MATERIAL DISCRIMINATION TECHNOLOGY FOR CARGO INSPECTION WITH PULSE-TO-PULSE LINEAR ELECTRON ACCELERATOR

S. Ogorodnikov#, M. Arlychev, I. Shevelev, R. Apevalov, A. Rodionov, I. Polevchenko,
LLC "Scantronic Systems", Oktyabrskaya emb. 104, build. 14, St. Petersburg, 193079, Russia

Abstract

In the present article a complex of technological solutions based on 6/3.5 MeV pulse-to-pulse linear accelerator, detectors made of CWO scintillators coupled with PIN photodiodes and image processing algorithms proposed. Energies, dose rate and other parameters of accelerator were optimized to reach high performance of the x-ray system and to carry out robust and reliable material discrimination in the mass thickness range up to 120 g/cm^2 at least. Evaluation of effective atomic number of materials of main three groups (organics, mineral/light metals, metals) was fulfilled with preciseness ±1 for the optimal mass thickness range at the scanning speed 60 cm/s. Instrument for evaluation of physical mass of the separate objects on the image is proposed and realized.

INTRODUCTION

World globalization and as a result growing every year traffic of cargo across the borders are placing a challenge for the customs authorities all over the world to solve a problem of efficient disclosure of contraband, weapons, explosives, drugs and other goods prohibited for transportation. Most widely used technology is the single energy x-ray transmission technology, which provides shadow radioscopic image uses linear or cyclic electron accelerators in 1-10 MeV energy range as a source of bremsstrahlung radiation. One of new methods for inspection is the dual energy transmission technology, which was demonstrated first on an experimental prototype of x-ray customs control system is usage of 8/4 MeV pulse-to-pulse linear electron accelerator [1, 2]. Later this method further developed by different research groups [3-5] and also was implemented by different commercial companies as an option to the existing x-ray transmission technology. Nevertheless the realization of this method in commercial products recommended itself as labile, instable and not repeatable in practical implementation. The aim of this article is to demonstrate that usage of pulse-to-pulse linear accelerator in combination with CWO detectors made of scintillators can lead to x-ray inspection system capable to achieve high radioscopic performances of x-ray inspection system, and implementation of special mathematical algorithms as a core of x-ray image processing software provide a reliable and robust material discrimination functionality including evaluation of effective atomic number with good precision as well as evaluation of physical mass of separate objects in cargo.

sergey.ogorodnikov@scantronicsystems.com

MATERIAL DISCRIMINATION BASICS

Generally the task of material discrimination is studied as a search of solution for system of integral equations in regard to atomic number and mass thickness of an unknown barrier on the base of experimentally given values of radioscopic transparencies at high and low radiation energies [1]. In work [2] it was shown that this system formally has a solution, and the key value for analysis of solution existence and evaluation of material discrimination effect on Z is the ratio of logarithms of transparency at nominal $E_1$and dual E_2 boundary energies of bremsstrahlung radiation. Calculation showed that discrimination effect for two materials with close atomic numbers is considerably small. For example, for carbon and iron with atomic number difference $\Delta Z=20$ at the bremsstrahlung energies 6 MeV and 3.5 MeV, it is about 4% for mass thickness 40 g/cm^3, and for water and ethylene $\Delta Z \cong 1.2$ the effect does not exceed 0.4%. The discrimination effect is raised with increase of mass thickness, but raise of quantum noise, related to exponential decrease of received by detectors radiation and increase of scatter, removes this effect to zero. In the case, when a barrier represent itself a combination of two and more materials forming a heterogeneous structure, identification of atomic numbers of components on the base one pair of radioscopic transparencies is impossible. Though, from the point of view of gamma-radiation absorption a heterogeneous barrier is equivalent to a homogeneous one with summarized mass thickness and weighted-mean total mass absorption coefficient that allows estimation of effective mass number of a tested barrier and material classification in groups. For the aims of customs inspection it is desirable to discriminate at least four groups of materials, namely:

- Light or «organic» materials with small atomic number (1<Z<10);
- Materials with average atomic number(10<Z<20);
- «Inorganic» materials (20<Z<50);
- Heavy metals with high atomic number (Z>50).

EXPERIMENTAL INSTALLATION

A series of experiments was carried out on the prototype of x-ray inspection system (mini-system), which included 6/3.5 MeV klystron linear electron accelerator, manufactured by company Scantronic Systems, collimator, 128-channel detector block, conveyor, control system and image processing workstation, which were developed by specialists of

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Scantronic Systems. The mini-system was built up in a configuration and functionality fully simulating operation of full-scale inspection system, what allows evaluating its performance on a compact x-ray image. The composition of mini-system included:

- Linear electron accelerator;
- 128 detection channels (scintillators from CWO);
- 5 m conveyor with drive, conjugated with mini-system control system, which simulates a relative movement between accelerator, detector and cargo;
- Electrical cabinet with PLC controller and interfaces to the elements of mini-system;
- Radiation safety subsystem;
- Computer system, consisting of control workstation and image processing workstation.

In experiments the accelerator worked in the mode of pulse-to-pulse scanning: at each even pulse the accelerator generated bremsstrahlung radiation with high energy and at each odd with low energy. A tested object was scanned with a fan-like beam, formed by the collimation system. Passed through the object radiation was registered by the detector line. Analog signals from detectors were digitized with 20-bit ADC and transmitted to a graphical workstation through Ethernet interface, where analysis and visualization of the object shadow image were performed. Distance between the accelerator target and the detector line was 8.2 m. Energies, dose rate and other parameters of accelerator were optimized to confirm the requirements of the technical specifications to x-ray inspection system for vehicles from Russian customs authorities.

