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# A new Compton scattered tomography modality and its application to material non-destructive evaluation

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**Abstract: -** Imaging modalities exploiting the use of Compton scattering are currently under active investigation. However, despite many innovative contributions, this topic still poses a formidable mathematical and technical challenge. Due to the very particular nature of the Compton effect, the main problem consists of obtaining the reconstruction of the object electron density. Investigations on Compton scatter imaging for biological tissues, organs and the like have been performed and studied widely over the years. However in material sciences, in particular in non-destructive evaluation and control, this type of imaging procedure is just at its beginning. In this paper, we present a new scanning process which collects scattered radiation to reconstruct the internal electronic distribution of industrial materials. As an illustration, we shall look at one of the most widely used construction material: concrete and its variants in civil engineering. The Compton scattered radiation approach is particularly efficient in imaging steel frame and voids imbedded in bulk concrete objects.

We present numerical simulation results to demonstrate the viability and performances of this imaging modality.

**Keywords: -** Compton scattering , Gamma-ray imaging , Non-destructive testing/evaluation (NDT/NDE), Concrete: structure and defects, Radon transform

## I. INTRODUCTION

In medicine, hidden structures of objects are routinely revealed by ultrasound imaging and radiation tomography, which comprises three modalities: transmission, emission and scattering. In material sciences, in addition of these, many more technological imaging processes are available, such as magnetic flux leakage, eddy current, infrared and thermal testing, Radar technology, etc.). However these methods although less costly and easy to operate lack accuracy and cannot deliver key physical quantities necessary for material evaluation. In this respect, radiation imaging, despite stringent safety restrictions, is more reliable in bringing accurate data on relevant physical quantities. This is the reason why many medical tomographic imaging modalities have been in transferred to non-destructive evaluation systematically.

Although transmission radiation imaging (tomography) has been in operation for a long time, it has been realized that there is a need to determine other physical parameters than the ones deduced from the absorption of radiation in matter. Moreover working with the propagation of radiation through matter, conventional transmission imaging cannot handle some large objects or objects that are improper to be inserted in an industrial tomograph. Transmission imaging provides line-integrated information along the radiation propagation path, which masks the position of an anomaly present along the line. Therefore, it is difficult, among other things, to determine the position of this anomaly from the transmission data.

Thus the need to remedy to that situation has led workers to propose the use of radiation scattering imaging. By recording the amount of deflected radiation from the object, any anomaly will not be hidden in the integrated data. Scattering also eliminates the need of accessing the target object from two opposing sides. Therefore, since both source and detector can be placed on one side of the object, examination of extended structures becomes possible. Pioneering works, done in recent years, have confirmed these advantages in non-destructive evaluation of industrial objects and materials.

One of the most widely used industrial material is concrete. It enters a large variety of objects in civil engineering. Therefore the monitoring of its status in time becomes of primary concern for safety and maintenance. What is needed is a non-destructive evaluation (NDE) or a non-destructive testing (NDT) of its status which could provide images of its interior, so as to see and determine anomalies ad their time evolution

[1,2]. The most common defects are internal cracks, voids, shallow delamination, honeycombing and surface opening cracks. They are the factors that affect most the durability of concrete. In the case of reinforced

concrete structures, other defects such as thickness variations, deteriorated zones, corroded reinforcing bars, see *e.g.* [3,4] and moisture may occur. Imaging of concrete structures is very important because it reveals aging and deterioration of infrastructures, as pointed out by [5]. Hence their detection is of utmost importance in order to prevent material failure which leads to accidents. Common detection techniques using ultra-sounds or radiography generally provide only qualitative information. Infrared thermography, radar and acoustic imaging are also applied but with coarser resolution. Radiography can be used to locate internal defects and reinforced re-bars position in concrete and general condition through differences in radiation intensity passing through the structure that is captured on photographic film placed on the opposite side of the structure from the source, see [6,7,8]. Computerized Tomography (CT) is a method that permits the development of three-dimensional radiograph views of an object. The degree of damage in concrete structures can be assessed using high resolution three-dimensional images obtained from this CT technique [9]. However the performances of CT have limitations as pointed out earlier. They may be overcome by scattered radiation imaging which also brings about useful complementary information.
Since gamma rays from radioactive isotopes have sharply defined energies, the analysis of the detected scattered signal is easier. Moreover, gamma-ray isotopic sources are readily portable, self-contained an usable in hostile environments. The most common modality in scattered radiation imaging proposed so far is a step by step procedure. It consists in determining the electron density at a site by measuring the deflected amount of radiation by Compton effect by a fixed scattering angle, given an incoming calibrated amount of incident radiation. This procedure has been tested and shown to be viable over the years. However it is time consuming and not very practical, although it enables the detection of local defects and the discrimination between materials of different density such as voids and steel in concrete. We propose an alternative modality whereby data acquisition is continuous: the detector is set to absorb only scattered radiation of given energy and the pair source-detector, set at a constant distance from each other, rotate around its middle point in a plane. Thus one gets an integrated data along various circular arcs of the electron density. The reconstruction of this density is shown to be possible thanks to an analytic inversion method, derived recently from that of A M Cormack for the transmission scanning modality of computerized tomography (CT) [24].

