NON-DESTRUCTIVE EVALUATION, INSPECTION AND TESTING OF PRIMARY AERONAUTICAL COMPOSITE STRUCTURES USING GRATING-BASED PHASE CONTRAST X-RAY IMAGING

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Abstract. The EU-project EVITA aims at bringing Grating-based Phase Contrast X-ray imaging technology to non-destructive evaluation and inspection of primary aeronautical composite structures. A demonstrator has been developed to meet the requirements of the aeronautic industry for the inspection of thin and thick carbon fibre reinforced polymer components. The technical specifications of the demonstrator and first results on the comparison of the new methodology with state-of-the-art techniques are presented.

The introduction of this innovative methodology is expected to provide the aeronautical industry with a reliable and detailed insight of the integrity of thin and thick composite structures as well as of complex geometry ones, such as integrated closed boxes and sandwiches. In particular, the detectability of defects such as resin rich areas and out-of-plane wrinkles are demonstrated in this paper.

By increasing the level of detectability of defects in composite structures, as well as by detecting defects invisible to standard industrial non-destructive testing methodologies, we envision that the novel method will allow to increase the non-destructive inspection process reliability.

Introduction

Grating-based Phase Contrast X-Ray Imaging is based on the so-called Talbot-Lau interferometer, which is made of the combination of a standard X-ray apparatus with three transmission gratings as documented in the literature [1]–[4].

The method derives its potential from the fact that three different contrast mechanisms are combined in a single measurement. Indeed, not only the conventional absorption image can be extracted but also the refraction image (also called differential phase contrast image) and the scattering image (also called dark field image), which are related respectively to the refraction of the X-ray beam inside the sample and to the ultra-small angle scattering caused by its microstructure. Preliminary studies have shown that the scattering image provides a powerful tool to detect any change in the arrangement of the fibres due to the presence of defects such as porosity, fibre waviness, micro-cracks or resin rich/resin poor areas [5]–[8].

Within the project EVITA (www.evita-project.eu), the requirements and needs of the aeronautics industry in terms of the non-destructive inspection of thick and thin composite components were collected and analysed. From there, a customized demonstrator was designed and realized in order to benchmark this novel technology against the following non-destructive inspection (NDI) techniques: water jet ultrasonic, phased array ultrasonic, thermography and computed tomography.

Materials and Method

A schematic view of the grating-based Phase Contrast X-Ray Imaging system is shown in Figure 1. It consists of a standard high power X-ray source (Varian HPW-160-11) and pixelated detector array (Dexela DEX2315) coupled to three gratings forming an X-ray interferometer. The principle of the X-ray grating interferometer is explained in details in the literature [1]–[3], [9].

A collimator made out of lead is used to control the illuminated area while a shutter allows to block the X-ray beam during the idle time of the detector. In the present configuration, the sample can be moved independently using an XY gantry (IAI axis).

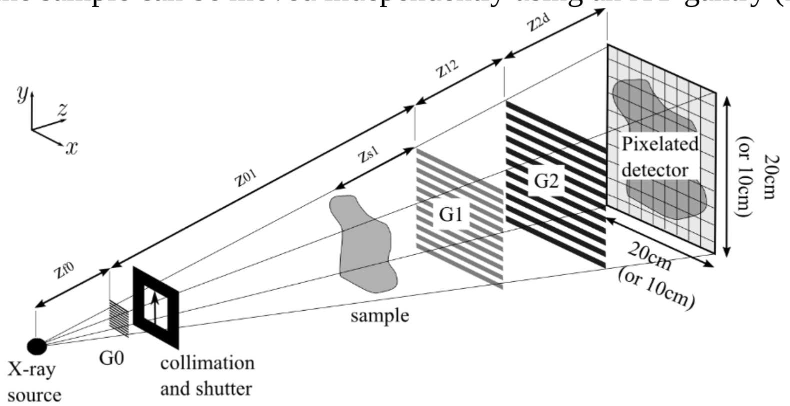

Figure 1. Schematic view of the grating-based Phase Contrast X-Ray Imaging system

The gratings were manufactured at CSEM using MEMS fabrication processes on Silicon wafers of diameter 150mm, which allows to achieve a grating size of 100×100mm on a single wafer.

The parameters of the demonstrator are summarized in Table 1.

