A practical aspect of gamma-ray based Compton scatter densitometry

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Abstract

In many practical studies, the electron density of a sample is of great importance to investigate its inherent structure. A densitometer system, operating in a non-destructive way, is presented to investigate the density variation in concrete structure. A well collimated beam of 662 keV gamma-rays from ^{137}*Cs radioactive source has been used to extract the information of density variation from interior of the sample by recording scattered spectra with a NaI(Tl) scintillation detector. An inverse matrix approach for unfolding of observed pulse-height distribution to a true photon spectrum is used for the measurement of scatted spectra. The Compton scattered intensity, obtained by unfolding the experimental pulse-height distribution of NaI(Tl) scintillation detector with the help of inverse response matrix, provides the desired information.*

1. Introduction

The scattering of gamma photons by electrons is a basic fundamental physical process yielding useful information about material structure. The inherent ability of Compton scattering can ascertain quantitative information of electron density of the target material. The potential of Compton (incoherent) scattering of gamma photons to inspect the density variation from interior of objects is studied as objective of present work. Examining an object by destructive methods does not allow the use of testing object for future and it becomes more costly by destroying the object. Moreover, inspection of large/thick size objects as a whole at once by destructive methods is inappropriate in many circumstances. Due to these limitations, part by part/sectional (tomographic) inspection of objects by non-destructive testing needs to be used to examine various objects of interest. The ability of gamma rays to penetrate deep in matter makes it attractive for use in non-destructive testing applications.

Various X-ray and gamma-ray transmission techniques are widely used in industrial and medical fields for tomographic evaluation. Traditionally these techniques are realized by equipment ranging from simple radioisotope gamma-gauges to complex radioscopic imaging and computerized tomography systems. However, in the last decade, Compton scattering inspection techniques have emerged increasingly. Based on the use of scattered photons to derive information about material density, their use is limited not only too industrial fields but can also be used for medical applications [1]. In addition to the transmitted gamma flux through the object to be investigated, scattering techniques can also be used for non-destructive testing and imaging of medical and industrial samples [2]. Zhu et al [3] constructed an in-line density measurement system based on X-ray Compton scattering for detection of density variation between the cogs of rings. Mullin and Hussein [4] used the energy spectrum of Compton scattered photons for detecting collinear defects, in aluminium blocks and in laminated composite materials, by employing ^{60}Co source and HPGe detector. Sharaf [5] presented a method for non-invasively generating profiles of density distribution within an object using Compton scattered X-rays and Si(Li) detector. More recently, we [6] have employed scattering of 662 keV gamma photons for investigation of aluminium and iron metal blocks.

Complex and sophisticated methods are being presently used to convert the observed pulse-height distribution to true gamma ray spectra. Although Monte Carlo calculations provide the detector response, but these are incapable of taking into account the effects of materials surrounding the detector and attenuation of photons in the entrance window. Besides this, the Monte Carlo calculations suffer from various discrepancies most probably due to the fact that the calculations are done for an idealised bare detector by assuming an infinitesimally narrow beam impinging at the centre of the detector whereas in the realistic situation, the beam is of finite size. In this context, the conversion of observed pulse-height distribution to a true photon energy spectrum is essentially required. We carry this with the help of inverse matrix approach whose details, construction of experimental response matrix, has already been reported by our group [6]. The present study using 662 keV gamma photons employs incoherent scattering flux to investigate the detection of internal concrete defects.

The principle of present tomographic scanning set-up relies on the fact that Compton scattered flux is proportional to the electron density of the target. The number of photons S scattered towards the detector is given by [3]

$$S = \frac{d\sigma}{d\Omega}\,\Delta\Omega\; n\;\Delta L\;\, N_i \qquad (1)$$

Where ($d\sigma / d\Omega$) is the collision differential cross-section, $\Delta\Omega$ is the solid angle under which the detector is seen from any point of the measurement volume, n is the electron density of the material, ΔL is the length of the primary beam path inside the volume, N_i is the number of incident photons arriving in V. The use of n in the preceding equation means that every atomic electron is involved in Compton process and the value of n is given by

$$N = \rho N_A Z / A \qquad (2)$$

Where ρ is the density of the sample, N_A is Avogadro number, and Z/A is the ratio of atomic number to atomic mass. The number of detected photons (N) depends on the number of scattered photons S, as well as on the attenuation along the path within the material. For a particular radiation source, geometry and collimation, it appears that the number N of detected photons is expected to be proportional to the density ρ of the material.

