Multi-energy X-ray Techniques for NDT: a New Challenge

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Abstract
Digital X-ray imaging is a well-known technique for NDT. Based on the energetic dependence of X-ray material absorption, multi-energy techniques can provide material information. Dual-energy techniques have been developed for that purpose. Proved to be efficient for materials differentiation, limits are encountered for materials with close attenuation. Beam hardening effect and detector imperfections may induce artefacts unacceptable for accurate quantification. For a few years, new types of detectors based on semiconductor technology have emerged with energy discrimination abilities. They reduce acquisition noise and provide multi-energy information. But imperfections due to charge sharing and induction signal cannot be neglected. Dedicated data processing methods are required. So then the question of improving dual-energy techniques with such detectors arises. Which problems can be solved, and which new problems appear? In this paper we give some indications on potential benefits of spectral X-ray imaging for NDT. We present preliminary evaluations of performance and limitations.

Keywords: NDT, radiography, X-ray tomography, spectroscopic detector, multi-energy imaging.

1. Introduction: from standard X-ray imaging to multi-energy techniques

Conventional X-ray imaging exploits the absorption of radiation through the examined object. This information may be sufficient, for instance in defect detection task considering an homogeneous mono-material sample, but is often inadequate when material characterization is required. More precisely, radiographic imaging provides a representation of the object in terms of line-integrals of the attenuation coefficient. Tomography provides, through a multi-view acquisition, a reconstructed volume in terms of absorption values, and gets rid of items superimposition. But in both cases, a single exposure using a standard detector which provides a single value per pixel can scarcely allow material identification.

In the usual inspection energy range, the attenuation for X-ray radiation is a combination of two photon-matter interactions: the photoelectric effect and Compton scattering. These interactions and their relative contribution to the total attenuation are energy dependant. This dependence can potentially be used to characterize materials – as long as the employed acquisition system permits to obtain this information. It is not the case of a conventional X-ray detector, which is composed of a scintillator layer coupled to photodiodes array and supplies the deposited energy integrated over the full energy range of the generator spectrum.

Dual-energy techniques have been developed for that purpose. In terms of system, energy discrimination can be done at source level or at detector one. In the first case two acquisitions are performed successively, the energy switch being realized by voltage tuning associated with the use of filters. This method is efficient in terms of energy separation, but assumes the object being static. The implementation using a 2D detector, either scintillator screen or flat panel, allows an acquisition rate at the detector speed but induces influence of scatter, problematic for numerical accuracy. Dual-energy may also be implemented within a single exposure technique. Adapted detectors consist in two receptor layers of scintillator-photodiode type separated by an intermediate filter. The front (resp. back) layer absorbs the low (resp. high) energy photons. The two images are acquired simultaneously, allowing to
inspect fast translating objects. A linear detector permits an efficient collimation. But the energy separation of this technique is poor (Figure 1).

Dual-energy techniques have been used successfully in the past twenty years for various applications. It has been proved to be efficient in medical field, especially for fat quantification and bone densitometry. Linear dual-layers detectors are used in airport security, for the inspection of luggage in a so-called line scan mode, the obtained accuracy at best only allows materials to be classified into broad bands such inorganic and organic. In NDT, dual–energy techniques have been tested for the inspection of composite materials, increasingly used in various industries. Applications to food industry have been developed.

To sum up, the performance of dual-energy systems depends on the number of materials, their differentiability, prior knowledge on their nature, the complexity of objects superimposition in radiography mode, the noise level, and of course the acquisition system. Optimizing the detection system is a challenging part of performance achievement [1].

A possible improvement consists in using more than two energies. Since Alvarez works [2], we know that any material can be decomposed onto a basis of two functions only (material basis, rho / Z, photoelectric / Compton scatter) in the usual energy range and if non K-edge material is present. But the relation between the unknowns (2 basis coefficients) and the measures is not linear, thus the inversion of system may take benefit from more than 2 measures. A system based on six acquisitions was proposed [3], and showed improved material identification at the price of system complexity.

