Delta F_0\}$ of the luminous flux F_2, which arrives at an achromatic lens, is set in advance, i.e. before the measurements are started, with a stated high accuracy or with the error Δ_{F0} in accordance with PET calibration results, written into PROM. This is done by means of the traditional white light sources with normalized characteristics. In practice, the specified size $\{\Delta F_0\}$ of the luminous flux F_2 can be set with a negligibly small relative error Δ_{F0} , the size of which is not worse, than $\{\Delta_{Fx}\}$ = (0,1...0,3)%. Hence, the main attention should be paid to a high quality of execution of the mechanical part of an optical system, i.e. of the ring diaphragm and of the hole area size control mechanism. The latter is to provide the accuracy of up to a micron for setting of the specified ring diaphragm hole area sizes. In this case, the value of the coefficient $k_{l\,1}$ should be set with the relative error $\delta_{kl\,1}$, the value of which is of $\{\delta_k\}$ = (0,01...0,03)%. And, in the same case, the relative methodological brightness measurement error δ'_{Bm} is of (0,1 ... 0,6)%.

Therefore, to measure brightness with the relative error, which is not higher, than 1%, it is necessary to provide the relative error of specification and regeneration of sizes of the PhoQ ΔF_0 , which is not worse, than 0.3%, and as for the coefficient k_l , it should be not worse, than 0.03%.

6 CONCLUSION

The proposed redundant measurements method provides an automatic correction of systematic errors, when brightness is measured.

To linearize a GTF of digital brightness meters with a power TF of their light-sensitive elements, the paper proposes the FAL method of linearization.

To decrease a methodological error, the main attention should be paid to creation of a highly-accurate mechanical part of an optical system, since the luminous flux F_2 of a specified size $\{\Delta F_0\}$ can be set with a sufficiently low relative error of $\{\delta_{F0}\}$=(0,1 … 0,3)%.

It is stated, that the value of the coefficient k_l should be regenerated with the relative error δ_k , the size of which is of $\{\delta_k\}$= (0,01…0,03)%. The relative methodological error δ'_{Bm} of brightness measurement can be decreased here up to (0,1 ...0,6)%.

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