2. Experimental set-up and Method of Measurements

The present experimental set-up used for non-destructive tomographic inspection of selected samples is shown in Fig. 1. A well collimated beam of gamma photons from 222 GBq (6-Ci) ^{137}Cs source irradiates the concrete sample to be inspected. Keeping in mind the biological effects of radiation, the radioactive source is properly shielded [6]. The source-sample assembly is aligned in such a way that the incident photon beam is confined to the region of interest only. Sample stage (Fig. 1) has the provision of horizontal and vertical motions, for change in position, with the help of two levers [L_H and L_V]. NaI(Tl) scintillation detector (having dimensions 51 mm x 51 mm) is placed at 110° to the primary incident beam such that area of

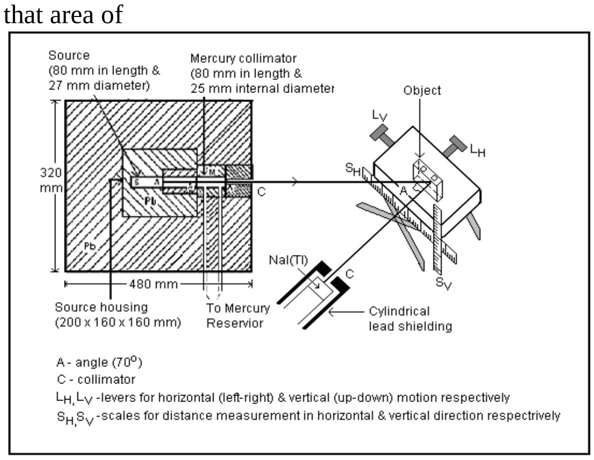

Fig. 1: Experimental set-up

intersection (voxel) of collimated source beam and detector's field of view lies at the inspection area of sample (concrete block in present study). Two collimators (hole-size of 4 mm in radius for source & slit size of 4 mm in width for detector) are used to define the volume of interest. The distances of symmetry axis of the voxel position (at sample to be inspected) from the source and detector collimators are kept 315 and 175 mm respectively. It has been checked that radiation scattered from the source collimator opening do not reach directly the active volume of detector, and the background near the detector assembly comes to natural background level in the laboratory when source window is closed.

The concrete sample, prepared with composition of ordinary Portland cement 20%, sand 40%, aggregate 40% and appropriate amount of water, of rectangular in shape (dimensions 180 mm in length, 80 mm in breadth and 70 mm in height) is used for the study of non-destructive tomographic inspection of defects in solid objects. Two long cylindrical voids, roughly at equal spacing, (simulating flaws) of diameter roughly 14 mm at the middle of block have been drilled in a direction perpendicular to the direction of incident beam. Spectrum for each position of concrete block is recorded by moving the sample stage. The experimental data are accumulated on a PC based ORTEC Mastreo-32 Multi channel analyser (MCA). For the densitometry study, sample-in scattered spectra are recorded for a period of 200 sec for concrete sample at desired positions. The background is recorded for the same duration of time after removing the object sample from the primary gamma beam, this results in registration of events due to processes independent of sample under inspection. To take into account the contribution due to low pulse-height counts resulting from the partial absorption of higher energy photons, we employed inverse matrix approach [6] which shifts these low pulse-height counts into their photo-peak energy region by unscrambling the pulse-height distribution recorded by NaI(Tl) gamma ray detector. A typical observed (after subtracting background) pulse-height distribution P(E') for concrete sample (at scan position 8.5 cm) is shown as curve 'a' of Fig. 2.