In this work, we describe this Compton scatter imaging modality. This gamma scattering tomography resolves some of the problems encountered in radiography and CT. A detailed comparison of these two techniques can be found in [9]. Since the sought quantity is the electron density of matter, Compton scatter imaging is particularly efficient in the detection and imaging of voids and steel rabars in reinforced concrete because of large discontinuities in traversing these defects. Moreover in concrete bulk a change in water content, which is due to higher porosity, may be also seen in variations of measured electron density. This may indicate a change in mechanical properties of concrete *via* a change of its compression Young modulus. Thus the knowledge of an electron density map for concrete may be extremely relevant for nondestructive evaluation. This quantity is becoming the focus of attention in recent years [10,11].

Up to now the most currently used method is the point-wise scanning, by which information can be obtained by focusing the field of view of the source and detector around a scattering volume. Then the measured scattered signal allows the determination of the density of the material. The disadvantages are relatively poor resolution, slow scanning speed and difficulties associated with numerical reconstruction of object's internal characteristics. The scattered signal is also affected by the attenuation of both incident and scattered photons which makes the reconstruction difficult. Collimation of the initial and scattered radiation allows the detection of relatively few scattered photons, and this is the reason why the statistics relative to this process are very poor, see [12,13]. Finally by scanning through a plane of interest within an object using raster motion, one may obtain density distribution in a whole plane.

Here we propose a different imaging approach by scattering of ionizing radiation. Previous work on the use of scattered radiation has originated from medical imaging but this idea has made quick headway to NDT and NDE through many proposals such as [14]. To generate scattering tomography at high resolution one follows the idea of Kondic by installing wide-angle collimated source and detector, see [15]. This allows counting almost all of the scattered photons leaving the object in the direction of the detector. Moreover to get the necessary complete data we must allow for the rotation of the pair source-detector around the object. In fact this was already foreseen long ago by [16] and [17]. But at this time no analytic inversion formula was available and numerical inversion of data has led to poor reconstruction results. Our proposal differs from that of [18,19], as well as [20,21,22,23], since in their scanning procedure, the detector runs along a line passing through the source which is not very convenient for practical operations except in the case of large flat structures. Of course their image reconstruction is based on a different approach. The recent derivation of the reconstruction formula for the electron density has prompted applications in medical imaging [26]. We propose now an application in non-destructive evaluation of concrete as an alternative to existing NDE methods. In section 2 we describe the new Compton scatter tomography modality, with image formation as well as image reconstruction. Then in the next section 3 we discuss the corresponding simulation results. Conclusion and possible future perspectives are given in the last section.

## II. A COMPTON SCATTER TOMOGRAPHY MODALITY

The principle of this imaging modality is simple: it makes use of the Compton effect or scattering of ionizing radiation by an electron. Fig. 1 briefly recalls the mechanism of Compton scattering. An incident X or gamma radiation of energy $E_0$ hits an electron at rest and is deflected from the initial direction of motion by an angle ω.

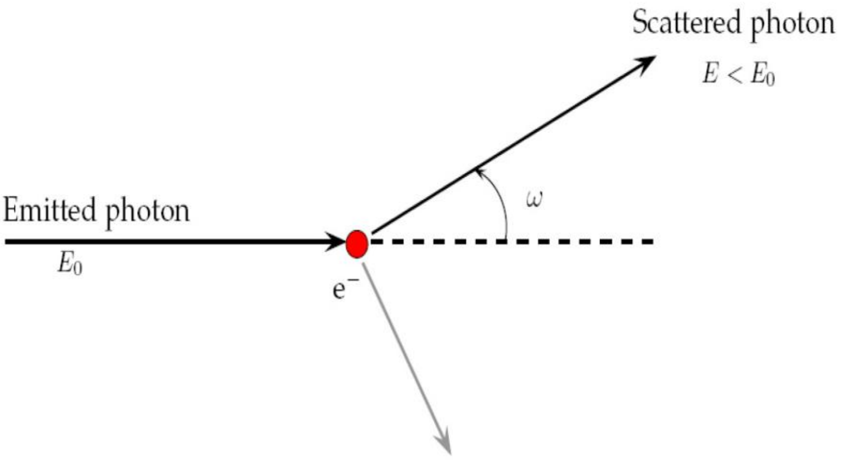

Figure 1. Compton scattering

The scattered radiation (or photon) carries the energy $E_0$ given by the famous Compton relation

