Dual and Multi-energy Radiography for CFRP Composites Inspection

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Abstract
Dual-energy X-ray imaging techniques are based on the energetic dependency of X-ray material attenuation, and provide information about material composition or thickness. The most extensively used processing method is the decomposition onto a material basis using a polynomial model, estimated from experimental dual-material calibration. In this study we focus on materials that are particularly close in terms of attenuation. The differentiation becomes almost impossible, noise being increased by the data processing steps. A typical application case is the inspection of CFRP composites. Carbon fiber and resin attenuations are close. In this study standard integration detector as well as semi-conductor based detectors are considered. Dual-counting and spectral modes provide dual energy information in a single exposure. Performances are compared to standard dual-energy decomposition. Multi-energy protocol is also investigated. We present preliminary results, driven by the context of CFRP inspection.

Keywords: Radiography, Dual-energy, Multi-energy, Spectral Imaging, CFRP, Composites.

1. Introduction

CFRP (carbon fiber reinforced polymer) composites are composed of carbon fibers and resin. The typical density of fibers and resin (epoxy polymer, composition $O_{4}C_{21}H_{24}$) within CFRP are respectively 1.35 g.cm$^{-3}$ and 1.70 g.cm$^{-3}$. Different types of defects should be considered. Voids (air) may be present, in the case of delamination, crack, or porosity. Variations of cumulative material composition occur in the case of inclusion of foreign material or change of fiber-to-resin ratio. Today’s main inspection technology for CFRP aerostructures is ultrasound [1]. Whereas, although being an efficient and cost effective technique, ultrasonic testing is limited in terms of spatial resolution and inspection time and encounters some difficulties to inspect non planar or inhomogeneous parts. X-ray imaging techniques are a promising method for nondestructive characterization of composites [2]. Considering pure radiography, the available information is a projection image. It means that only cumulative lengths of material should be considered, and an equivalent projection scheme may be used for analysis (Figure 1). One should note the influence of the spatial resolution: depending on the detector pixel size, porosity (air bubbles of variable diameters, typically between 10 and 100 µm) can be perceived individually or globally as change of density. Also, fibers structure can be visible in the image or not.

![Figure 1. Projection scheme and various defect types.](image-url)
Another important point is that, considering standard radiography, one cannot access to the localization of the defect: it is not possible to assess if a defect is present within fibers or resin. Indeed, considering for example the case of a delamination and a resin rich area, it is not possible with a single standard radiography to distinguish between them as they will produce similar contrasts. Using dual or multi energy technique allows to obtain material images providing the information about which material is affected by the defect. For that purpose, one should consider dual and multi-energy techniques that could bring material dependent information [3].

In this contribution we first introduce dual and multi-energy techniques, considering different acquisition protocol. Then we will present our simulation study used to estimate and compare the performances of each dual and multi-energy protocol within the context of CFRP inspection. Finally we show our first experimental results on material decomposition in a carbon/resin basis.

2. Dual and multi-energy techniques

As mentioned previously, the information provided by conventional X-ray imaging is not sufficient to characterize precisely the observed object in terms of composition. In the usual inspection energy range, the attenuation of X-ray radiation is a combination of two photon-matter interactions: the photo-electric effect and the Compton scattering. These two interactions and their relative contribution to the total attenuation are energy dependent. Thus, dual or multi energy measurements should permit the separation of the attenuation into its basic components, which can be used to identify materials, and finally to produce material-specific image. Nevertheless, the accuracy on the final images depends on the photon flux, the system disturbances, the object thickness, and the closeness of the considered materials. Thus, the interest of dual energy technique has to be evaluated for each application, both for radiography and computed tomography (CT) modes, and for that purpose simulation is a very helpful tool. In the following, we use LE for Low Energy, and HE for High Energy. We will consider here standard dual-energy technique using scintillator based detectors, dual-counting and spectral counting using semi-conductor based detector.

