DUAL ENERGY METHOD OF MATERIAL RECOGNITION IN HIGH ENERGY INTROSCOPY SYSTEMS

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INTRODUCTION

Element analysis based on so-called dual energy method is widely used throughout the world in X-ray customs inspection systems for luggage control in airports. It facilitates the routine work of customs officer on identification of illegal drugs and explosives hidden in luggage. Due to the absorption rate difference in material of X-rays generated by sources with different energies, discrimination of materials becomes possible. So the scanned image of inspected object can be represented in physical palette where materials are coloured according to their atomic number.

METHOD

The physical principle of dual energy method is based on the fact that due to the exponential law of gamma radiation attenuation the ratio of logarithmic transparencies at nominal and dual energy

$$\delta\left(E_{\gamma 1}, E_{\gamma 2}, Z\right) = \frac{\ln\left(T_1\right)}{\ln\left(T_2\right)} = \frac{\mu_{tot}\left(E_{\gamma 1}, Z\right)}{\mu_{tot}\left(E_{\gamma 2}, Z\right)} \quad (1)$$

characterizes material of the barrier irrespective to its thickness.

As far as effectiveness of dual energy method is determined by Z-dependence of total attenuation coefficient, it is evident that X-ray energy range <0.5 MeV, where the process of photoelectric interaction dominates with its strong Z-dependence ($\sigma_\tau \sim Z^5$), is the most preferable for element analysis. Opposite to the photo-effect Compton scattering with $\mu_c \sim Z/A$ has poor Z-dependence. This ratio is approximately the same for elements from, at least, top of periodic table, compositions of those define the whole variety of organic substances. However our goal is to investigate the possibility of materials discrimination for the energy range 1<E<10 MeV, where Compton scattering dominates. One can see the little difference between total attenuation coefficients of different elements for energies from 1÷10 MeV range on Fig. 1.

Among many factors that stipulate its low sensitivity the major one is the influence of scattered radiation. Therefore we should carefully eliminate one by collimating of the photon beam and all subsequent formulas and calculations are fulfilled for the narrow photon beam.

As far as we use flow of bremsstrahlung quanta with continuous spectral distribution in our work, first let us introduce new transparency T (inverse value of absorption) of a barrier with atomic number Z and thickness t (gr/cm^2) for flow of bremsstrahlung with boundary energy E_{ac} (MeV).

$$T\left(E_{ac}, t, Z\right) = \frac{\int_0^{E_{ac}} \frac{dP}{dE_\gamma}\left(E_{ac}, E_\gamma\right) \cdot e^{-\mu\left(E_\gamma, Z\right)t} \cdot dE_\gamma}{\int_0^{E_{ac}} \frac{dP}{dE_\gamma}\left(E_{ac}, E_\gamma\right) \cdot dE_\gamma}, \quad (2)$$

where energy distribution proportional to signal of detector is a product of spectral distribution of bremsstrahlung intensity according to Schiff formula [1] and detector response factor.

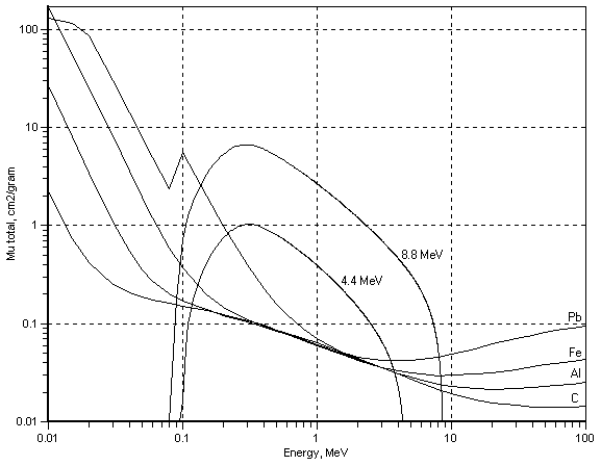

Fig. 1. Total attenuation coefficient [2] as function of energy for Carbon (Z=6), Aluminium (Z=13), Ferrum (Z=26) and Plumbum (Z=82). Red curves are spectral distributions of bremsstrahlung quanta (rel. units) emerged from thick tungsten target for dual energies of electron beam 8.8 MeV and 4.4 MeV.

