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Analytical Approximation of Spectrum for Pulse X-ray Tubes

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Abstract. Among the main characteristics of the pulsed X-ray apparatuses the spectral energy characteristics are the most important ones: the spectral distribution of the photon energy, effective and maximum energy of quanta. Knowing the spectral characteristics of the radiation of pulse sources is very important for the practical use of them in non-destructive testing. We have attempted on the analytical approximation of the pulsed X-ray apparatuses spectra obtained in the different experimental papers. The results of the analytical approximation of energy spectrum for pulse X-ray tube are presented. Obtained formulas are adequate to experimental data and can be used by designing pulsed X-ray apparatuses.

1. Introduction

One hundred and twenty years ago, Wilhelm Rontgen made one of the greatest discoveries of modernity, which gave him the title of the first Nobel laureate in physics. X-rays were discovered – quanta with wavelengths ranging between the optical range and gamma radiation. At the phenomenological level, Rontgen studied all the basic properties of X-rays, and, in particular, made an attempt to evaluate the energy spectrum of the open radiation on the basis of a penetrating facility of radiation. In modern parlance, Rontgen used the method of filters, which nowadays is the most accurate, coupled with making use of modern pulsed X-ray detectors.

It is interesting to note that in his first experiments this Rontgen identified two main areas of application of X-rays: medicine and fault detection. And now, in literature, you can find links to pictures of hands of Roentgen's assistant and Roentgen's spouse, which show the structure of their hands. Less well known is the fact that one of the first images taken by Roentgen was a shadow image of a gun barrel. Here is how the researcher wrote: "Through one handset ... I got a pretty good picture shotgun barrels. It was clear and sharp to see all the details of bullets and internal irregularities Damascus barrels "[1].

In the late 1930s, it had been received short pulses of X-rays lasting a few tenths of microseconds marking the birth of pulsed X-ray technology. In the 1960s, it began learning to handle the nanosecond range of the X-ray pulses. They created the first small-size pulsed X-ray apparatuses (PXAs) and offered empirical methods of calculating the basic characteristics of the pulse tubes [2–4].

Among the main characteristics of the PXAs the spectral energy characteristics are the most important ones: the spectral distribution of the photon energy, effective and maximum energy of quanta, pulsed exposure dose, and power of exposure dose.

Knowing the spectral characteristics of the radiation of pulse sources is very important for the practical use of them in non-destructive testing. In one way or another all flaw characteristics – the thickness of the tested material, the focal length, exposure, sensitivity – are connected with the energy of the radiation and its distribution. Knowledge of the spectral and energy characteristics has become essential in new areas by use of the pulsed X-ray sources for inspection and customs testing, in the X-ray location and navigation.

2. Processing of experimental data

At the end of the 1960s, the making of the first home apparatuses of series "IRA" and "MIRA" has led to the extension of theoretical and experimental studies of the spectrum of pulsed devices [5–7]. In the majority of papers, the spectral distribution is calculated from the experimental dose characteristics. Note, as detectors, silicon and thermoluminescence detectors are used [8,9].

The intensity distribution of the X-ray pulse can be described by the following relation [10]:

$$F(\lambda) = \frac{(\lambda - \lambda_0)^2}{\lambda^4},$$

where $F(\lambda)$ is a density of radiation intensity; λ is a wavelength of radiation quantum; λ_0 is a short-wavelength of radiation border. The most likely wavelength quantum is determined from the relationship:

$$\lambda = 2\lambda_0 \qquad (1)$$

Thus, the spectrum of pulse emitters has longer wavelengths than the spectrum of X-ray apparatuses with the sinusoidal and constant anode voltage.

The experimental results of a study of the spectrum of devices with supply voltages in the range of 100-500 kV show a number of significant deviations from these dependences. Enumerate the main reasons of such situation: the errors of detector, the influence of radiation absorption, the contribution of scattered radiation, peculiarities of the supply voltage. The effective power can become displaced to lower energies than it follows from (1) [10–12].

