Application of dual energy method for non-destructive testing of materials designed to work in extreme conditions

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Abstract. The description of the dual energy method (DEM) for non-destructive testing (NDT) of materials and products is presented. It highlights the key factors that determine its accuracy and performance and shows the possibilities for its further improvement. The correlation between the quantum noise level and the DEM precision of the effective atomic number was found.

1 Introduction

The quality control is the most massive operation in the production process, because no detail can be made without measuring its performance. The complexity of the control operations in the industry is increasing dramatically due to the complexity of the new technology and a steady increase requirement of its reliability [1-3]. Thus, in developed countries, the quality control costs are on average from 1 to 3% of the product, and in industries such as defence, nuclear and aerospace, quality control costs increases to 12-18% of [4]. These costs quickly pay for themselves, because due to NDT at all stages of production and acceptance the quality of products radically improving and its reliability is increased.

A variety of practical problems of control, by the target, its content and their terms involves the quality problem solution by various physical methods. In this regard, in the science and practice many NDT methods have developed, which are mainly used for the product examination (bulk defect detection) with the untreated surface and a complex shape. With the development of the nuclear instrumentation, accelerator technology the scope of the technical arsenal of radiation control means greatly enhanced.

Currently the digital radiography occupies one of the dominant positions among the different radiation NDT methods. The term "digital radiography" means the aggregate of radiation NDT methods and diagnostics, which converted at some point the radiation image of the testing object (TO) into a digital signal [5-6]. Subsequently, this digital signal is stored in computer memory and converted into two-dimensional array of measuring data, which can be subjected to various digital signal processing (contrast enhancement, scaling, antialiasing, and the like), and finally, it is reproduced on the display screen as halftone (or colour) image directly perceived by the operator. Currently, digital radiography system

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(DRS) are widely used in industrial and technical flaw diagnosis in medical diagnostics, as well as for screening baggage, carry-on baggage, containers, etc. to ensure the safety of traffic and deter illegal trafficking of prohibited items [7].

Dual-energy method (DEM) is used for improving the efficiency of control in many DRS. Testing object in this method is radiated twice - at two different voltages on the X-ray tube (corresponding to two effective energies of radiation). Radiation detection results are processed by a certain algorithm to obtain an estimate of the atomic number Z (or effective atomic number) material TO [8].

There are various modifications in the implementation of this method, for example - with a single registration TO by two radiation detectors arranged one after the other along the X-rays [9], but instead of high-energy x-ray tubes are used the radiation sources [10].

It is obvious that the possibility of determining the atomic number (or effective atomic number) TO material makes the examination process significantly more informative. This is particularly important during examination of responsible products, designed for operation in extreme conditions, in particular for NDT of structural elements of spacecraft.

2 Basics of dual energy method

In the dual-energy method based on measuring the attenuation of X-rays of two energies, two maximum of some parameters are measured separately, further – DEM parameters. One of the DEM parameter is depended from thickness hand density ρ of TO material, and second one from the effective atomic number. There are several ways to define DEM parameters. The most physically based method associated with the solution of integral equations of two-parameter systems [11]:

$$
\begin{aligned}
-\ln \frac{\int_0^{E_1} E_A(E) f(E,E_1) \exp(-Ag_1(E) - Bg_2(E))\varepsilon(E)dE}{\int_0^{E_1} E_A(E) f(E,E_1)\varepsilon(E)dE} = Y(E_1) \\
-\ln \frac{\int_0^{E_2} E_A(E) f(E,E_2) \exp(-Ag_1(E) - Bg_2(E))\varepsilon(E)dE}{\int_0^{E_2} E_A(E) f(E,E_2)\varepsilon(E)dE} = Y(E_2)
\end{aligned} \tag{1}
$$

Here $f(E,E_1)$, $f(E,E_2)$ is the energy spectra of X-rays with a maximum energy E_1 and E_2 correspondingly; $g_1(E)$, $g_2(E)$ are the energy dependences of attenuation coefficient of photon radiation for the two physical effects of photon interaction with matter; $E_A(E)$ is an average value of the absorbed energy to a photon with energy E, which is registered by detector; A and B are desired DEM parameters; $\varepsilon(E)$ is the effectiveness of the radiation detecting energy E for the detector; $Y(E_1)$, $Y(E_2)$ are first and second informative parameters (converted radiation measurement results corresponding to both maximum energies E_1 and E_2).