$$E_\omega = \frac{E_0}{1 + \frac{E_0}{mc^2}(1 - \cos\omega)}, \qquad (1)$$

where $mc^2$ is the rest energy of the electron or 0,511 MeV.

1) Image formation and circular arc Radon transform.

Fig. 2 shows how data acquisition is performed in this new Compton scattering tomography modality. Test objects under study are put inside a circular frame and are illuminated by an isotropic radiation source S of definite energy $E_0$ situated on the circular frame. A radiation detector at site D, diametrically opposite to S *via* a multichannel analyzer registers scattered radiation at scattered energy $E$. From the known kinematics of Compton scattering, the radiation amount collected by a unit surface of detector per unit time is proportional to the integral of the object (concrete) electron density along a circular arc joining the point source site S to the detector site D, the circular arc subtending the angle (π-ω), for details see [24]. We denote the sought electron density by $f(r,\theta)$ which describes the inner state of the object. The line SD has a length $2p$ and rotates around its center O during scanning, the rotation state of the apparatus being conveniently labeled by the angle φ. The detected radiation flux density at D is $Cf(\varphi,\omega)$ and given by the integral of $f(r,\theta)$ on the circular arc C(φ,ω) up to a factor representing the Compton scattering phenomena (this factor is absorbed in the definition of $f(r,\theta)$ for simplicity)

$$\mathcal{C}f(\varphi,\omega) = \int_{\mathcal{C}(r,\theta)\in(\varphi,\omega)} f(r,\theta)\,ds \qquad (2)$$

where $ds$ is the arc integration element, computed from the arc equation

$$r = p\left(\sqrt{1+\tau^2\cos^2\gamma} - \tau\cos\gamma\right) \qquad (3)$$

with $\tau = \text{cotan}\,\omega$ and $\gamma = \pi - \omega$. Note that for $\omega = 0$, the circular arc reduces to a line, and the detector receives non scattered radiation, which is to be excluded

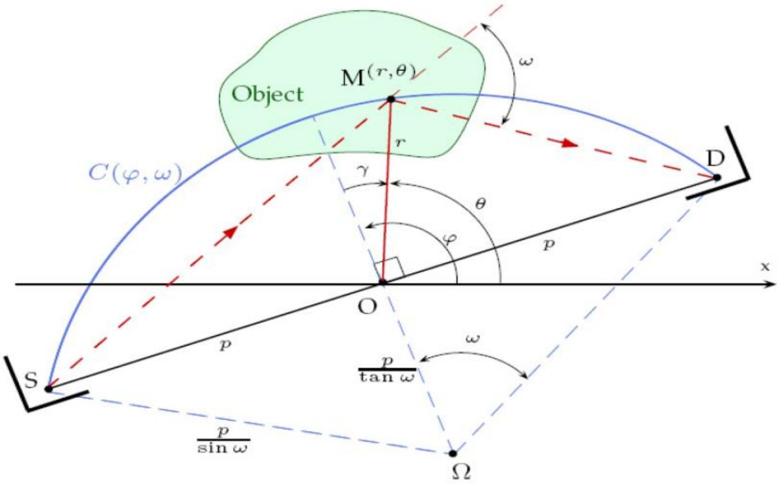

Figure 2. Image formation and circular arc Radon transform

The set of all integrals *Cf(φ,ω)* represents what is called the circular arc Radon transform of the object electron density *f(r,θ)* . It is a function of two angular variables (φ,ω)

$$\mathcal{C}f(\varphi,\tau) = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} f(r(\gamma),\gamma+\varphi)r(\gamma)\frac{\sqrt{1+\tau^2}}{\sqrt{1+\tau^2\cos^2\gamma}}d\gamma \tag{4}$$

**Remark** The electronic density of a material is in fact given by the formula

$$f(r,\theta) = \rho(r,\theta)N_A\frac{Z}{A} \tag{5}$$

where ρ is the mass density , $N_A=6.022\text{x}10^{23}$ $\text{mol}^{-1}$ is the Avogadro number, A the mass number and Z the atomic number.