We have attempted on the analytical approximation of the PXA spectra obtained in the different experimental papers. We analyzed data on the PXA spectrum starting with the papers, in which were used the first serial models of the pulsed X-ray apparatuses “IRA”, “RINA”, and the like. The level of the supply voltage in these devices does not exceed 400–500 kV.

Further research we conducted with making use of “MIRA-2”. Its energy distribution $F(x)$ [5] was tabulated by values shown in table 1, where $x = 15\times(E/E_0)$, E–energy of quantum, E_0– energy of maximum quantum.

Table 1. The tabulation of energy distribution $F(x)$.

x	0.5	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
F(x)	0	1.6	4.3	7	9.5	11	11.5	12	10.7	9.6	8	6.3	5	3	1.2	0

Using a discrete set of data, i.e. table 1, it is necessary to obtain an estimate of the analytical form of the function $F(x)$.

The problem was solved for the two options: the first, on the base of all data of table 1; the second, on the base of the same table, but without the first column of data, i.e. without the pair of numbers 0.5 and 0. Such approach allows to "cut" short-wave boundary of the spectrum, for which the most likely error.

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The analytical form of the function $F(x)$ was obtained using parametric and nonparametric approaches. In the case of the parametric approach, the function $F(x)$ is approximated by a polynomial of the third degree and the corresponding parameters are found by the least squares method. As a result, we got the expressions

$$F_1(x) = 0.01352x^3 - 0.5284x^2 + 5.0642x - 3.0522,$$

$$F_2(x) = 0.01546x^3 - 0.581x^2 + 5.4851x - 3.9801$$

for the first and second options, respectively.

The graphs of functions $F_1(x)$ and $F_2(x)$ are shown in figure 1.

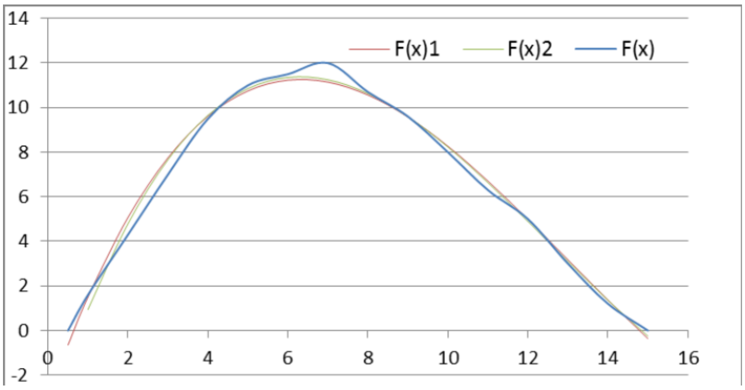

Figure 1. Approximation of the spectrum (parametric approach).

To evaluate the accuracy of the parametric models, absolute deviations of the estimates from the true values were calculated by the formulas:

$$A_1(x) = |F(x) - F_1(x)|;$$

$$A_2(x) = |F(x) - F_2(x)|.$$

The simulation results and respective deviation values are shown in table 2.

Table 2. Results of approximation and deviations.

x	*F(x)*	$F_1(x)$	$F_2(x)$	$A_1(x)$	$A_2(x)$
0.5	0	-0.651	-	0.6505	-
1	1.6	1.4971	0.9395	0.1029	0.6605
2	4.3	5.0708	4.7898	0.7708	0.4898
3	7	7.7498	7.6635	0.7498	0.6635
4	9.5	9.6154	9.6536	0.1154	0.1536
5	11	10.749	10.853	0.2514	0.1473
6	11.5	11.23	11.354	0.2695	0.1464
7	12	11.142	11.249	0.8578	0.7509
8	10.7	10.565	10.632	0.1352	0.068
9	9.6	9.5794	9.5951	0.0206	0.0049
10	8	8.267	8.231	0.267	0.231
11	6.3	6.7089	6.6326	0.4089	0.3326
12	5	4.986	4.8927	0.014	0.1073
13	3	3.1795	3.104	0.1795	0.104
14	1.2	1.3705	1.3593	0.1705	0.1593
15	0	-0.36	-0.249	0.36	0.2486