As a first approach to the goal we estimated the effectiveness of value introduced in (1) with newly introduced transparencies for the purpose of material discrimination. Unfortunately due to the continuous character of bremsstrahlung spectrum δ depends on thickness of barrier and therefore is not applicable for the purpose of discrimination. Nevertheless, our first approach has one important drawback. We restricted ourselves with taking into account the ratio of transparencies at nominal E_{acc1} and dual E_{acc2} energies therefore a part of information has been lost. In order to get rid of it we represent clusters on two-dimensional absorption plane (inverse value of transparency), where the most of materials can be discriminated irrespective to their thickness since intersection of two data sets is always lesser than their union.

Fig. 2 shows thickness curves for range from 0 to 120 gr/cm^2 of a set of elements, where X-axis represents inverted logarithmic transparency α_1 (absorption) scaled by factor Scale=1000 for nominal energy E_{acc1}=8 MeV and Y-axis – $(\alpha_2-\alpha_1)$ – difference of absorptions for dual E_{acc2}=4 MeV and nominal energies:

$$\alpha_1 = \left(1 - \ln T_1\right) \cdot Scale$$
$$\alpha_2 - \alpha_1 = \left(\ln T_1 - \ln T_2\right) \cdot Scale \quad (3)$$

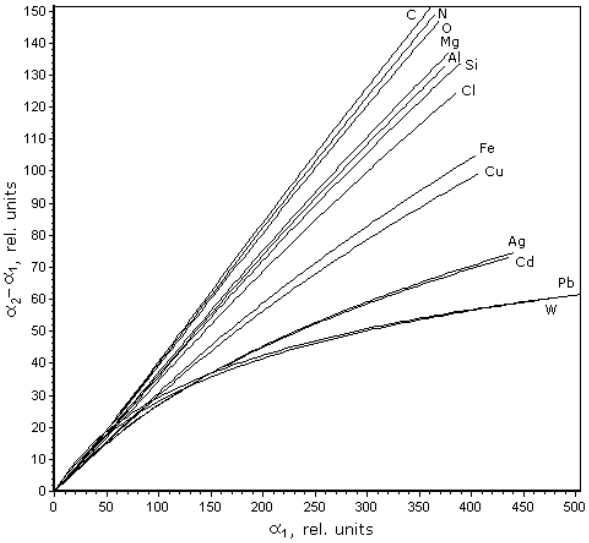

Fig.2 Absorption curves of different elements for thickness range from 0 to 120 gr/cm^2. Energies: nominal E_{acc1}= 8MeV and dual E_{acc2}=4MeV.

From figure one can see that absorption curves of elements are separated for the whole thickness range, except group of heavy metals (plumbum, tungsten) and diverge as thickness increases. Now, therefore, our aim is to formulate the recognition task in mathematical terms for the common case.

Suppose we have two experimentally measured transparencies at nominal and dual energies of a barrier of unknown material and thickness: $T_{1\,exp}$, $T_{2\,exp}$. Our goal is to associate them with material (Z) and optionally with thickness t. So, using (2) we can write system of two non-linear integral equations:

$$\begin{cases} T_{1\exp} = T(E_{ac1},t,Z) = \dfrac{\int_0^{Eac1} \frac{dP}{dE_\gamma}(E_{ac1},E_\gamma)\cdot e^{-\mu(E_\gamma,Z)t}\cdot dE_\gamma}{\int_0^{Eac1} \frac{dP}{dE_\gamma}(E_{ac1},E_\gamma)\cdot dE_\gamma} \\ T_{2\exp} = T(E_{ac2},t,Z) = \dfrac{\int_0^{Eac2} \frac{dP}{dE_\gamma}(E_{ac2},E_\gamma)\cdot e^{-\mu(E_\gamma,Z)t}\cdot dE_\gamma}{\int_0^{Eac2} \frac{dP}{dE_\gamma}(E_{ac2},E_\gamma)\cdot dE_\gamma} \end{cases} \quad (4)$$