Recently emerged semiconductor based X-ray detectors offer new capabilities in counting mode with energy discrimination [4], [5]. They are able to count the photons in several energy channels, giving potentially access to the energetic dependence of X-ray absorption, and enabling specific material imaging. Also they should decrease image noise, enhance contrast, and remove artefacts. Nevertheless, the imperfections of these detectors cannot be ignored when evaluating their benefits, and lead to the requirement of dedicated data processing.

This paper is aiming at evaluating the interest of this new generation of detectors depending on the envisaged application. First we present the principle of semi-conductor based detectors. Then we remind the nature of spectral data. Radiographic and tomographic mode potential applications are discussed.

2. Spectroscopic detectors

2.1 From two counters to a hundred ones

Semiconductor (CdTe or CZT) based detectors have shown outstanding performance for X-ray or γ-ray spectrometry when operating at room temperature. Thanks to a direct conversion
from photon to charges that are collected, they are able to count the photons in a few energy channel. These detectors combine a fast read-out electronic circuit providing high count rate capabilities, and a coarse energy resolution obtained with a finite number of counters for each detector pixel. Prototypes have been developed and their performance evaluated [6][7][8].

LETI associated to MultiX has developed a novel fast read-out system capable of taking high-resolution spectrometric measurements at high count rates, thus optimized for objects inspected on line scan mode. For each pixel, the signal is continuously digitized by a 100 MHz ADC, while a FPGA controls acquisition and sets up the energy spectrum on 256 bins. The set of read-out electronic components is coupled to CdTe linear array detectors. Pixel size is 0.8 x 0.8 mm² and detector is 3 mm thick. Characterization of spectrometric performance in terms of energy resolution and count rate at high fluxes are described in [9]. Other prototypes optimized for medical and NDT applications are currently under developments in our laboratory. The challenge is to achieve a matrix detector of reasonable size, while providing accurate spectral information.

Any energy-resolved detector is the result of a compromise. Small pixel pitch increases charge sharing, occurring when a charge impacts several anodes (a photon is then counted as two smaller energy ones). Larger pitch increases pile-up phenomenon corresponding to a pair of photons that are countered as a single higher energy one, due to non-zero dead time. Most of detector developers propose charge sharing correction, typically by comparing charges measured by neighbouring anodes – or other processes such as pile-up rejection to get a “cleaner” spectra - but these corrections never totally remove imperfections.

Another important aspect is the lack of homogeneity for pixel array, mainly due to material inhomogeneity. Standard calibration for gain and offset correction may be not sufficient and the correction should manage multi-dimensional data.

2.2 Modelling the Detector Response

An accurate model of a semiconductor detector has been developed in our lab to predict the detector response at any energy [10]. It takes into account various physical phenomena inside the detector: matter-photons interactions (absorption, diffusion and fluorescence, modelled using a Monte-Carlo software) and electronic processes (charge collection, charge sharing, pulse pile-up, K-shell escape). The output is composed of all the responses of the detector to each energy bin, this set being stored in a matrix format (Detector Response Matrix - DRM). Figure 2 presents the DRM of a linear detector 3mm thick, 800µm pitch - it would be diagonal if the detector was perfect. Figure 2-right displays the comparison of profiles at 80keV (thus the response to a 80 keV pulse) for two detectors: a linear one, 800µm pitch and 2D one, 500µm pitch. The tailing, which results from charge sharing, is non negligible.

Other authors have proposed similar models [11]. Such modelling software permit to predict the detector response depending on detector characteristics such as pixel size or detector thickness. By that way, the detector can be optimized depending on application constraints.

Pile-up events occur because of non-zero dead time (typically 70ns), and are particularly important at high photon fluxes. Pile-up results in loss of count-rate and distortion of the energy spectrum (Figure 3). Various models have been proposed in order to compute the detector count statistics. We developed an analytical model closed to [12] of a 2-photons pile-up characterized by a non-paralysable detector. Pile-up effect is not linear and the pile-up model cannot be integrated into the DRM formalism.
When such a detector model is coupled with a program providing realistic simulated radiographs, the resulting software allows the evaluation of the detector performance in terms of radiograph quality or any image criteria, and the validation of developed processing methods [13].