Approximation of the spectrum using a nonparametric approach was carried out by the formulas

$$F_3(x)=\frac{\sum_{i=1}^{n}F(x_i)\exp\left(-\frac{(x_i-x)^2}{0.084}\right)}{\sum_{i=1}^{n}\exp\left(-\frac{(x_i-x)^2}{0.084}\right)},\quad n = 16;$$

$$F_4(x)=\frac{\sum_{i=2}^{n}F(x_i)\exp\left(-\frac{(x_i-x)^2}{0.076}\right)}{\sum_{i=2}^{n}\exp\left(-\frac{(x_i-x)^2}{0.076}\right)},\quad n = 16$$

for the first and second options, respectively.

The graphs of functions $F_3(x)$ and $F_4(x)$ are shown in figure 2.

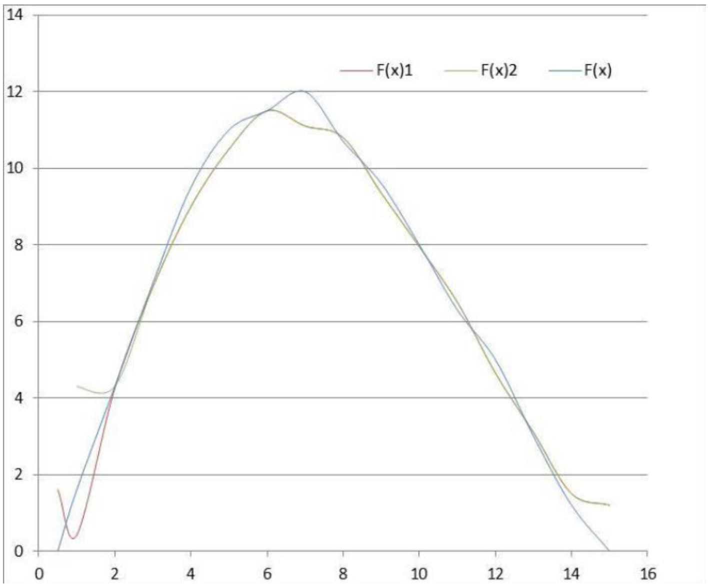

Figure 2. Approximation of the spectrum (non-parametric approach).

The accuracy of the non-parametric model is evaluated by analogy with the parametric approach using the following formulas:

$$A_3(x)=\left|F(x)-F_3(x)\right|;$$

$$A_4(x)=\left|F(x)-F_4(x)\right|.$$

The simulation results and values of the corresponding deviations are presented in table 3.

Table 3. The simulation results (non-parametric approach).

x	*F(x)*	$F_3(x)$	$F_4(x)$	$A_3(x)$	$A_4(x)$
0.5	0	1.607		1.607	-
1	1.6	0.419	4.3	1.181	2.7
2	4.3	4.248	4.3	0.052	0
3	7	6.9	6.9	0.1	0.1
4	9.5	9	9	0.5	0.5
5	11	10.5	10.5	0.5	0.5

6	11.5	11.5	11.5	0	0
7	12	11.1	11.1	0.9	0.9
8	10.7	10.8	10.8	0.1	0.1
9	9.6	9.35	9.35	0.25	0.25
10	8	7.95	7.95	0.05	0.05
11	6.3	6.5	6.5	0.2	0.2
12	5	4.65	4.65	0.35	0.35
13	3	3.1	3.1	0.1	0.1
14	1.2	1.5	1.5	0.3	0.3
15	0	1.2	1.2	1.2	1.2

As shown in tables 2 and 3, obtained analytical approximations of the spectral characteristics have rather good accuracy for practice. So, they can be used in the design of PXAs, as well as to estimate the effective atomic number of the substance, based on the dual-energy method.

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