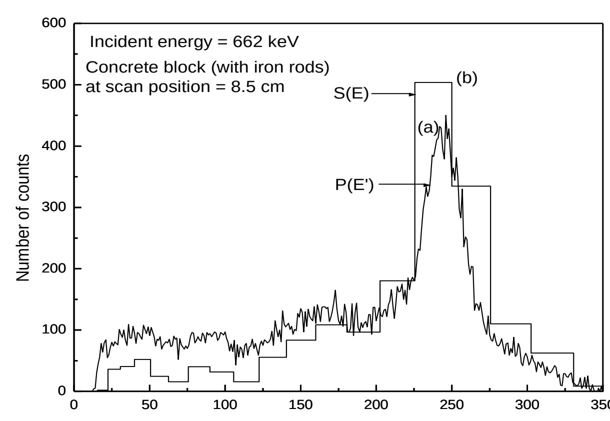

Fig.2: Experimentally observed pulse-height distribution, P(E'), curve-a obtained after subtracting background events (unrelated to sample), and resulting calculated histogram (curve-b) of S(E) converting pulse-height distribution to a true photon spectrum.

3. Results and Discussion

From non-destructive tomographic inspection of sample (concrete block with two holes), the measured values of Compton scattered intensity (response corrected) at different scan positions are plotted as a function of position in Fig. 3. As the air void intersects the sensitive volume, there is a decrease in the total electron density of the material comprising the sensitive volume, results in lesser gamma photons to scatter towards the direction of detector. The emergent scattered intensity values do not change appreciably during scanning when voxel lies at positions having no defect, but intensity value starts decreasing as the region of flaw (void) approaches the voxel and bottom of the counting-rate valley estimates the defect position. The information obtained by this technique is strongly related to the material density, thus allowing changes in the material uniformity to be monitored. It is clearly visible from Fig. 3 that the technique is sensitive to detect the two defects in concrete block of 80 mm in thickness. Although, the data of Fig. 3 is sufficient to show presence of defect/inclusion in concrete samples but tomographic images (reconstructed by MATLAB) are also shown in Fig. 4 to pinpoint the inhomogeneities in samples under investigation.

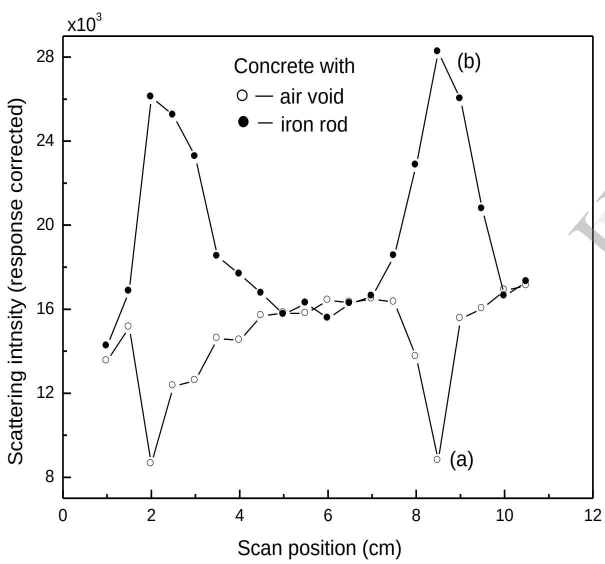

Fig. 3: Experimental variation of scattered intensity, as a function of position, for concrete block with empty void and void filled with iron are shown by curves (a) and (b) respectively. The measured uncertainty in data lies within the dimensions of data points shown by different symbols.

