Simulation study for optimization of X-ray inspection setup applied to CFRP aerostructures

Konstantinos Tigkos¹, Kristina Bliznakova², Aris Dermitzakis², Nicolas Ducros³, Ulf Haßler¹, Zacharias Kamarianakis², Ahmad Osman¹, Veronique Rebuffel³, Mathieu Tartare¹

¹Fraunhofer Development Center X-ray Technologies (EZRT), Dept. Application Specific Methods and Systems (AMS), Dr.-Mack-Straße 81, 90762 Fuerth, Germany, (FHG)
e-mail: ulf.hassler@iis.fraunhofer.de

²Biomedical Technology Unit, University of Patras, Greece, (UPAT)
e-mail: krisi@upatras.gr

³CEA Leti, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France, (CEA)
e-mail: veronique.rebuffel@cea.fr

Abstract
The goal of this contribution is the development and configuration of a simulation scenario for 2-D (radioscopic) and 3-D (computed tomography) X-ray inspection setups for CFRP aerostructures. Characteristics taken into account are object shape, defect types, their form and spectral properties. The simulations are carried out using analytical simulation software. The simulation procedure and preliminary optimization results are illustrated for the case of thermoplastic CFRP specimens.

Keywords: non-destructive testing, X-ray imaging, computed tomography, simulation, acquisition optimization, aerostructures, CFRP

Introduction
With the increase of the use of carbon fiber reinforced polymers (CFRP), the requirements for non-destructive testing (NDT) of these structures are increasing accordingly. Today’s main inspection technology for CFRP aerostructures is ultrasound [1]. Whilst being an efficient and cost effective NDT method, ultrasonic testing has limits regarding the required inspection time for a 100 % inspection. Other drawbacks include the difficulty to inspect non planar samples or inhomogeneous parts, as well as the limited spatial resolution. X-ray imaging techniques are a promising method for nondestructive characterization of composites [2]. The EU funded project QUICOM comes as an effort to escalate the conventional NDT techniques with cutting edge X-ray methods. Part of this project is the simulation of the X-ray inspection process, in order to optimize acquisition parameters, finding optimal trajectories and developing adequate reconstruction algorithms for specific CFRP components. Within this contribution, a simulation study for a relatively small CFRP specimen will be presented.

1 Materials and methods
1.1 Simulation environment
For our objective we need versatile simulation tools, able to provide realistic radiographs in terms of objects (shape and composition), geometry and acquisition system characteristics. The considered aeronautic parts can be large and complex, and it is important to precisely describe their geometrical shape for acquisition geometry optimization. CFRP is composed of carbon fibers included in resin binder following a complex internal structure. To image this structure, or to test the visibility of
porosity inside it, it is necessary to model this woven tissue of fibers at a high resolution scale. And of course, both aspects, shape and structure, have to be combined, requiring to insert complex fiber structure inside complex shape part. Thus it was necessary to design a versatile simulation framework, to be used at different complexity level depending on the optimization task. This framework setup relies on different simulation software available at each partner’s site, each one offering common functionalities but also some unique ones. Data exchange is possible at several steps of the simulation process.

Examined parts can be described in Constructive Solid Geometry (CSG) format or in facet one. Data can come from CAD model, from a CT acquisition, or designed directly by the user. The considered tools need a geometrical description of the acquisition system. Using ray-tracing, a stack of mono-energetic line-integral images are produced. This scheme allows to take into account various detector responses and detector types, including dual-energy acquisition or counting mode detector. XRayImagingSimulator, Scorpius XLab and Sinbad can provide the final output, or the intermediate images for data exchange (Fig. 1). Additional functionalities such as modeling the focal spot size or the MTF of the detector can be employed to get more realistic images. Finally, simulation of scatter radiation is possible at the price of a longer computation time.

**XRayImagingSimulator (UPAT)**

For this study the in-house developed XRayImagingSimulator [3] was used. This software tool is dedicated for simulation of 2-D and 3-D X-Ray imaging techniques. It consists of four components: Image acquisition, Absorber, Image formation and Visualization. Software phantoms are modeled as a synthesis of geometrical or voxelized primitives. Simulated projection images are calculated using an analytical ray tracing approach or by Monte Carlo simulation.