Thus we have two non-linear equations and two unknown quantities: material and its thickness. Formally this system must have solution as the transparencies are obtained from experimental measurements, but this solution might be not unique (as we have seen that for heavy metals). This means that the same pair of transparencies may correspond to a few different materials with different thickness. Adding the next measurements (for example, triple energy method and so on) we may theoretically eliminate this uncertainty, but practical realization of it is too complicated. The next difficulty is how to solve this system. If the first variable - thickness - is a continued variable then second one - material - is discrete. The most common method that has been used, is minimization of functional. Let's build positive form as

$$Functional = \sqrt{\left(T(E_{ac1},t,Z) - T_{1\exp}\right)^2 + \left(T(E_{ac2},t,Z) - T_{2\exp}\right)^2} \quad (5)$$

and start to minimize it as two-dimensional function. Taking into account that Z variable is discrete and number of materials is limited it is possible to search minimum for thickness variable only and move along Z. Minimum searching of one variable function can be fulfilled either by Fibbonachi or Gold Cross-section method. Graphically the minimization of functional (5) can be represented as searching of the shortest distance between experimental point (pixel on image) with transparencies T_{exp1}, T_{exp2} (logarithmic absorptions α_{exp1}, α_{exp2}) and a curve of certain material from the set of absorption curves. If procedure of minimization delivers nil value functional with certain precision, this asserts that material of barrier and its thickness are found and that can be graphically represented for example by colorizing of pixel on data image. This method effectively works for the most of substances, but has one major obstacle on the way of its practical realization. The procedure of discrimination takes long time and cannot be performed for each pixel in real time mode because number of image pixels might reach several millions. Therefore we can apply this method locally only, for small zone of experimental image.

As we mentioned before solving of system of non-linear equations (4) is a task that cannot be performed in real time mode. The system is to be solved for each data pixel and their number in image might exceed million. Nevertheless the number of mathematical operations fulfilled by computer processor can be dramatically reduced and material recognition procedure becomes possible for large data images. The first main time eating procedure is calculation of transparencies at high and low energies $T_1(E_{ac1},t,Z)$, $T_2(E_{ac2},t,Z)$ in (5) can be substituted by their interpolation algorithm. Indeed as far as we evaluated high and low energy (we used the absorption method) and also due to the fact that Z variable is discrete we can build material recognition base for the limited number of materials. The base represents itself as a set of frame points:

$$R_{ij} = \left(t_i, Ln\left(T_{1i}(Z_j)\right), Ln\left(T_{2i}(Z_j)\right)\right), \quad i = 1...n, \quad j = 1...m \quad (6)$$

where n – number of frame points, m – number of materials. This set serves as interpolation base for evaluation of high and low transparencies. As far as transparency is exponential function of thickness, for minimization of interpolation error its logarithmic values were taken. Second, criterion of material discrimination is minimization of Functional (5), which also can be drastically simplified. Instead of searching the shortest distance between experimental point defined by a pair (T_{1exp},T_{2exp}) and the closest thickness curve from recognition set we use a new criterion. Indeed, solving each of equations (4) relatively thickness t with fixed Z, we can correspond high T_{1exp} and low T_{2exp} experimental transparencies to the thicknesses t_{1exp} and t_{2exp}. It is evident that if Z is chosen right the both thicknesses must coincide. Therefore our new criterion for material discrimination is evaluation of the ratio:

$$\frac{\left|t_{1\exp}(Z_i) - t_{2\exp}(Z_i)\right|}{t_{1\exp}(Z_i)} \le Tol_i(Z_i) \quad i = 1,\ldots,m \quad (7)$$

where m – number of chosen materials for recognition.

Though from the common point of view it looks unusual to operate with two virtual thicknesses while the physical value is unique. Nevertheless due to the low sensitivity of method and noise of experimental data the introduction of tolerance for each material in recognition base is required.

So, now the discrimination procedure is simplified considerably and requires only estimation of ratio (7) for each material from recognition set. It does not require numerous iterations and its duration is defined by the number of materials m.