### 2) Reconstruction of the electronic density

The inverse formula of equation (4) has been worked out in [24]. Hereafter we give a short account of its derivation. Let us introduce the angular Fourier components of *f(r,θ)*

$$f(r,\theta) = \sum_{l=-\infty}^{\infty} f_l(r)\,e^{il\theta} \qquad \text{with} \qquad f_l(r) = \frac{1}{2\pi}\int_0^{2\pi} f(r,\theta)e^{-il\theta}d\theta. \tag{6}$$

The angular Fourier components of *Cf(φ,ω)* are similarly defined. Then equation (4) is transformed into the following integral equation for the Fourier angular components $Cf_l(\tau))$ and $f_l(r)$

$$\mathcal{C}f_l(\tau) = 2\int_0^{\frac{\pi}{2}} r(\gamma)\frac{\sqrt{1+\tau^2}}{\sqrt{1+\tau^2\ \cos^2(\gamma)}}\ f_l(\gamma)\ \cos(l\gamma)d\gamma \tag{7}$$

where τ = cotan ω. To extract the sought components $f_l(r)$ we use the method of [25] and get

$$f_l(r) = (-)\frac{2p(p^2+r^2)}{\pi(p^2-r^2)^2}\left[\frac{d}{dt}\int_t^{\infty}\frac{\cosh(l\ \cosh^{-1}(\frac{q}{t}))}{q\sqrt{(\frac{q}{t})^2-1}}\frac{\mathcal{C}f_l(\frac{1}{q})}{\sqrt{1+q^2}}dq\right]_{t=\frac{2pr}{p^2-r^2}} \tag{8}$$

where q= 1/τ. Another change of variable in equation (8) leads to the final result

$$f_l(r) = (-)\frac{2p(p^2+r^2)}{\pi(p^2-r^2)^2}\left[\int_t^{\infty}\frac{\cosh(l\ \cosh^{-1}(\frac{q}{t}))}{\sqrt{q^2-t^2}}\frac{d}{dq}\left(\frac{\mathcal{C}f_l(\frac{1}{q})}{\sqrt{1+q^2}}\right)dq\right]_{t=\frac{2pr}{p^2-r^2}} \tag{9}$$

Finally *f(r,θ)* is reconstructed by summing over its angular components $f_l(r)$ according to equation (6).

## III. SIMULATION RESULTS

Concrete is an interesting test material for this new investigation method. Let us recall how it behaves under standard non-destructive evaluation using standard radiation attenuation method. Here the mathematical tool is of course the classical Radon transform. What is reconstructed is the attenuation map of the material. By using a careful pixel thresholding of the attenuation image, it is possible to deduce the porosity of the concrete sample.

This would yield, through the Féret formula, its compression limit and elasticity modulus. So long as the found numerical values are acceptable, the state of the investigated material can be declared safe for further use. It is expected that the reconstructed electron density would lead to similar conclusions and thereby complement the information obtained from the attenuation map.

Simulations are performed using a synthetic image of the reinforced concrete with iron grid. The original concrete electron density is given in Fig. 3. For simplicity, the pixel intensity is normalized. It is to be noted that iron grid holds the highest electron density and the lowest electron density is located in the empty spaces. The acquired data is given in Fig. 4 in the coordinate system $(\varphi,\omega)$. Using equation (9) and the previous data the reconstructed concrete electron density is given in Fig. 5. This reconstruction procedure is recent and need to be perfected. The results are however convincing. The Mean Quadratic Error is 0.5266%. The image is that of a reinforced concrete with iron grid.

Another series of simulations are performed on a crack inside a concrete piece. The results are presented in Figs. 6, 7 and 8 with the same image quality.

An analysis of concrete properties can be carried out in the same way as in X-ray CT. Here a notable advantage resides in the fact that large doses of radiation are not needed due to a better confinement of radiation. Moreover this scanning modality can be used on small objects in civil engineering. For large objects the modality advocated by [18] is appropriate since the scanning by scattered radiation is done only on one side of the object. However it presents an inconvenient displacement of the detector along a line passing through the source. There is a possibility of using Compton scattering at angles larger than $\pi/2$ with the present modality to scan the half space of a large object. This has been already pointed out in [26].