**Scorpius XLab (FHG)**

For the fast simulation of the complete radiographic imaging process at energies up to 450 keV, ScorpiusXLab has been developed at Fraunhofer EZRT [4]. It models physical effects (source spectrum, object and detector scattering, MTF, DQE, quantum noise, focal spot etc.) analytically. Phantoms can be generated by nested primitives, e.g. cubes or cylinders, and triangulated surfaces from STL-models. To reduce the computation time for STL data, it is performed on the graphics card. Key application of the software is the validation of algorithms that are developed for reconstruction and artifact correction. In addition, ScorpiusXLab may be employed for the estimation of the uncertainty of measurements [5].

**Sindbad (CEA)**

Sindbad is a simulation tool providing realistic radiographs and scanner data. A large number of possibilities are offered for the design of the object, and the description of the acquisition parameters.
Various simulation modes are proposed: analytical method for primary flux simulation, Monte Carlo one for scatter, and a combined one [6]. Developed by CEA for its own purpose, it has been integrated as the X-ray module in Civa, a commercialized NDT simulation tool [7]. Recent advances concern the model of emerging semi-conductor detectors providing spectral radiographs [8].

1.2 Target specimen
One industrial goal within the QUICOM project is the inspection of carbon fiber reinforced thermoplast parts. Their thickness ranges between 2 and 4 mm, their outer hull diameter is approx. 200 mm, height ranges between 200 mm and 500 mm. The matrix material used is epoxy resin. Goal of the inspection is a fast and reliable detection of foreign materials, voids/porosities and of delaminations. For the simulation setup, we assume a fiber volume fraction of 50%. The density of the fibers is 1.75 g/cm³ and of the resin 1.35 g/cm³.

1.3 Phantom Modelling

1.3.1 Small complex part
The CFRP phantom is modeled as a set of layers that contain carbon fiber bundles, arranged in the following sequence: 0⁰, 90⁰, 45⁰ and -45⁰ [9]. The smallest unit in the CFRP model is the carbon bundle. It is modeled as a simple cylinder, with user defined dimensions and composition of material with atomic number 6 and density of 1.7 and 2.267 g/cm⁻³, while the resin layer is simulated from epoxy polymer with composition O₄C₂₁H₂₄ and density of 1.35 and 1.8 g/cm⁻³. Modeling of the following defects was accomplished: porosity, missing fibers, lack of resin and delamination and inclusion of fibers with different composition than that of the carbon ones (Fig. 2).

Figure 2: Software models of (a) layer porosity, presented as hundreds of ellipsoids generated randomly within the layer, (b) missing carbon fibers, (c) fibers with different composition that the carbon ones, (d) delamination.

Porosity is the most common defect within a CFRP part that is a presence of small voids in the resin volume. The geometrical primitive that is used to simulate a pore is an ellipsoid. Porosity may be simulated either in a CFRP volume or in a CFRP layer. In order to simulate layer porosity, several hundred air-filled ellipsoids in a randomly chosen resin layer were introduced. The dimensions of these ellipsoids are randomly chosen in a range defined as (0.2 - 1.0)*(dimension of the carbon bundle). The distribution of the ellipsoids may be randomly uniform or non-uniform. Fibers with different composition were introduced as paraffin inclusions. Delamination is a separation between adjacent plies in a multilayer structure. It is simulated as an air-filled area.
1.3.2 Complete part

In order to get a real size simulation scenario, an STL surface from a helical CT scan was created. The helical scan was chosen due to the fact that it is free of Feldkamp artefacts. For the simulation of simple inner structures of the specimen, a tool was implemented for the creation of patches containing carbon fiber bundles of different orientation as well as pore distributions of different size (Fig. 3(a)). Due to the fact, that the system resolution will be far lower than the diameter of a single carbon fiber, the fiber bundles are modeled by using a mixed composition of 85% carbon and 15% epoxy resin. The STL surface will serve as a cavity in which several patches are introduced in different locations (Fig. 3(b)). The patches are placed at the four faces of the part, in order to verify the isotropic behavior of the CT reconstruction. The patch composition is shown in Table 1.