3. Processing spectral data

3.1 Formalism of spectral measurement

For an incident spectrum \( N_0(E) \) the expected number of transmitted photons at energy \( E \) through an object of thickness \( th \) and composed by a material characterized by its linear coefficient attenuation \( \mu(E) \) is given by:

\[
N(E) = N_0(E) e^{-th \mu(E)}
\]  

(1)

For a non-homogeneous object, the attenuation \( th \cdot \mu(E) \) is easily generalized by \( \int \mu(l, E) dl \).

For an integrating mode detector we get for the measured signal:

\[
I = \sum\limits_{E} E.N(E) = \sum\limits_{E} E.N_0(E)e^{-th \mu(E)}
\]  

(2)

To obtain a realistic measure for a spectroscopic detector, the detector response has to be considered.
When using the DRM previously introduced, assuming a linear discrete formalism, the number of photons effectively measured at energy $E$ is:

$$N(E) = \sum_{E'} DRM(E, E') N(E')$$  \hspace{1cm} (3)

A “true” spectroscopic detector with narrow bins – about 1keV width – provide such information. Most of multi-energy detectors provide in fact the summation over larger bins. For a channel $k$ defined by an energy range $[E_{k,\text{min}}, E_{k,\text{max}}]$:

$$N_k = \sum_{E_{k,\text{min}}}^{E_{k,\text{max}}} N(E) = \sum_{E_{k,\text{min}}}^{E_{k,\text{max}}} \sum_{E'} DRM(E, E') N(E') = \sum_{E_{k,\text{min}}}^{E_{k,\text{max}}} \sum_{E'} DRM(E, E') N_0(E') e^{-\theta \mu(E)}$$  \hspace{1cm} (4)

Notice that the channels are not necessarily contiguous. The counters number ($K$) is equal to 1 for a counting mode detector. The measured attenuation is given by the $K$-vector:

$$\text{att} = (\text{att}_1, ..., \text{att}_k, ..., \text{att}_K) \quad \text{with} \quad \text{att}_k = -\log \frac{N_k}{N_{0,k}}$$  \hspace{1cm} (5)

The final relationship is obtained by substituting Equation (4) in (5). It is clear that attenuation measurement is not linear in material thickness due to the combination of log function, summation and matrix product. This non-linearity induces the well-known effect call beam hardening, and results in quantification error in radiography and artefacts such as cupping or streaking one in CT. This non-linearity is due to channel width, but still exists for thin channels (“true” spectroscopic detector) due to non-diagonal DRM property.

In terms of noise consideration, it is important to notice that the fact to dispose of a high number of channels at a constant total number of photons implies that noise level for each channel data is high.

Finally two effects are not integrated in our formalism: the pile-up phenomenon, which, as mentioned previously, cannot be modelled in such a linear way, and the scatter radiation that is significant for non-collimated geometries.

### 3.2 Spectral radiographic data processing

Spectral data are multi-dimensional and the data set may be difficult to be stored and processed, especially in tomographic mode. Thus a reduction of dimensionality is required when using a detector able to provide a high number of narrow bins. The use of larger channels may be preferred. Formerly the information is then similar to those produced by a multi-counting detector using electronic counters. Numerical merging of spectral data is more complex but offers capabilities such as adaptability by tuning the channels thresholds, or detector imperfections correction before merging. Also, detector imperfections induce non-linearity. For all these reasons dedicated data processing methods should be developed, in order to extract material information while remaining at an acceptable noise level.

