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Parameter identification method for dual-energy X-ray imaging

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ABSTRACT

The paper presents a method for parameter identification of dual-energy X-ray imaging. This method is based on pre-calculated or experimentally obtained dependencies between the right sides of the system of two integral parametric equations and two required parameters within the ranges interesting to a customer. This method is characterized by a high processing speed depending on the speed of random access memory. Thus, it is used in different implementations of dual-energy X-ray imaging, namely digital radiography and computed tomography.

1. Introduction

A method for performing dual-energy X-ray imaging (DEXI) is one of the most promising and developing methods of non-destructive testing. Originally, DEXI was developed to compensate the negative effect produced by energy inhomogeneity on the accuracy of image reconstructions in X-ray computed tomography [1–6]. Further DEXI was applied in industry, for example, to study three-phase flow [7]. Lately, the different implementations of DEXI are used for substance identification of test objects and their fragments [8–14]. Two implementations of DEXI exist, namely digital radiography and computed tomography. The substance identification implies the estimation of its effective atomic number or other identification parameter directly or indirectly connected with it.

DEXI is based on several physical lows:

1. The linear gamma-radiation attenuation coefficient equals to the sum of the linear attenuation coefficients due to effects of interactions of photons with attenuating material (photo-effects, coherent scattering, non-coherent scattering, and effect of pair creation).
2. Due to the different interaction effects the linear gamma-radiation attenuation coefficients are dependent different from the effective atomic number and the attenuating material density and from the photon radiation energy.
3. For various parts of the X-ray source energy spectrum the contributions of the different processes to the total linear attenuation coefficient are different.

In DEXI, two certain parameters are estimated separately on the basis of X-ray attenuation measurements of two specially selected maximal energies. One of the two parameters depends on thickness and density of the test object, while the second depends on the effective atomic number as well. There exist several methods for parameter identification of DEXI. The work [4] connects the final DEXI parameters with primary radiographic signals by use of two-dimension regression of second order. This approach has a high performance, but its precision does not meet the modern consumer. The method [5] is based on pre-builting tables, connecting source and destination DEXI parameters for the base medical materials, and on usage of the tables to estimate DEXI parameters by real data interpolation. The work [6] proposes to use the iteration methods of the corresponding system of equations for a more accurate determination of the DEXI parameters compared with the method [5]. The computing error 10^{-6} of method [6] is achieved by 10 iterations. The solution of the system of two nonlinear integral parametric equations suggested by Osipov et al. [15] is a more physically proven method. As recommended in the work of Nedavnii et al. [12], Newton's method or secant method can be used to solve the system of nonlinear equations. The main disadvantage of these methods is conditioned by the type of nonlinear integral parametric equations and lies in their low productivity due to integration with rather composite subintegral function at each step of the iteration. This disadvantage is characterized for method [6] also. In practical use of DEXI, modern radiographic installations process two-dimensional images containing over 10^6 pixels, whilst industrial X-ray tomography installations

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process three-dimensional images containing over 10^9 pixels. The existing methods of solving the systems of nonlinear integral parametric equations do not fully satisfy the user because the formation of original radiographic images is inadmissibly time spread and includes visualization of final 2D or 3D images. As is obvious from the above-stated, the problem of developing high-performance and high-precision parameter identification techniques for DEXI is still relevant. This problem has special significance to inspect the inhomogeneous objects, whose have the values of the mass thickness of fragments and the effective atomic numbers of material fragments from wide ranges.

2. Principles of dual-energy X-ray imaging

In first stage of the dual energy method the radiometric signals of maximal X-ray radiation energies E_1 and E_2 are acquired. Let N_i photons of X-ray radiation with maximal energy E_i fall on the front surface of the radiometric detector with thickness h_d during the measurement. The connection of radiometric signal I_i, $i=1, 2$, with the inspection object characteristics for the maximal X-ray radiation energy E_i is described by expression

$$I_i(h) = N_i \int_0^{E_i} E_{ab}(E) f(E, E_i) e^{-\mu(E)h} \varepsilon(h_d, E)\, dE, \quad (1)$$

where $f(E, E_i)$ is an energy spectrum of the X-ray radiation with maximal energy E_i; $\mu(E)$ is an energy dependence of the linear attenuation coefficient (LAC) of photon radiation by the inspected material; $E_{ab}(E)$ is a mean value of the absorbed energy for the quantum with energy E, recorded by detector; $\varepsilon(h_d, E)$ is the radiation detection efficiency for energy E and detector with thickness h_d.

The introduction marks the physical laws, underlying DEXI. In formalized form they are reduced to the following presentation of the energy dependence of LAC by the inspected material:

$$\mu(E) = a_1 g_1(E) + a_2 g_2(E), \quad (2)$$

where $g_1(E)$ and $g_2(E)$ are the energy dependences of photon radiation attenuation coefficients for two physical effects of the photon radiation interaction with material; a_1 and a_2 are the coefficients, dependent on density ρ and the effective atomic number Z of the inspected material.