<table>
<thead>
<tr>
<th>Fiber bundle semi axes</th>
<th>200 µm, 2000 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle density</td>
<td>1.69 g/cm³</td>
</tr>
<tr>
<td>Porous layer 1</td>
<td>1 % porosity, diameter range [100 µm, 300µm]</td>
</tr>
<tr>
<td>Porous layer 2</td>
<td>1 % porosity, diameter range [300 µm, 500µm]</td>
</tr>
</tbody>
</table>

Table 1: Simulated patch composition.

Figure 3: (a) Patch used for the simulation of inner structures. (b) Cavity based on part surface and location of patches.

1.4 Figures of merit

In order to carry out an objective evaluation of the results two figures of merit (FOM) were employed. The contrast to noise ratio (CNR), measures the separation in terms of average intensity between two materials of interest and is defined as:

\[
\text{CNR} = \frac{|\text{ROI} - \text{BCK}|}{\sigma_{\text{BCK}}}
\]

The Relative Variation (RV) is used in this study to measure the beam hardening effect along a line profile and expresses the difference between the maximum and minimum values of the profile normalized to the mean value since the attenuation coefficient varies for different energies. The relative variation is defined as:

\[
\text{RV} = \frac{\text{max(profile)} - \text{min(profile)}}{\text{profile}}
\]
2 Radioscopy, DTS, CT on small complex part

The XRayImagingSimulator allows simulation of several X-Ray imaging acquisition geometries: radiography, tomosynthesis, circular and helical CT. In this study 3 different X-ray acquisition modalities were investigated: a) Radiography where projection images are acquired at 0 degrees, b) Axial Cone Beam CT (CBCT) where projection images are obtained at different angles within a full circle and c) Digital Tomosynthesis of various angles (DTS) where projection images are acquired at different angles within a limited arc.

In all modalities monochromatic projection images of energy range from 10 to 90 keV were simulated with a 1 keV step. The monochromatic images were used to synthesize the desired energy spectrum. Different energy spectra from 40 to 90 kVp of 245 um Be and 1mm Al filter were investigated.

The radiographs generated at 0° were used for the dual energy approach presented in Chapter 3.

Tomograms were reconstructed with an in-house (UPAT) developed image reconstruction platform. For this study, two different reconstruction techniques were used. Cone Beam CT (CBCT), where 361 projection images were acquired in a full circle, with 1° step and Digital Tomosynthesis (DTS) were the source/detector pair was considered to move similarly in a circular isocentric trajectory, 121 projection images every 1° were acquired in a limited arc from -60° to 60°. In the case of tomosynthesis, tomograms were reconstructed using a Filtered BackProjection (FBP) algorithm while in the case of Axial CT the standard FDK algorithm was used. In all cases, the target was to bring in focus the planes of interest (e.g. the layers with porosity, delamination, missing fibers). Figure 4 shows reconstructions in focus planes where the defects exist in each case. The CT reconstructed slices can be seen in Figures 4(a) to 4(d) where a standard FDK algorithm was used, while in Figures 4(e) to 4(h) DTS reconstructed slices are shown where FBP algorithm was used. In both cases tomograms were 850x850 pixels, with voxel size of 0.025 mm.

The superposition and blurring effect caused by the underlying structures of out of focus planes in the case of DTS (Figures 4(e) to 4(h)) can be seen. Table 2 summarizes the CNR of each defect.

Although axial CT provided better results in terms of discrimination and localization of the underlying structures in individual reconstructed planes, DTS with 120 degrees acquisition arc produces also satisfactory results and could be used for larger parts where complete rotation is not applicable. In terms of defects visualization, delamination produces shadow artifacts on the out-of-focus planes in all modalities. Porosity can be visualized with 120° FBP DTS, however, CT offers better visualization. Finally, missing fibers can be detected with both modalities but their boundaries are better discriminated when CT is used.