## IV. CONCLUSION AND PRSPECTIVES

We have presented in this work a new NDT/NDE modality based the phenomena of Compton scattering by gamma rays produced by radioactive isotopes. The use of gamma radiation allows to get an excellent spatial resolution as it is able to penetrate deeply in bulk material, hence perfectly adapted to concrete. As there exists no universal NDT/NDE method, capable of providing all interesting parameters, our proposal provides complementary information to the existing ones via the reconstruction of matter electron density. In this way, the porosity of concrete can be located and evaluated, so that resistance to compression, elasticity modulus and permeability of concrete can be deduced. This method has the advantage that it need not to be in physical contact with the object to be investigated such as the geo-radar. It gives very convincing simulation results and stands as a valid competitor for current methods of NDT/NDE. It is evident that not all the properties of this Compton scatter tomography have been exploited. A major challenge is this research is the problem posed by radiation attenuation. The way attenuation comes into the problem differs from that of the known classical Radon transform. It leads to a very cumbersome inversion problem for which there is no solution at present. However one may proceed by performing attenuation corrections, which have turned out to be very successful in recent studies, see [27]. Efforts in this direction will be dispatched in the future.

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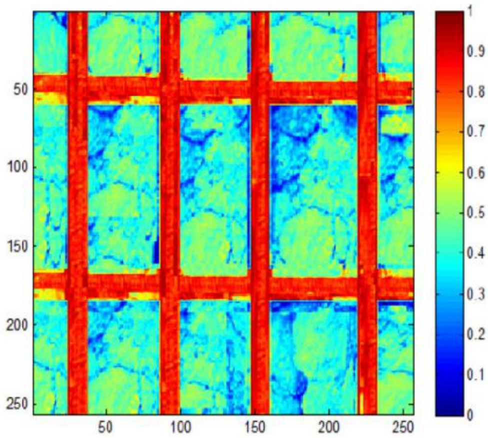

Figure 3. Original concrete electron density

Figure 6. Original crack in concrete

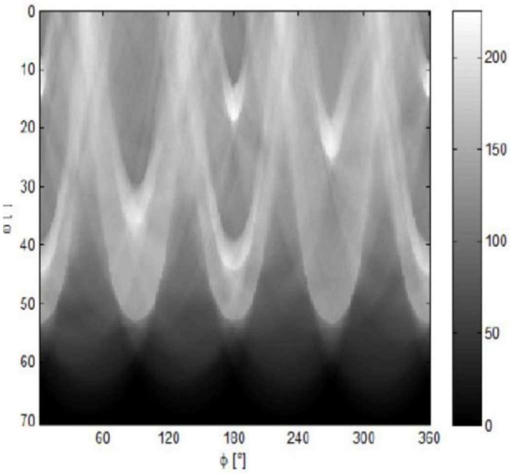

Figure 4. Acquired integral data

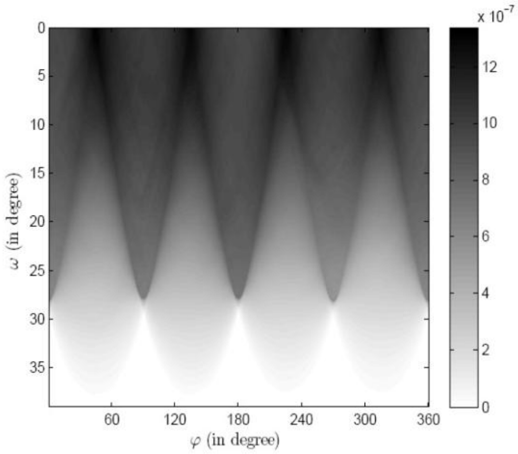

Figure 7. Acquired integral data

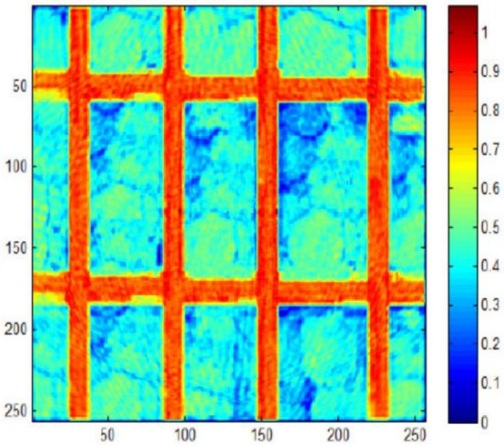

Figure 5. Reconstructed concrete electronic density

Figure 8. Reconstructed crack in concrete