	Parameters
Source acceleration voltage	40 – 70 kV
Maximal sample thickness (CFRP)	50 mm
System length (source to detector)	1.45 m
Measurement area (stitching mode)	1× 0.75 m^2
Image size (single field)	7 × 7 cm^2
Effective pixel size	50 - 60 µm

Table 1. Key parameters of the EVITA demonstrator

Three images are obtained using the EVITA demonstrator, namely the absorption, refraction and scattering images. The absorption image corresponds to the conventional X-ray image, except that the blurring effect due to the Compton scattering is suppressed in the direction perpendicular to the grating lines. The absorption image is related to the attenuation coefficient of the material and its thickness.

The refraction image is proportional to the refraction angle measured pixel-wise by the interferometer. The refraction angle is linked to the derivative of the phase shift in the direction perpendicular to the grating lines (direction y in Figure 1). In contrast to the absorption image, the refraction image is thus related to the refraction coefficient as well as to the thickness of the sample [4].

Finally, the scattering image is related to the ultra-small angle X-ray scattering (USAXS) of the beam inside the sample. It has been shown that the USAXS can be expressed in terms of variations of the electronic density of the material at the microscopic level [10]. The scattering image is thus a perfect tool to probe the microscopic texture of composite materials and detect porosity, cracks and variations of the fibre density or orientation [11].

The images were reconstructed using the phase stepping method [9], where the phase stepping was achieved by translation of the grating G2. The X-ray tube source was set to the small focal spot (0.4×0.4mm^2) with the acceleration voltage at 60kVp and the anode current at 10mA. 19 phase steps were acquired over 4 periods with an individual exposure time of 750ms. The measurement was repeated 4 times and averaged. The measurement time for a single field inclusive reconstruction amounts to about 60s.

Results

The demonstrator was assembled in the premises of CSEM in Alpnach, Switzerland (see Figure 2) and started operation in January 2015. It was evaluated using coupon samples with different artificially prepared flaws. The samples were made out of Epoxy-carbon prepreg (HexPly 914C-T300H(6K)-5-34%). The results presented here were obtained with a 32 plies quasi-isotropic lay-up (+45°/90°/-45°/0°)4s with a thickness of about 4mm.

The results obtained with the EVITA demonstrator were benchmarked against four state-of-the-art NDI methods: water jet ultrasonic, phased array ultrasonic, thermography and computed tomography. The benchmarking measurements were performed at the University of Manchester, United Kingdom.

Figure 2. Picture of the EVITA demonstrator at CSEM in Alpnach, Switzerland. The demonstrator is operational since January 2015 and is acquiring data since then.

Figure 3 shows the results of the comparison for the first sample, where the mid-plane ply was cut across the width of the laminate perpendicular to the 0° direction. The spacing between the cut fibre ends amounts to 8mm, 4mm, 2mm, 1mm, 0mm (see Figure 3-a). The cut fibres can be detected in the scattering image (red arrows) using the EVITA demonstrator as well as with the phased array system. All other benchmarking methods were not able to detect the defects.