<table>
<thead>
<tr>
<th>Delamination</th>
<th>Porosity</th>
<th>Missing Fiber</th>
</tr>
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<tbody>
<tr>
<td>CT DTS 120</td>
<td>CT DTS 120</td>
<td>CT DTS 120</td>
</tr>
<tr>
<td>CNR</td>
<td>CNR</td>
<td>CNR</td>
</tr>
<tr>
<td>7.625</td>
<td>10.809</td>
<td>1.278</td>
</tr>
<tr>
<td>3.556</td>
<td>6.034</td>
<td>0.612</td>
</tr>
</tbody>
</table>

Table 2: CNR for the in focus planes of (a) delamination, (b) porosity and (c) missing fiber.
Figure 4: In focus reconstructed planes from CT ((a) to (d)) and DTS ((e) to (h)) modalities. Depicted defects are: porosity at Z=0.5 mm ((a) & (e)), delamination at Z=1.0 mm ((b) & (f)), missing fibers ((c) & (g)) and fiber inclusion with different material ((d) & (h)).

3 Dual energy radioscopy on small complex part

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, measurements at two distinct energies 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 CT modes, and for that purpose simulation is a very helpful tool [10]. In the following, we use LE for Low Energy, and HE for High Energy.

Let us consider now an example of dual-energy technique simulation. The object is the small flat CFRP part as presented before. Figure 5(a) shows the mass attenuation coefficient (cm²g⁻¹) for the two materials (carbon fibers and resin). One can note that they are very close. The volumetric densities differ (1.35 and 1.7 gcm⁻³), but this fact is more helpful in CT than in radiography where one is provided by projection image only. A dual exposure protocol is performed, with following parameters: LE 40kV, filter 100 µm Samarium, HE 90kV, filter 200 µm Copper (Figure 5(b), spectra after filtering).
Figure 5: (a) Mass attenuation coefficient $\tau$ (cm$^2$.g$^{-1}$) of carbon fibers and resin matrix. (b) Simulated spectra after filtering.

The distance between the source and the object is 67.15 mm and the distance between the source and the detector is 80.58 mm. We consider here a standard integrating detector with resolution of 20 ppmm (50 µm pixels) and 600x600 pixels. The simulated LE and HE radiographs are presented in Figures 6(a) and 6(b) respectively.

To process the two energy images, we applied a standard decomposition onto a material basis [11]. The lengths of the two materials are expressed by a polynomial function of the attenuation measurement pairs LE and HE, the coefficients of this polynomial being estimated during a preliminary experimental calibration step. Figures 6(c) and 6(d) present the resulting images, corresponding to the thickness of fiber and resin, where the cumulative length of basis materials are provided by the aforementioned algorithm.

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. 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.
4 CT simulation of complete part

In this section, the complete CT acquisition and reconstruction chain is investigated, in order to optimize the protocol with respect to defect detectability. Measurements were done as a reference for the simulations. We scanned the thermoplast part at a micro CT setup in axial and helical geometry. The acquisition parameters are given in Table 3.

<table>
<thead>
<tr>
<th>Detector matrix</th>
<th>2048²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector element size</td>
<td>200 µm * 200 µm</td>
</tr>
<tr>
<td>Exposure time</td>
<td>332 ms</td>
</tr>
<tr>
<td>Voltage</td>
<td>120 kV</td>
</tr>
<tr>
<td>Current</td>
<td>600 µA</td>
</tr>
<tr>
<td>Filter</td>
<td>0.5 mm Cu</td>
</tr>
<tr>
<td>Voxel size</td>
<td>(108 µm)³</td>
</tr>
<tr>
<td>Number of projections</td>
<td>1201 (axial) / 2102 (helical)</td>
</tr>
</tbody>
</table>

Table 3: CT acquisition parameters.

The simulation settings were chosen to match the actual measurement parameters. Different kV setups were simulated, including the voltage of the source in the real measurements. The simulated voltages were 50, 80 and 120 kV and the SNR in the primary beam was 210.

