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A model of X-Ray emitter emission characteristics measuring

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A model for measuring of the X-ray emitter individual emission characteristics for computerized X-ray control system has been created. The strategy of empirical data generation for calculating the coefficients of the transformation function of the typical emission characteristics to individual ones in order to improve the accuracy of the results has been defined. An accuracy estimation of the results has been performed.

Key-words: *X-ray emitter, emission characteristics, model of measurement, estimation of measurement uncertainty.*

Створено модель вимірювання індивідуальних емісійних характеристик рентгенівського випромінювача для комп’ютеризованої системи управління рентгенівською установкою. Визначена стратегія формування емпіричних даних для розрахунку коефіцієнтів функції перетворення типових емісійних характеристик на індивідуальні з метою підвищення точності отриманих результатів. Проведена оцінка точності отриманих результатів.

Ключові слова*: рентгенівський випромінювач, емісійні характеристики, модель вимірювання, оцінка невизначеності вимірювання.*

Создана модель измерения индивидуальных эмиссионных характеристик рентгеновского излучателя для компьютеризированной системы управления рентгеновской установкой. Определена стратегия формирования эмпирических данных для расчета коэффициентов функции преобразования типовых эмиссионных характеристик на индивидуальные с целью повышения точности полученных результатов. Проведена оценка точности полученных результатов.

Key words: *рентгеновский излучатель, эмиссионные характеристики, модель измерения, оценка неопределенности измерения.*

1. Introduction

Nowadays the medicine all over the world has no alternative to an X-ray diagnostic research [1]. According to experts, more than 80% of diagnoses which require serious medical intervention are established by using X-rays, the results of X-ray and X-ray tomography. However, an X-ray tube is a source of artificial electromagnetic ionizing radiation that makes an application of X-ray diagnostic methods potentially dangerous for the health of patients and attendants [2], [3].

The research and analysis of available literary sources [4], [5] allows making a suggestion that the problem of reducing the ionizing radiation dosage [6] received by the patient and medical staff during X-ray diagnostics is relevant. The reduction of the ionizing radiation dosage is possible by optimization of the operating modes of the X-ray tube during a diagnostic research as well as timely detection of the deviation of the technical parameters from nominal values and their operational elimination [7].

In modern computerized X-ray management systems a required value of the anode current is achieved by pre-setting of the cathode heating current to a given level. This is due to impossibility to provide the stabilization of the current at initial stages of exposure by means of feedback systems due to high inertia of the cathode's thermal state.

Availability of individual design features such as state of vacuum inside the device, the cathode surface quality and other factors, including changing the emission characteristics of the cathode during the X-ray tube usage, require preliminary and periodic calibration of computerized X-ray management systems in order to ensure the accuracy of the anode current setting. In [8] the method of adapting of typical emission characteristics of X-ray emitter to experimental data by deformation of the coordinate plane has been proposed. The purpose of this article is to design the measurement model for the reliability assessment of individual characteristics which have been obtained by using this method as well as accuracy increasing of investigation results by choosing the strategy of empirical data formation used for determination of the transformation function coefficients during conversion of typical emission characteristics to individual ones.

2. Main part

The method of individualization of X-Ray emitter typical emission characteristics is to transform them taking into account the empirical data which have been obtained during the series of test exposures. In other words computerized X-ray control system uses the corresponding function for a preliminary calculation of the cathode heating current, which must be set up before the start of exposure to provide the required anode current. This function presents the dependence of the heating current on the value of the required anode current at a given value of the anode voltage and can be written as follows:

$$y_u = f(x, z_u(x), A_0 \dots A_5), u \in U, \tag{1}$$

where y_u – the cathode heating current (ignition code) which must be set to provide the given anode current x with the value of the anode voltage u which corresponds to the emission characteristics of a particular instance of the X-ray emitter;

x – the value of the anode current;

u – the value of the anode voltage;

z_u (x) – the dependence of the cathode heating current y on the anode current x at the measured anode voltage u according to the typical emission characteristics of the X-ray emitter;

U – a set of anode voltage values that can be set by computerized X-ray control system;

A_0 ... A_5 – coefficients of the mathematical transformation of the X-ray emitter typical emission characteristics to the individual ones.

The mathematical transformation of the X-ray emitter typical emission characteristics which is used to obtain the output value estimation is following:

$$y_u = (A_0x^2 + A_1x + A_2)z_u(x) + A_3x^2 + A_4x + A_5. \tag{2}$$

The model function describes the measurement procedure and the evaluation method simultaneously. It shows how the output values y_u are derived from the input values x_i.