Early works in spectral data processing consisted in the adaptation of the well-known dual material decomposition. Alvarez relation for basis decomposition:

$$\mu(E) = a_1 \mu_1(E) + a_2 \mu_2(E)$$  \hspace{1cm} (6)

allows reducing dimensionality and gives the final equation, simpler but still non-linear:

$$N_k = \sum_{E_{k,\text{min}}}^{E_{k,\text{max}}} \sum_{E'} DRM(E, E') N_0(E') e^{-\lambda_1 \mu_1(E) - \lambda_2 \mu_2(E)}$$  \hspace{1cm} (7)

where $A_1$ and $A_2$ are the equivalent lengths of basis materials.
A material basis is chosen and a calibration step is performed using calibration samples of basis material. The relationship between equivalent thickness of basis material and attenuation measurement is assumed to be polynomial, the coefficients being computed from calibration samples using a least square method. This method has been proved to be efficient for standard dual energy approach. By this way, the non-linearity (due for standard detectors to the integration over the whole energy range) is learned implicitly by the experimental calibration. The method is directly applicable to a spectroscopic detector with 2 counters. An example of dual counting decomposition of materials for various DRM is shown in figure 4.

![Figure 4. Example of material decomposition of a PMMA/PVC phantom using a dual-counting detector. Performances depend on DRM quality (decreasing from left, ideal detector) to right. Simulation.](image)

In fact, several works in the medical field conclude that performances of dual counting techniques are not necessarily higher than standard dual exposure one (but higher than using a dual-layer detector) [14]. The main advantage is to get rid of human motion artefacts. The method can be generalized for a greater number of counters. But polynomials become complex and the resolution instable when using 4 or more counters [15][16].

Another way for exploiting more than 2 energy bins consists in using a calibration basis and performing the decomposition by fitting the measured spectrum or attenuation vector to the closest interpolated spectrum from the calibration database [17]. Noise model can be integrated in the process thanks to a likelihood test.

Another approach assumes that an accurate and explicit model of the detector response DRM is known (using simulation and/or synchrotron measurement), and performs an inversion of the equation (7). Basis decomposition (on material basis or on photoelectric / Compton basis) is used to reduce dimensionality and regularize the inversion [18]. Other works have tested a reduction of dimension by techniques such as PCA [19].

In any cases pile–up at high flux is problematic. The solution may be a preliminary pile-up correction, which is not obvious especially for high order pile-up. Another possibility is to integrate pile-up into the direct model in case of an inversion scheme - current works on that topic are conducted by various research teams. It is also possible to learn it during a database calibration, assuming that calibration is performed at (and dedicated to) a particular flux level.
3.3 Computed tomography

Two main approaches can be distinguished in Computed Tomography (CT). Spectral data processing (such as material decomposition) can be applied on radiographs, the reconstruction being then performed into the transformed space – this corresponds to the so called “projection-based” method. On the opposite, reconstruction can be performed for each energy channel and the spectral information exploited afterwards (so called “image-based”). For the first one, the radiograph processing methods presented in the previous § are applicable and the corresponding remarks still valid. For image-based one, algorithms have been proposed for medical applications [20][21]. They are able to manage variable densities materials, but they assume that only a few large channels are used to avoid noise increase.

The choice between the two approaches should integrate system characteristics and constraints, materials closeness and noise consideration. System non-linearities are generally more difficult to correct – at least to interpret – for image-based approach, because of the combination of geometry and spectral aspects. In case of a high bins number, a dimension reduction is required, which can be ensured by projection-based pre-processing. For both approaches, the data processing step should perform a linearization in terms of line-integrals, in order to reduce CT artefacts such as beam hardening.

3.4 K edge imaging

Most of these last years published papers on multi-energy imaging addressed contrast agent imaging for medical or pre-clinical applications. Contrary to the standard subtraction method (DSA), consisting of subtracting acquisitions before and after an agent injection, the spectral technique could benefit from the Kedge discontinuity in a single exposure protocol. The known Kedge energy is used for positioning accurately counters boundaries. But the distortion of the measured attenuation due to the DRM should be considered (figure 5).