4.1 Comparison of measurements to simulation

One drawback of conventional axial CT scanning is the cone beam artifact, increasing with the distance from the central plane. This is illustrated in Fig. 7, where two comparisons are made: On the left side, reconstructed slices from the axial and helical CT measurements are shown for a region far away from the central plane. It can clearly be seen, that in axial geometry, object contours are strongly blurred, and the material distribution is very inhomogeneous. On the right side, reconstructed slices from the respective simulations are shown. This region contains patch No. 3 as pictured in Figure 3(b). Nearly the same artifacts appear, showing that the simulation is in good accordance with the measurement. Note that even in axial reconstruction, the simulated porosity can be visualized, due to the relative density changes.

Figure 7: Reconstructed slices of the part demonstrating the Feldkamp artifact: (a) axial CT measurement, (b) axial CT simulation, (c) helical CT measurement, (d) helical CT simulation.
4.2 Evaluation of CT simulation

Several quantitative evaluations of the simulations were carried out. Figure 8 shows line profiles across regions containing porosities, bundles and epoxy in the reconstruction of the axial CT simulated data as well as a line profile taken across a region without defects in the in the reconstruction of the measured CT data. As far as the measurement is concerned, the line profile (purple) has a mean attenuation coefficient of about 0.23 and the peaks are attributed to the different structures within the specimen. For the simulated data, the region containing only epoxy (green) has a mean attenuation coefficient of about 0.24 and small variations are attributed to the noise. This mean value can be set as a threshold to distinguish between different structures such as the bundles (red) and porosities (blue). It is evident that the contrast induced by the simulated pores (ø 100-300 µm) allows them to be clearly distinguished, leading to the conclusion that smaller pores can be simulated and detected.

![Figure 8: Line profiles from regions with different structures: (a) porosities, (b) bundles, (c) line profiles of epoxy (green), bundles (red), pores (blue) and healthy region in measurement (purple).](image)

In the following, we compare simulated reconstructions at 50, 80 and 120 kV. As an estimation for the beam hardening, we compute the relative variation along a line profile. It can be seen in Fig. 9 that the relative variation increases for higher voltage. This behavior can be explained by the fact that the beam hardening effect depends on the width of the spectrum. Therefore, the wider the spectrum, the stronger the beam hardening effect will appear. This fact points out that future measurements need to be carried out with detectors sensitive to lower energies. Another interesting conclusion can be drawn by examining the relative variation corresponding to the line profile taken from the actual CT measurement which differs from the simulation (120 kV) by a factor of 3.4. This difference highlights another important aspect of the detector, namely the efficiency which defines its spectral characteristics and was not considered in this set of simulations. The difference in the relative variation is attributed to the fact that the spectral characteristics of the detector also have an influence on the beam hardening effect. It is therefore important to take the spectral characteristics of the detector into account in future simulations.


5 Discussion and conclusion

Subjective visual assessment and quantitative evaluation indicated good correlation of characteristics between simulated and actual radiographic data. The analysis of radiographs highlighted the importance of using multi-energy methods in order to better detect and gain additional information about the nature and properties of the material and the defects that may appear in contrast to single energy radioscopy. For the optimization of the dual-energy protocol investigated here, a lot of parameters should be tuned: voltage and filter (material and thickness) of the LE and HE source and their relative weight (mAs for instance). Further numerical simulations considering these parameters and integrating industrial constraints such as acquisition time are of great interest and will be communicated in following contributions.

Axial and helical CT provided the best results in terms of defect visualization and detectability, helical CT having the additional advantage of eliminating the Feldkamp artifact. Nevertheless, DTS proved to be a viable alternative in cases where the size and shape of the specimen does not allow a full rotation. The beam spectrum of the source and the spectral characteristics of the detector proved to be important parameters for the scanning protocol optimization. These parameters do not only affect the imaging contrast but also other effects present in radioscopic data such as beam hardening and artifacts that appear in the reconstructions. Hence, one important parameter to consider for further simulations is the spectral detector efficiency. Another important aspect is the evaluation of the results. More sophisticated figures of merit could be employed that better reflect the defect detectability and take into account artifacts and other effects such as beam hardening that appear globally or locally in particular regions of the reconstructed volume. These aspects will be taken into consideration in further communications.

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References