To estimate the coefficients of the mathematical transformation from the typical emission characteristics of an X-ray emitter to individual ones, the data series from n previous control exposures are used. They are represented as the set of empirical points B:

$$B = \{(x_k, y_k, u), k = 1..n\}, \tag{3}$$

where y_k – the real value of the cathode heating current obtained empirically by the operator for the anode current x_k at the value of the anode voltage u.

Estimates of the parameters of the desired dependence are determined by the method of least squares, since the sum of the squares of deviations of the experimental values from the calculated ones must be minimal.

$$\sum_{k=1}^{n}\left[y_k - f(x_k, z(x_k), \hat{A}_0, ..\hat{A}_5)\right]^2 = \sum_{i=1}^{n}\delta_k{}^2 = Q = \min, \qquad (4)$$

where $\hat{A}_0 \ldots \hat{A}_5$ – estimates of the values of the mathematical transformation coefficients of the X-ray emitter typical emission characteristics to the individual characteristics;

δ_k – deviation of the experimental values of a specific instance emission characteristics of the X-ray emitter from the calculated emission characteristics which are obtained by using the method of individualization of the X-ray emitter typical emission characteristics by means of mathematical transformation (2) on the basis of empirical data;

Q – sum of the squares of the experimental values deviations from the calculated ones.

Thus, the task is to determine the values of the coefficients when the condition (4) will be fulfilled. Therefore we should write the expression for the deviations at each experimental point:

$$\begin{cases} \left(\hat{A}_0 x_1{}^2 + \hat{A}_1 x_1 + \hat{A}_2\right) z(x_1) + \hat{A}_3 x_1{}^2 + \hat{A}_4 x_1 + \hat{A}_5 - y_1 = \delta_1; \\ \left(\hat{A}_0 x_2{}^2 + \hat{A}_1 x_2 + \hat{A}_2\right) z(x_2) + \hat{A}_3 x_2{}^2 + \hat{A}_4 x_2 + \hat{A}_5 - y_2 = \delta_2; \\ \ldots \\ \left(\hat{A}_0 x_n{}^2 + \hat{A}_1 x_n + \hat{A}_2\right) z(x_n) + \hat{A}_3 x_n{}^2 + \hat{A}_4 x_n + \hat{A}_5 - y_n = \delta_n. \end{cases} \qquad (5)$$

According to the least squares method, the best values of the coefficients will be those for which the sum of the squares of deviations is minimal, so in our case it is necessary to find the minimum of the function of the following form:

$$Q = \sum_{k=1}^{n}\delta_k{}^2 = \sum_{k=1}^{n}\left((\hat{A}_0 x_k{}^2 + \hat{A}_1 x_k + \hat{A}_2) z(x_k) + \hat{A}_3 x_k{}^2 + \hat{A}_4 x_k + \hat{A}_5 - y_k\right)^2. \qquad (6)$$

A typical functional dependence of the cathode heating current z on the current of the anode x at the value of the anode voltage u is presented as a table and the intermediate values are obtained by means of interpolation. The absence of an analytic expression as well as the additional error and uncertainty that appear during the determination of the second-order polynomial coefficients by which it is possible to approximate the emission characteristics of X-ray tube, leads to the fact that the desired function (2) is considered by the authors as a function that depends on two variables (x and z). In this case the analytical solution of the problem (6) is complicated, and the quality of the transformation results of the typical emission characteristics depends on the preparation strategy and the choice of empirical data for the calculation.

Let’s assume that to determine the coefficients of the transformation function (2), we use a subset B_1 of six points of the set of empirical data B. In this case, the calculation of the coefficients of the transforming function of the X-ray emitter typical emission characteristics to individual ones for a specific instance of an X-ray emitter is the solution of the system of six equations, provided as $x_0 \neq x_1 \neq x_2 \neq x_3 \neq x_4 \neq x_5$:

$$\begin{cases} y_1 = \hat{A}_0 x_1^2 z_1 + \hat{A}_1 x_1 z_1 + \hat{A}_2 z_1 + \hat{A}_3 x_1^2 + \hat{A}_4 x_1 + \hat{A}_5; \\ y_2 = \hat{A}_0 x_2^2 z_2 + \hat{A}_1 x_2 z_2 + \hat{A}_2 z_2 + \hat{A}_3 x_2^2 + \hat{A}_4 x_2 + \hat{A}_5; \\ \ldots \\ y_6 = \hat{A}_0 x_6^2 z_6 + \hat{A}_1 x_6 z_6 + \hat{A}_2 z_6 + \hat{A}_3 x_6^2 + \hat{A}_4 x_6 + \hat{A}_5. \end{cases} \tag{7}$$

The analytic expression of the only solution of this system of algebraic equations with six unknowns could be compactly written by the Cramer's rule:

$$A_i = {}^{\Delta_i}\!/_{\Delta}, \ \ \Delta \neq 0, \ \ i = 0 \ldots 5. \tag{8}$$

Δ – determinant of initial matrix;

Δ_i – determinant of the matrix obtained from the original matrix by replacing the i-th column.