In the case of standard dual energy technique, the acquisition protocol consists in two successive acquisitions, the energy discrimination being performed by switching the kV and adding filters in front of the generator. Another possibility is a dual-layer (sometimes called sandwich) detector, allowing to perform the acquisition in one shot but with a poor energetic separation. Such a detector is often used for security application, but in the case of CFRP the first protocol is preferable. One can also use semi-conductor counting detector with two or more energy threshold which allows obtaining dual or multi energy images into one single exposure instead of two distinct acquisitions at different voltages.

In terms of criteria, a contrast to noise ratio can be generalised to the multi-dimensional information content summing up the contrast-to-noise of each energetic image. But this computation does not fully benefit from the information provided by the dual-energy technique which is material specific. The more commonly used dual energy processing method consists in the decomposition onto a two materials basis. The obtained information is then the “equivalent” length of the two basis materials. A figure of merit can then be defined by the accuracy on material thicknesses (bias and/or standard deviation).

In the case of CFRP the attenuation of the two materials is very close, as shown on Figure 2, so the decomposition in material basis is expected to be difficult. The volumetric densities differ (1.35 and 1.7 g.cm⁻³), but this fact is more helpful in CT than in radiography where only
one projection image is provided. Decomposition onto material basis needs to first proceed to
calibration measurements using (in the case of CFRP) a basis of pure carbon and resin
samples. Two different approaches are considered here: in the case of dual acquisition and
dual counting protocols we proceed to a polynomial decomposition into carbon and resin
thicknesses using the calibration measurements and in the case of spectral protocol we
proceed to a fit of the acquired spectrum with the interpolated spectra obtained from the
calibration measurements. The fact that calibration phantom of various thickness of both
materials can be easily manufactured is in favour of these methods.

Figure 2. Theoretical massic attenuation coefficients \( \tau \) (cm\(^2\).g\(^{-1}\)) of carbon fibers and resin matrix.

It is important to note that the contrast of “air” defect (delamination, porosity…) cannot be
increased by such a technique. The contrast between fibers and resin matrix could be
enhanced. More precisely, dual-energy technique may allow the discrimination between two
configurations producing the same contrast in the standard radiograph but that differ in terms
of material (if noise is sufficiently low). The noise in the material image is due to the noise in
LE and HE images, but also to the “distance” between the considered materials. The closest
the materials are, the more difficult the material decomposition is.

In that case, considering a standard integration detector, the signal, in the case of a perfect
response without taking into account the acquisition noise, is given by:

\[
Signal = \sum_{\text{energy}_i} N_{ph}(i)E_i
\]

Another possibility is to use semi-conductor based detectors in counting mode. They are also
called direct conversion detectors because they directly transform the absorbed photons into
charges that are collected at the electrodes of the semi-conductor. Such detector can provide
the total number of photons per pixel (generally counted only if their energy is greater than a
noise threshold). Using a discrete formalism, the perfect signal is given by:

\[
Signal = \sum_{\text{energy}_i} N_{ph}(i) = N
\]

By adding a few thresholds/counters, they provide the number of photons in a few large
energy bins (“dual-counting”, or “multi-counting”). Usually the number of channels is 2 to 6.
Prototypes developed at CEA, thanks to dedicated electronics, can provide a hundred of bins.

The corresponding signal is, for a large channel and a perfect detector:
\[ \text{channel}_{C_k} = \sum_{C_{j} \text{ min}}^{C_{j} \text{ max}} N_j \]

And for spectral mode and a perfect detector:

\[ \text{channel}_{C_k} = N_k \]

In the case of standard acquisition using an integration detector we will consider in the following two successive acquisitions at different voltage and filtration (high and low energy acquisition) and then proceed to a standard polynomial dual energy decomposition onto a carbon and fiber basis. In the case of counting detector we will first consider a dual counting detector (i.e. with two energy threshold) and then proceed to a similar polynomial dual energy decomposition. Finally we will consider a multi energy detector with a 1 keV channel width and proceed to a decomposition by fitting the measured spectrum to the interpolated calibration spectra (i.e. finding the equivalent carbon and fiber thicknesses producing the closest spectrum to the measured one) [4]. In the following we present our simulation and experimental results in the context of CFRP inspection considering these three different acquisition and analysis protocols.