EXPERIMENTAL RESULTS

In order to get approval of our method a series of experiments were carried out at NPK LUTS NIIEFA stand "Inspector" equipped with:

- Industrial linear electron accelerator UELV-10-2D-40 on travelling wave with energy at the nominal mode up to 7-10 MeV and at dual 3-7 MeV. Pulse duration – 5 μsec; repetition rate – 100 Hz (interlaced mode).
- Collimating system of bremsstrahlung beam consisting of two beam forming units and collimator of detector line. Narrowed beam scans in vertical plane.
- Detection line consists of 5 modules. Each module contains 128 channels of detection; as a sensitive element p-i-n diodes in combination with scintillator crystals are used; a pitch of sensitive elements in the array - 3,5 mm.
- System of transportation of tested samples across radiation beam.

The procedure of experiment, data processing and visualization were in the following order:

1. The electron accelerator operated at so called interlaced mode, when its each even pulse generates nominal energy and each odd – dual;
2. Raw data interlaced file is decomposed into high energy and low energy image files;
3. Each file is processed separately: non-uniformity of detectors and also angular anisotropy of bremsstrahlung intensity are eliminated by means of vertical correction of image;
4. Data counts are converted into transparencies by means of normalization to the white field count level;
5. Data of both files are taken logarithmic and one of them is visualized in gray palette; each pixel on image is characterized by two transparencies;
6. Both energies of accelerator are evaluated by absorption method;
7. Material recognition is fulfilled by means of processing of each pixel and its colorizing on successful completion according to material recognition palette.

In a series of experiments we used flat and wedge samples made of polyethylene, duralumin, steel and lead. Data processing according to above presented method allowed us to discriminate and coloured samples irrespective to their thickness (Fig. 3).

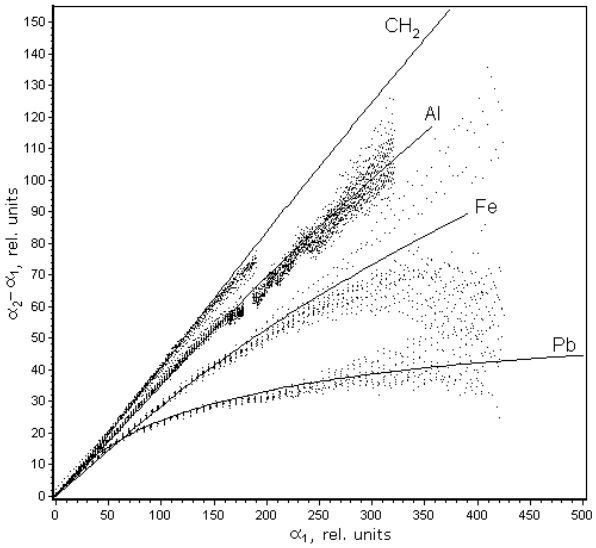

Fig. 3. Calculated absorption curves and spreads of experimental data of polyethylene (50cm), duralumin (40cm), steel (18cm) and lead (8cm) wedge samples at E_{nom}=9.04 MeV and E_{dual}=4.65 MeV.

CONCLUSION

Theoretical consideration and experimental results have shown that above represented algorithm allows to carry out discrimination of materials according to their atomic number and irrespective to their thickness at dual energies of accelerator from 1÷10 MeV range. Low sensitivity of the method, noise level and non-linearity of detectors restricted discrimination in our experiments with Z-precision ~10. In order to perform effective recognition of materials for custom inspection purposes the installation has to satisfy the following requirements:

- Accelerator must have high energy stability; nominal and dual energy of accelerator must be measured with proper precision;
- Accuracy of transparencies measurement must be enough in order to ensure the third-fourth significant digit, therefore the number of bits of ADC must equals at least 16;
- Signal to noise ratio should be enough to assure the correct transparency evaluation, therefore during scanning averaging might be applied;
- The theory is based on the linear approach, therefore the linearity of detectors has to be provided;
- Speed of processor should be enough to fulfill the necessary processing of large volumes of data;
- Discrimination ambiguity at small thickness of the barrier requires the necessity of bremsstrahlung filtering.

REFERENCES

[1] Shiff L. J. // Phis. Rev. 1951 v 83, Num 2.

[2] Storm E., Jsrael H. Photon Cross Section from 0.001 to 100 MeV for Elements 1 through 100. - Los Alamos Scientific Laboratory, New Mexico, 1967.