The quality of the obtained individual characteristics could be evaluated by means of expression (6) on the whole set of empirical points B.

Apart from the task of minimizing the Q function during the strategy determination of the empirical data generation, we have considered the necessity of creating a special technological mode of the power supply device as well as high costs of the technical staff’s work time and the problem of the radiation influence on the service personnel. Numerous experiments have shown that the best results are obtained when four points are chosen uniformly in one of the curves as a calculation point, for example, in the upper curve of the family (emission characteristic with minimum value of the anode voltage u_{min}). This allows the most accurate determination of the curvature of the desired individual emission characteristics. To determine the coefficients of scaling of the original emission characteristics the last two points should be maximally spread to the edges of the lower curve (emission characteristic with the maximum value of the anode voltage u_{max}). Since the experimental point located on the right edge of the lower curve often cannot be obtained due to exceeding the maximum power permitted, it can be replaced by a point on another family curve. Therefore, as the last calculated point, the point with the maximum anode current value x_c on the curve for which the exposure power will not exceed the maximum permissible is chosen.

Thus let's define:

$$\begin{gathered} u_{min} := \forall u \in U, \ \ u > u_{min}, \\ u_{max} := \forall u \in U, \ \ u > u_{max}, \\ u_{mid} := \forall u \in U, \ \ (| u_{max} - u_{mid} | \leq | u_{max} - u |) \wedge (u_{mid} x_c < 0{,}9 \, P_{max}), \\ x_c := \forall \, (x, y, u_{mid}), \ x < x_c, \ P_{max} \text{ — const}. \end{gathered} \tag{9}$$

Where u_{mid} is the emission characteristic with the highest value of the anode voltage, for which the exposure power with the maximum current value of the anode x_c will not exceed the maximum permissible power P_{max}.

In this case, we form the set B (3) as follows:

$$B = \{(x_i, y_i, u_{min}) \mid i = 1 \ldots n, \ \ n \geq 4\} \cup$$

$$\{(x_i, y_i, u_{max}) \mid i = 1...k,\ k \ge 1\} \cup\ , \qquad (10)$$
$$\{(x_i, y_i, u_{mid}) \mid i = 1...p,\ p \ge 1\}.$$

Let’s choose a subset B_1 to calculate the transformation coefficients:

$$B_1 \subset B,\ B_1 = \{(x_1, y_1, u_{min}) : \forall(x, y, u_{min}) \in B,\ x > x_1\} \cup$$
$$\{(x_2, y_2, u_{min}) : \forall(x, y, u_{min}) \in B,\ x < x_2\} \cup$$
$$\{(x_2, y_2, u_{min}) : \forall(x, y, u_{min}) \in B \,|\, x - (x_1 + \frac{x_2 - x_1}{3}) \,| > |(x_3 - (x_1 + \frac{x_2 - x_1}{3})| \} \cup$$
$$\{(x_2, y_2, u_{min}) : \forall(x, y, u_{min}) \in B \,|\, x - (x_1 + \frac{x_2 - x_1}{3}) \,| > |(x_3 - (x_1 + \frac{x_2 - x_1}{3})| \} \cup$$
$$\{(x_5, y_5, u_{max}) : \forall(x, y, u_{max}) \in B,\ x > x_5\} \cup$$
$$\{(x_6, y_6, u_{mid}) : \forall(x, y, u_{mid}) \in B,\ x < x_6\}. \qquad (11)$$

Let the Q function for the solution of system (7) for subset B_1 (11) be equal to some value Q_1. To reduce the contribution of a random measurement error that occurs during obtaining empirical data in the course of test exposures, it is necessary to carry out some iterative variation of a subset of the points selected to calculate the conversion factors of the typical emission characteristics for the purpose of individualization. The minimum of the investigated values of Q is denoted by Q_{min}. In the first stage, it takes the value Q_1 with a corresponding subset of empirical points, denoted as B_0:

$$Q_{min} = Q_1,\ B_0 = B_1. \qquad (12)$$

We change the point, which corresponds to the minimal value of the anode current on the curve to the next one, and denote a new subset of the points for the calculation as B_2.