Prevailing effects of the interaction of photon radiation with matter in the range of X-ray energies up to 200 keV is the photoelectric effect and the Compton Effect (incoherent scattering). Therefore according to [11-12] we have:

$$A = Z^{3.5}\rho h; \tag{2}$$

$$B = \rho h \tag{3}$$

$$g_1(E) = C_1 E^{-2.8}, \ E \geq 0.02 \text{ MeV} \tag{4}$$

$g_1(E)$ is the energy dependence of the photoelectric effect; C_1 is a constant;

$$g_2(E) = C_2 \left\{ \frac{1+\alpha}{\alpha} \left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{ln(1+2\alpha)}{\alpha} \right] + \frac{ln(1+2\alpha)}{2\alpha} - \frac{1+3\alpha}{(1+2\alpha)^2} \right\} \tag{5}$$

$g_2(E)$ is the energy dependence of the Compton effect, where $\alpha=E/0.511$, E is energy in MeV; C_2 is a constant.

Kramers formula as well as its various modifications used traditionally to describe the X-ray energy spectrum in the region of maximum energy of 200 keV. Equations (1) - (5) are the basic analytical relationships that express the essence of DEM using sources with a continuous energy spectrum of radiation with maximum energy in the spectrum up to 200 keV.

3 Factors determining the accuracy and quick dual energy method

From (1) - (5) it follows directly that DEM accuracy is mainly determined by the following factors:

- the accuracy of approximation the interaction of photon radiation with matter in the energy range of X-rays up to 200 keV photoelectric effect and the Compton effect;
- accuracy of the measurement of informative parameters $Y(E_1)$, $Y(E_2)$, is determined, in particular, the accuracy (capacity) of analog-to-digital conversion of output processes of the radiation detector and the statistical fluctuations of the radiation detection results caused by the quantum nature of radiation;- accuracy of estimation of maximum energy in the spectrum of the radiation source;
- setting up of the energy spectrum of the radiation generated by the source;
- accuracy of estimation of the average value of the energy absorbed by the detector;
- accuracy of estimation (calculation) radiation detection efficiency of the detector;
- precision of parametric solution of the integral equations.

Examination of each of these factors, individually and in various combinations, represents a significant scientific problem. In particular, in the field of radiological methods the efforts of many experts focused on the search for more accurate analysis of the cross section of the photoelectric energy. For example, instead of formula (4) in [13] there was proposed a formula like $g_1(E)=C_1E^{-3}$. It should be noted that the preference in the choice of a particular analytical relationship is usually set empirically for a particular group of materials to be recognized.

It is quite obvious that the DEM accuracy can be somewhat improved if the formula (1) to add one more, taking into account the effect - coherent scattering. In particular, based on the data presented in [14], the energy dependence of the coherent scattering type analytically approximated function adequately $f_{coh}(E)=1/E^2$.

The solution of the integral system of parametric equations (1) is one of the biggest difficulties of DEM. In [11] provides a method for the solution of this system based on the concept of a two-dimensional line-level functions, and offered its simple physical implementation.

With regard to DEM performance, then it will be determined by the following steps of determining the parameters of the algorithm A and B. In the first stage, calculated value functions describing the energy dependence of the cross sections of the photoelectric effect and incoherent scattering. In the second stage there is calculated a value of the function approximating the actual energy spectrum of the radiation source. Then function values are calculated, describing the detection efficiency of the radiation detector, and estimated a value of the function that describes the average value of the energy absorbed by the detector. Then the integrals are evaluated in the system of integrated-parametric equations

(1). Finally, the parameters A and B are calculated. Each of these procedures are characterized by a number of arithmetic operations that determine the actual speed of data processing algorithm based on the DEM. It should be noted that the total number of arithmetic operations significantly depends on the method of numerical integration and convergence speed.

4 Conclusions

At the present stage of the development of digital radiography systems, implementing DEM, there were analysed the images from 256 × 256 to 1024 × 1024 elements, and more, that is, in the pre-processing stage is necessary to find solutions from 65536 to 1048576 or more systems integrated-parametric equations of type (1). Thus, the total number of computational operations required for processing of all data set (dual digital radiographs), can be very large. Therefore, the entire process will not take place in "real time" and, consequently, to minimize the number of arithmetic operations at each stage of the overall algorithm is a very important task.

Thus, further DEM improvement can be done in many different ways. In particular, it is important to establish the quantitative dependence of quantum noise on the accuracy of the material's atomic number estimation.

The correlation between the quantum noise level and the DEM error of the effective atomic number for the aluminium plates, used for the aircrafts sheathing, was found as a result of our theoretical numerical studies.

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