4. NDT applications

4.1 Radiography

Initially developed for medical and security applications, spectral imaging can benefit to NDT applications. Within NDT context, constituting objects materials are generally known (for instance: resin matrix/fibre) and of constant volumetric density. Also, castings geometries are known. Furthermore, calibration samples can often be manufactured. The consequence is that a multi-energy technique, whichever it is, should be rather easily implemented. The question raised on the advantage of spectral technique using an energy resolved detector compared to a standard dual energy one.
As already mentioned in medical context, dual-counting detectors are not necessarily better than dual exposure technique but better than dual-layer detectors. Within NDT applications, standard systems use dual-layer detectors in case of speed constraints (fast translating objects on a conveyor belt), but when it is possible dual exposure technique is preferred and can be applied without motion artefact. Thus first systems should benefit from spectral detectors, but for the second ones, the gain of performance when using two counters spectral detectors is not obvious. If available, the use of more than two counters can be investigated, especially if more than two materials are present. Another aspect concerns acquisition noise, almost absent for counting mode detectors, thus favour them when long acquisition time is needed.

Composites materials, especially CFRP for aeronautic industry, is a promising application. The authors of [22] developed a modified version of Medipix with a large field of view (up to 14cm) called Widepix, and they use it for the CFRP inspection (figure 6 – from [22]).

Multi-energy techniques do not improve defect detection but can determine if a difference of local contrast in a radiograph is due to a variation of material ratio or to foreign materials. Spectral techniques are of particular interest if more than two materials are present (CFRP, honeycomb, foam...) [23]. Other composites (for instance insulation industry) can be concerned. Radiography is particularly convenient for manufacturing chain control.

Food industry already makes use of dual energy techniques [24]. The methods developed for the medical domain could benefit to food industry, where no motion or dose constraint occur, but the challenge is to get an image by scanning the object on-line without interrupting the process flow of the factory. Waste sorting is a particular application already addressed by dual-energy, which is in fact close to luggage inspection (speed constraints, unknown materials) and should benefit from developments in security. K-edge materials may be present and it is a possible (but very specific) application of K-edge imaging in NDT.

4.2 Tomography or Tomosynthesis

3D techniques are increasingly used in NDT inspection for process optimization, and more recently for in-line manufacturing control or in-service inspection, thanks to the progress of devices. Axial CT, helical CT, and tomosynthesis (also called planar tomography) for particular object geometries have been implemented. All of them could potentially benefit from spectral techniques. The objective is a better material differentiation, but also artefact reduction – even for mono-material objects. But for CT, dimension reduction and linearization of spectral (thus multi-dimensional) data is absolutely required. In this case, differentiation of close materials can be achieved.
4.3 Other modalities

The diffraction effect is due to coherent scatter, predominant in small angle forward scatter, and allows material identification especially for crystalline ones. A high energetic resolution of the detector is required for material identification, and semiconductor detectors could replace commonly used Germanium ones that require complex cooling system. Todays, such systems exist for security applications – the use for NDT has not been investigated.

X-ray backscatter technique is an alternative for configurations where conventional radiography is not convenient: too attenuating objects, or sided-only access ones. Large and complex objects (wing, wind blade, boat hull) are concerned. To detect subsurface delamination defects, multi-energy technique is not required but the low noise level of counting mode detectors is helpful. Multi-energy detectors are required if material differentiation should be addressed (several materials subsurface layers).

Phase contrast technique could benefit from spectral information, but the low thickness of objects than can be analysed limits the potential applications.

5. Conclusion

Multi-energy techniques can certainly push back dual-energy limitations, especially when close materials are concerned. Spectral information should improve material imaging, but also enhance contrast and reduce artefacts especially in CT. An obvious advantage of semiconductor type detectors is the very low level of acquisition noise.

But the design of a spectral detector is always the result of a compromise. Pixel pitch, counters number and configuration, and electronics, determine the detector response and thus the final performance. Particularly important is the non-linearity of spectral data due to charge sharing and pile-up effects. The relation between detector characteristics and performance in terms of image quality is not evident and simulation is a very helpful tool for that purpose.

Optimization is essential and should integrate application constraints. Furthermore, dedicated multi-dimensional data processing algorithms are required. When these requirements are fulfilled, NDT could benefit of the impressive developments of spectral detectors and techniques.

References