3. Results

3.1 Simulation study

In the case of standard dual energy acquisitions we considered for our simulations a perfect integration detector without taking into account the acquisition noise which depends in particular of the integration time. We used our simulation tool SINDBAD [5] [6] to simulate spectra considering a realistic generator. Using SINDBAD, the filtration, voltage and mA.s were set in order to optimize resin and fiber separation. The resulting LE and HE simulated spectra are shown on Figure 3-left.

![Figure 3. (left) Simulated spectra used for dual acquisition simulation after filtering, considering 100 µm tin at LE and 200 µm copper at HE. (right) Simulated spectrum used for dual counting and spectral acquisition simulations after filtering considering 1 mm aluminium.](image)

In the case of semiconductor counting detector, it is necessary to go further the perfect response to take into account charge sharing, fluorescence, collection loss... The previous formalism (2) assumes a perfect detector. In fact it is not, and a key point concerning the exploitation of multi-energy information concerns the instrument response that corrupts measurements. We developed a model for the spectral detector that accounts for both fluorescence and charge sharing. The simulation tool computes the Cd(Zn)Te detector
response (Interaction photons / matter, Drift / Diffusion of charges in semiconductor, electronics modelling) depending on detector characteristics [7]. The result is a detector response matrix, shown on Figure 4.

Figure 4 Example of a CdTe detector response matrix (DRM) used to model the detector response in dual counting and spectral modes and the response to a given energy (80 keV) considering a detector with a 225 μm pitch.

Considering dual counting, we set the threshold to a value optimizing the separation between resin matrix and carbon fibers. The incident spectrum used for dual counting and spectral acquisition is shown on Figure 3-right.

For spectral acquisition, we do not proceed to a polynomial decomposition, considering the number of channels (90 channels of 1 keV width in that case). Instead we proceed to a fit of the acquired spectrum to an interpolated spectrum obtained from the calibration measurements as mentioned above.

In order to evaluate the performance of each acquisition protocol (dual acquisition, dual counting and spectral) we first proceed to a 1 dimension simulation considering realistic CFRP composition (75% carbon fiber and 25% resin) for different CFRP thicknesses between 3 and 6 mm. We chose two figure of merit to compare each protocol: the standard deviation and the bias of the estimated carbon and resin thickness. For each protocol the total number of incident photons remains constant and is set to $10^7$. The calibration thicknesses considered here are the same for each protocol. The bias and the standard deviation of the estimated carbon and resin thickness are computed from 10 000 noisy realisations at each simulation point. Obtained results on standard deviations and biases are shown on Figure 5.
One can see that dual acquisition is the approach being the most sensitive to the noise in terms of estimated thicknesses, dual counting producing less noise. Spectral acquisition produces the best results considering standard deviation of the estimated thicknesses. In the case of the bias, for spectral acquisition the bias is relatively constant and below 20 µm over the entire thickness range while for dual acquisition and dual counting the bias is more important and non-constant which could be problematic, particularly in the case of low thickness CFRP. These results advocate in favour of spectral acquisitions over dual acquisition and dual counting protocol as it leads for the same statistics and calibration basis to a lower standard deviation of the estimated thicknesses and a lower and constant bias over the entire thickness range.

We also performed image simulations, considering a realistic 3D CFRP model [8] in order to illustrate an example of material decomposition with realistic defects. Simulated defect here are missing carbon fibers, lack of resin, porosity, delamination and inclusion of parafin fiber. In this example we performed a decomposition using a dual counting protocol similar to the one used previously for our 1D simulation. The simulated LE and HE radiographs are presented in Figures 6(a) and 6(b) respectively. Figures 6(c) and 6(d) present the resulting images, corresponding to the equivalent thickness of fiber and resin.