Note 1: DEXI is used for two ranges of X-ray maximal energies. Photoelectric effect and Compton effect (incoherent scattering) prevail in the interaction between photon radiation and substance within the range of low X-ray energies (maximal energies up to 200 keV). As for high X-ray energies (maximal energies up to over 2 MeV), Compton effect and pair production prevail in the interaction between photon radiation and substance.

For clarity, let us compare the energy dependence $g_1(E)$ with the photoelectric effect for low X-ray energies and that one with pair production for high X-ray energies. The function $g_2(E)$ corresponds to Compton effect.

The system of nonlinear integral parametric equations is produced from expressions (1) and (2). It connects the ray thicknesses $Y(E_1)$ and $Y(E_2)$ measured in photon mean free paths with the required $A = a_1 h$ and $B = a_2 h$ parameters of DEXI. The system of the integral parametric equations is as follows [15]:

$$-\ln\frac{\int_0^{E_1} E_{ab}(E) f(E, E_1) e^{-Ag_1(E) - Bg_2(E)} \varepsilon(h, E)\, dE}{\int_0^{E_1} E_{ab}(E) f(E, E_1) \varepsilon(h, E)\, dE} = Y(E_1);$$
$$-\ln\frac{\int_0^{E_2} E_{ab}(E) f(E, E_2) e^{-Ag_1(E) - Bg_2(E)} \varepsilon(h, E)\, dE}{\int_0^{E_2} E_{ab}(E) f(E, E_2) \varepsilon(h, E)\, dE} = Y(E_2); \quad (3)$$

Denote $Y(E_1)$ and $Y(E_2)$ the first and the second informative signal parameters, respectively.

In view of the above mentioned, the value of the parameter A equals to the product of some function of the effective atomic number Z and the density ρ of the test object substance and its current thickness h. The product ρh is called the mass thickness. For the photoelectric effect and pair production the function $A(Z, \rho h)$ has different forms [8]:

$$A(Z, \rho h) = \begin{cases} Z^{3.8} \rho h & \text{photoelectric effect [7],} \\ Z \rho h & \text{pair production [16].} \end{cases} \quad (4)$$

It is assumed that the function $B(Z, \rho h)$ is described by equation

$$B(z, \rho h) = \rho h. \quad (5)$$

Equations in the literature [1,16] are given to describe energy dependencies $g_1(E)$ for the photoelectric effect:

$$g_1(E) = C_1 E^{-3}, \quad E \geq 0.02\ \text{MeV}, \quad (6.1)$$

and for pair production [17]

$$g_1(E) = C_2 \begin{cases} 0, & E < 3.424\ \text{MeV} \\ \frac{14}{3} \ln(3.914E) - \frac{109}{9}, & E \geq 3.424\ \text{MeV} \end{cases} \quad (6.2)$$

Coefficients C_1 and C_2 in Eqs. (6.1) and (6.2) are constant. Note that the probability of photons interaction with the material by the pair creation scenario has a nonzero value starting from energy 1.022 MeV. The threshold value of energy $E = 3.424$ MeV in (6.2) provides the positivity condition of function $g_1(E)$.

The dependence between Compton cross-section and the energy can be obtained from [1,16]

$$g_2(\alpha) = C_3 \left\{ \frac{1+\alpha}{\alpha^2} \left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{\ln(1+2\alpha)}{\alpha} \right] + \frac{\ln(1+2\alpha)}{2\alpha} - \frac{1+3\alpha}{(1+2\alpha)^2} \right\}, \quad (7)$$

where $\alpha = E/0.511$, E is the energy in MeV; C_3 is the constant coefficient.

The dependence between the detection efficiency of photon radiation and energy E and thickness h_d of the sensitive volume of detector has the form

$$\varepsilon(h, E) = 1 - e^{-\mu_d(E) h_d}, \quad (8)$$

where $\mu_d(E)$ is the dependence between the linear attenuation coefficient of photon radiation and the energy that can be obtained from the different gamma data libraries, described, for example, in [18].

Energy dependence of the mean value of absorbed energy for detected photon can be obtained from the above-mentioned gamma data library [18] or functions $E_{ab}(E)$ accounting for the size and the type of detectors and presented in the work of Zav'yalkin and Osipov [19].

The implementation of any way of solving the system of integral parametric equation (1) considerably depends on the range of maximal energies of X-ray sources applied in DEXI. This is conditioned by two factors, the first of which is given in *Note* 1, and the second is connected with the description of X-ray energy spectrum.

Traditionally, for the description of X-ray energy spectrum, Kramers formula is used for maximal energies up to 200 keV, and Schiff formula for energies over 2 MeV as well as their modifications. In works [20–22], classical formulas are given for detecting X-ray energy spectrum for different ranges. These formulas quite adequately represent real energy spectrums of X-ray sources used in various implementations of DEXI. These formulas can be reduced to the following equation to calculate the digital energy spectrum of