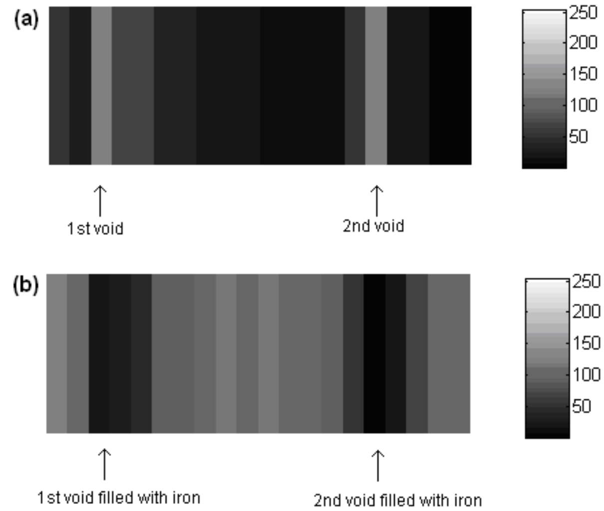

Fig. 4: Grey scale image of concrete block: (a) - empty void and (b) - iron filled void.

Based on the use of scattered photons to derive information about material density, their use is not only limited to concrete industry but can also be used to know the density/nature of liquid flowing through the pipeline. For this purpose, the spectra are recorded by filling the iron pipe (wall thickness 2.5 mm) with different density liquids (petrol, diesel, multipurpose engine oil API CF, water and glycerine). The plot (shown in fig. 5) of scattered intensity versus liquid density shows that technique can be used to know the liquid flowing in pipe (having close values of density such as petrol and diesel).

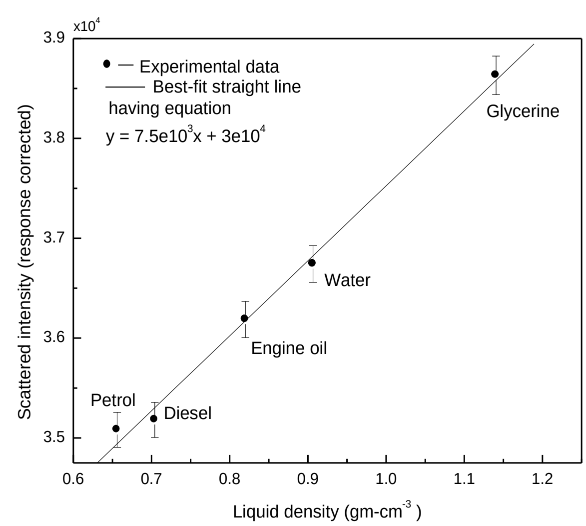

Fig. 5: Experimental variation of scattered intensity (response corrected) as a function of liquid density.

The present work provides the ability of incoherent scattered gamma rays (recorded with low resolution detector like NaI(Tl) scintillation detector) to extract the information about density variation from interior of sample. Although the system presented is simple and still at an incipient stage but the promising results confirms the industrial applicability of the system to process diagnosis. Thus the method can be used to repair or replace the specific area of large size concrete objects. The use of inverse matrix approach for detector response, results in higher authenticity (as incorrect physical data are obtained from an analysis of recorded gamma-ray spectra without application of unfolding methods) of present gamma-ray scattering application in comparison to the work already reported by workers for density variation of different samples of medical and industrial interest. The scattering angle chosen in the present measurements is 110^{o} but similar results are expected at other scattering angles also. Not only the provisions of variable geometry, but access from one side (important for extended or thick structure) and to provide three-dimensional information are the important advantages of scattering technique over the transmission one. So, Compton scattering method becomes more favourable when the objects located at the positions where transmission methods could not be used.

It is recognized that further work is required (for air voids of sizes less than 14 mm) by employing automatic stepping motor system and a linear detector array so that measurement times can be further reduced to acceptable limits for practical use. As, detection of flaws before these propagate to the point of causing failure is essential, so we believe that our experimental findings will be quite useful to other investigators in improving their experimental design for inspection of in-situ objects. Moreover, a suitable Monte Carlo simulation of the present work will provide a better understanding of the use of incoherent scattering of gamma photons for non-destructive tomographic inspection of samples.

4. References

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