$$B_2 = (B_0 \cup \{(x_1', y_1', u_{min})\} \Delta \{(x_1, y_1, u_{min})\} \qquad (13)$$
$$(x_1', y_1', u_{min}) \in B, \forall\ (x, y, u_{min}),\ x_1 < x_1' < x,\ x_1' \ne x_3.$$

Then we calculate the alternative conversion coefficients as well as the values of all squares of deviations obtained empirically from the estimated values and choose the best result:

$$Q_2 < Q_{min} \Rightarrow Q_{min} = Q_2,\ B_0 = B_2\,. \qquad (14)$$

At the second stage, we evaluate a new subset of points for the calculation of B_3. We change the point on the curve u_{min} in which the value of the anode current is maximal to the one that is located in front of it, and again choose the best result:

$$B_3 = (B_0 \cup \{(x_2', y_2', u_{min})\} \Delta \{(x_2, y_2, u_{min})\},$$
$$(x_2', y_2', u_{min}) \in B, \forall\ (x, y, u_{min}),\ x_2 > x_2' > x,\ x_2' \ne x_4\,, \qquad (15)$$
$$Q_3 < Q_{min} \Rightarrow Q_{min} = Q_3,\ B_0 = B_3\,.$$

The third, fourth, fifth and sixth stages (iterations) consider the points that are left and right of the points (x_3, y_3, u_{min}) and (x_4, y_4, u_{min}), that is:

$$B_4 = (B_0 \cup \{(x_3', y_3', u_{min})\} \Delta \{(x_3, y_3, u_{min})\},$$
$$(x_3', y_3', u_{min}) \in B,\ \forall\ (x, y, u_{min}),\ (x_3' < x_3) \wedge ((x > x_3) \vee (x < x_3')) \wedge (x_3' \ne x_1),$$
$$Q_4 < Q_{min} \Rightarrow Q_{min} = Q_4,\ B_0 = B_4\,.$$
$$B_5 = (B_0 \cup \{(x_3', y_3', u_{min})\} \Delta \{(x_3, y_3, u_{min})\},$$
$$(x_3', y_3', u_{min}) \in B,\ \forall\ (x, y, u_{min}),\ (x_3' < x_3) \wedge ((x_3' < x) \vee (x < x_3)) \wedge (x_3' \ne x_4),$$
$$Q_5 < Q_{min} \Rightarrow Q_{min} = Q_5,\ B_0 = B_5\,.$$
$$B_6 = (B_0 \cup \{(x_4', y_4', u_{min})\} \Delta \{(x_4, y_4, u_{min})\},$$
$$(x_4', y_4', u_{min}) \in B,\ \forall\ (x, y, u_{min}),\ (x_4' < x_4) \wedge ((x > x_4) \vee (x < x_4')) \wedge (x_4' \ne x_3),$$
$$Q_6 < Q_{min} \Rightarrow Q_{min} = Q_6,\ B_0 = B_6\,.$$
$$B_7 = (B_0 \cup \{(x_4', y_4', u_{min})\} \Delta \{(x_4, y_4, u_{min})\},$$
$$(x_4', y_4', u_{min}) \in B,\ \forall\ (x, y, u_{min}),\ (x_4 < x_4') \wedge ((x_4' < x) \vee (x < x_4)) \wedge (x_4' \ne x_2),$$
$$Q_7 < Q_{min} \Rightarrow Q_{min} = Q_7,\ B_0 = B_7\,.$$

The last two iterations consider the points which are to the right of the points (x_5, y_5, u_{max}) and (x_6, y_6, u_{mid}), that is:

$$B_8 = (B_0 \cup \{(x_5', y_5', u_{max})\} \Delta \{(x_5, y_5, u_{max})\},$$
$$(x_5', y_5', u_{max}) \in B, \forall\ (x, y, u_{max}),\ \ x_5 < x_5' < x,$$
$$Q_8 < Q_{min} \Rightarrow Q_{min} = Q_8,\ \ B_0 = B_8\,.$$
$$B_9 = (B_0 \cup \{(x_6', y_6', u_{mid})\} \Delta \{(x_6, y_6, u_{mid})\},$$
$$(x_6', y_6', u_{mid}) \in B, \forall\ (x, y, u_{mid}),\ \ x < x_6' < x_6\,,$$
$$Q_9 < Q_{min} \Rightarrow Q_{min} = Q_9,\ \ B_0 = B_9\,.$$

The value Q, which is found in this way, will be considered as a minimal subset of B_0 and the corresponding estimates of the $\hat{A}_0 ... \hat{A}_5$ coefficients will be considered as the best.