Table 1: Main Parameters of 6/3.5 MeV Pulse-to-Pulse Accelerator

Parameter	Value
High energy	6 MeV
Low energy	3.5 MeV
Dose rate at high energy	2.0 Gy/min at 1 m
Dose rate at low energy	2.0 Gy/min at 1 m
Dose energy at pulse-to-pulse mode	4.0 Gy/min at 1 m
Repetition rate at high energy mode	200 Hz
Repetition rate at low energy mode	200 Hz
Repetition rate at pulse-to-pulse mode	2x200 Hz
High energy stability	0.5%
Low energy stability	0.5%
Dose rate stability at high energy	2%
Dose rate stability at low energy	2%
Focal spot size	< 2 mm

After scanning was completed the received data were decomposed on two images, corresponding to high and low energies. Processing of shadow images included correction of dose rate instability, correction non-uniformity of the detector channels, estimation of boundary energies of bremsstrahlung radiation by the absorption method, colorization in accordance with material-to-color lookup table.

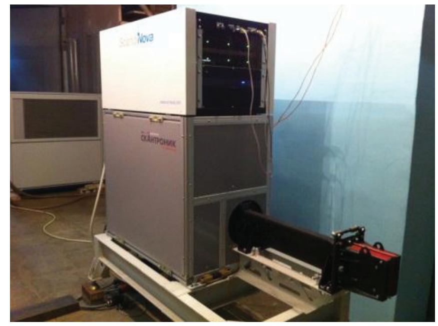

Figure 1: 6/3.5 MeV pulse-to-pulse accelerator with collimator for mini-system.

RESULTS

A series of experiments included penetration, steel wire resolution, contrast sensitivity and material discrimination tests. Testing samples were manufactures according to the European Standard - IEC 62523 "Radiation protection instrumentation – Cargo/vehicle radiographic inspection systems", which describes instruments and methods for attestation of x-ray systems performances. Evaluated general radioscopic performances of the mini-system are summarized in table 2. It is necessary to note that all the experiments were carried out at the nominal speed of conveyor: V= 60 cm/s, fully simulating operation of full-scale x-ray inspection system.

Table 2: General Radioscopic Performances of the Mini-System

Parameter	Value
Penetration in steel equivalent	390 mm
Steel wire resolution:	
- without barrier	0.8 mm
- 100 mm steel barrier	2 mm
- 250 mm steel barrier	6 mm
Contrast sensitivity at half penetration	0.5%
Mass thickness range of discrimination	5-120 g/cm^2

The evaluated radioscopic performances are in full conformance with general requirements of the Russian Customs authorities to such type of x-ray scanners. In the present work we tried to extend the material discrimination criteria of the Standard including evaluation of effective atomic number and mass evaluation.

Table 3: Attestation of Material Discrimination (speed of conveyor: V= 60 cm/s)

Material	**Parameter**	**Testing step-wedge**				
		1	**2**	**3**	**4**	**5**
Steel (Fe) Z=26 ρ=7.85 g/cm^3	Thickness, mm	15	30	60	90	150
	Nominal weight, kg	4.24	8.48	16.96	25.43	42.39
	Color conformance, Y/N	Y	Y	Y	Y	Y
	Evaluated Z	25.8	25.9	26.6	26.5	28.2
	Evaluated weight, kg	4.6	8.7	17.6	26.6	43.8

Figure 2: Steel step-wedge, pistol, canister with ethyl spirit, canister with water (speed of conveyor: V= 60 cm/s.

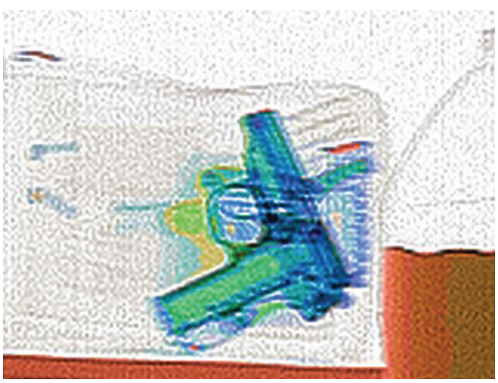

Figure 3: Fragment of image with pistol in holster with bullets and cartridges.

The results are summarized in table 3 and Fig. 2-3. The evaluation methods are realized in software tools of image processing workstation. One can see that for steel step-wedge there is good accuracy of atomic number evaluation, which signifies that method could be used as a precise tool for material discrimination and makes it possible to separate materials even inside groups. It is necessary to note that with the increase of mass thickness, there is a growth of atomic number and weight evaluation error. This effect is mainly stipulated by influence of scatter and which can be minimized by a better collimation of fan-like x-ray beam. The mass of testing objects, which can be picked up from mass thickness value, is also evaluated with a good precision and the method implemented in an image processing software tool can be a powerful instrument providing operator with indication of mass of separate objects as well as cargo in whole. The fragments of images (Fig. 3) also give impression about the spatial resolution achievable by system due to the 3 mm pitch of detectors. Small details like bullets on a fragment with pistol are clearly visible despite presence of quantum noise, amplified by the sharpening algorithm applied. One can see the accuracy of image, sharpness and absence of false colorization at the edges.

CONCLUSIONS

Summarizing the result we would like to note that complex of technological solutions realized in equipment of mini-system in combination with image processing algorithms allowed to carry out robust and reliable material discrimination in the mass thickness range up to 120 g/cm^2 at least. Evaluation of effective atomic number of steel (organics, mineral/light metals, metals) with $Z_{eff} \leq 30$ can be fulfilled with preciseness ±1 for the optimal mass thickness range. Evaluation of physical mass of the separate objects on the image as well as mass of cargo in whole is possible with preciseness better than 10%. Concept of full-scale scanner with efficient material discrimination is approved and its performances are evaluated.

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