Both defects (delamination and lack of fiber) appear darker than the background (lower values) in (LE, HE) initial attenuation images. On material images, delamination is visible on both carbon and resin images. Resin rich area is visible on carbon image (lack of carbon) and on the resin image, as values higher than background. Furthermore, the values in the material images provide an estimate of the thickness of these defects. One can also see the distribution
of the porosities on the resin image. It is also interesting to note than the paraffin inclusion (line crossing the image from upper left to lower right) is visible on the carbon image as a value higher than background and as a value lower than background for the resin image, as expected from a material decomposition using carbon and resin as material basis. Finally, the contrast of the defects in material images is not necessarily higher than in (LE, HE) ones, but an additional information about the nature of the material is provided and can be exploited.

3.2 Preliminary experimental results

We proceeded to a first validation of our dual acquisition protocol, considering the same LE and HE voltage and filtration using a Hamamatsu flat panel detector with a 50 µm pixel pitch. Our calibration acquisitions were made using 500 µm pure carbon samples and 450 µm pure epoxy resin samples considering a total carbon thickness between 0 and 2.5 mm and a total resin thickness between 0 and 2.25 mm. We then proceeded to LE and HE acquisitions with a simplified test sample with an thicknesses of 1.25 mm of pure carbon and 1.6 mm of pure resin. The HE and BE images are shown on Figure 7 (image (a) and (b) respectively) and the resulting images corresponding to the estimated thickness of fiber (c) and resin (d).

![Figure 7. Acquired LE (a) and HE (b) radiographs. Resulting decomposition onto equivalent thicknesses of carbon (c) and resin (d).](image)

One can notice the high noise level in the decomposed images. The resulting noise for the estimated thickness images depends on the closeness of the materials in terms of attenuation: the closer the attenuations, the higher the noise. Moreover this noise depends also of the acquisition noise, which is higher in the case of integration detector like flat panel than in the case of semiconductor counting detector. The obtained noise is higher than what was expected from our simulations but one should note that we were considering the case of a perfect integration detector, without taking into account the acquisition noise. The mean estimated carbon thickness obtained from image 6c is 1.45 mm (0.2 mm bias) and the mean estimated resin thickness from image 6d is 1.7 mm (0.1 mm bias). The obtained biases are close to what was expected from our 1D simulation. These noise and bias values are probably too high for the to size of defect considered in the case of CFRP, where defects sizes around 50 µm are expected. In order to obtain estimated thickness images with less noise and bias, as shown from our simulation studies, one should go further with dual counting and spectral protocol, were the acquisition noise and expected standard deviation and bias on the estimated thickness are lower.

These results illustrate the need to optimize the calibration procedure (and particularly in terms of efficient sampling of the relevant attenuation domain) as well as the need of spectral or dual counting acquisitions to enhance the thickness estimation quality.
4. Conclusions and perspectives

In this contribution we evaluated the potential of dual and multi energy techniques using radiography for CFRP inspection. We investigated different protocols (dual acquisition, dual counting and spectral) by developing a 1D simulation in order to compare their respective performances. We showed that, considering equivalent calibration basis and a constant number of incident photons, spectral decomposition exhibits the best results in terms of standard deviation and bias of the estimated carbon and resin thicknesses compared to dual counting and dual acquisition protocols. It is worth mentioning that these results being obtained from a 1D simulation, the performance comparison did not take into account X-ray scattering that would affect the results for non-collimated geometries (multi lines detector).

We also performed images simulations, showing an example of material decomposition considering a realistic CFRP model with various defects, allowing to assess whether the defects are present within carbon fibers or resin matrix and illustrating the interest of a decomposition into equivalent carbon and fiber thicknesses.

Finally we showed the results of our first experimental validation with a standard dual acquisition protocol, illustrating the need of an optimization of the calibration procedure in order to reduce the standard deviation and bias of the estimated thickness as well as the need for counting detector with at least two energy thresholds.

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