The standard DSTU ISO / IEC 17025: 2006 indicates the need to estimate the uncertainty of measurement during calibration [9].

The model approach to uncertainty estimation of measurements involves the model equation usage (1), where the function of model f describes simultaneously the measurement procedure and the evaluation method. It shows how the output values of y_u are derived from the input values x, $z_u(x)$ and the coefficients $A_0..A_5$.

In this case, there are many sources of uncertainty in the measurement, such as the subjective systematic error of the operator when taking measurements, approximation and simplification used while determining exposure parameters through a table representation of emission data in a computerized X-ray management system, inaccurate values of reference tables, imperfection of the measured value determination implementation, etc. In addition, some sources of uncertainty correlate with each other. Therefore, estimating measurement uncertainty is not just a mathematical problem, but requires a detailed investigation of the nature of both measured value and measurement process.

The situation is also complicated by the fact that multiple measurements are excluded. Therefore, there is an a priori estimation of uncertainty based on the information obtained from the test measurements carried out previously and the passport data of the X-ray source. The scattering of measurement results is characterized by an estimated standard deviation and is called the standard uncertainty type B. The estimation of type B standard uncertainty is as reliable as the one of type A, in a situation where a type A estimation can only be based on a small number of statistically independent observations [10]. To determine the standard uncertainty of type B λ, a standard estimated deviation is used. It is obtained as a positive square root of the variance, which is calculated on the basis of the fund of relatively reliable information, such as data of the previous measurements and data of the typical emission characteristics of the passport of the X-ray source.

$$\lambda = \sqrt{Q} = \sqrt{\sum_{k=1}^{n} \delta_k^{\,2}} = \sqrt{\sum_{k=1}^{n} \left((\hat{A}_0 x_k^{\,2} + \hat{A}_1 x_k + \hat{A}_2) z(x_k) + \hat{A}_3 x_k^{\,2} + \hat{A}_4 x_k + \hat{A}_5 - y_k \right)^2}$$

This estimation makes it possible to assess the uncertainty of the proposed measurement procedure and the quality of the results obtained.

The estimation of a standard uncertainty λ is used instead of the function Q, the search of the smallest value of which is laid in the strategy of finding the best solution during the variation of the points used for calculation.

3. Conclusions

The measurement model of individual emission characteristics of an X-ray emitter for computerized X-ray control system based on mathematical transformations of typical emission characteristics given in the X-ray tube passport by using experimental data of control exposures series has been suggested in this article. This model allows estimating the accuracy of the results obtained in the concept of the uncertainty theory that fully corresponds to Ukraine's transition to the calibration procedures of measuring instruments in accordance with the international requirements [11], [12]. In addition, the obtained measurement uncertainty estimation has been used as a minimized function during a formation of a strategy for selecting a subset of empirical points for calculation. The strategy allows increasing an accuracy of the received individual emission characteristics by eliminating points with a large random measurement error. The evaluation of the results has been performed. The described model has been used as a basis for the software that allows the calibration of a computerized system of an X-ray emitter. The software application has been tested and the comprehensive operational test has been performed in the Laboratory of intelligent electronic systems (IEC) at the Department of Electronics and Control Systems of V. N. Karazin Kharkiv National University. The program has been tested with the X-ray tubes of the following types: 20-50BD22- 6-10BD8- 150 and 125 produced by the scientific and production enterprise "Svetlana" (St. Petersburg) as well as some models of X-ray tubes produced by "Siemens". Testing has been carried out by using high-frequency power supplies IEC-F7 and IEC-R8 developed in the laboratory. As a result of the performed calibrations the individual emission characteristics have been obtained. Therefore at the beginning of the exposure (before the system of automatic stabilization of the current is turned on) the deviation of the X-ray tube anode current from the set value does not exceed 1.5% within the entire working range. By estimating absolute and relative errors, the quality of the results is significantly better than the results of calibrations obtained by using the previous versions of the program. The accuracy of the calibration meets the requirements of the existing standards completely and provides for the possibility of widespread application of the developed algorithm for adjusting X-ray power supplies of IEC series. The program is included in the SMaster service package for maintenance of X-ray power devices developed by the IEC Laboratory.

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