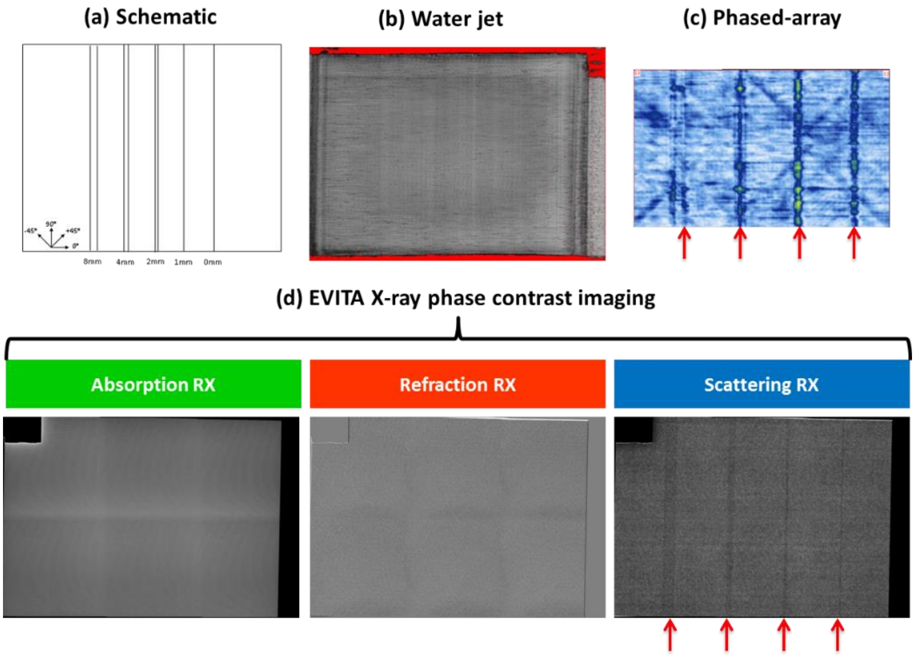

Figure 3. Results obtained on a coupon sample with cut fibres positioned as shown in (a). The images obtained by water jet and phase array ultrasonic are shown in (b) and (c). The absorption, refraction and scattering images obtained with the EVITA demonstrator are shown in (d).

Figure 3 shows the results of the comparison for a second sample, where an out-of-plane wrinkle was induced by adding additional plies at 90° as depicted in see Figure 4-a. The out-of-plane wrinkle can be detected in the scattering image (red arrows) using the EVITA demonstrator as well as with the water jet ultrasonic system. All other benchmarking methods were not able to detect the defects.

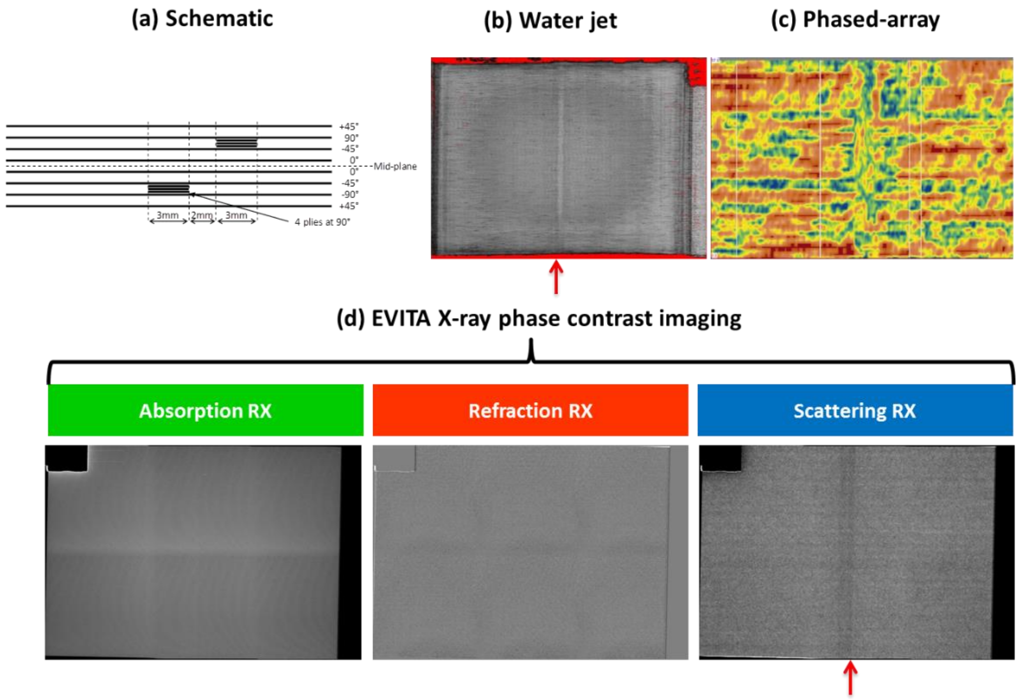

Figure 4 Results obtained on a coupon sample with an out-of-plane wrinkle induced by the layup shown in (a). The images obtained by water jet and phase array ultrasonic are shown in (b) and (c). The absorption, refraction and scattering images obtained with the EVITA demonstrator are shown in (d).

Conclusion

The EVITA demonstrator was presented and its performance was illustrated using two coupon samples with two types of artificial flaws: fibre cut and out-of-plane wrinkle. The flaws could be detected by the EVITA demonstrator with a comparably fast exposure time. No other NDI method used for the benchmarking was able to detect both flaws. The images obtained still display some artefacts which penalize the sensitivity of the method. However, new algorithms are currently being developed to reduce the artefacts and improve image quality.

The introduction of this innovative methodology is expected to provide the aeronautical industry with a reliable and detailed insight of the integrity of thin and thick composite structures as well as of complex geometry ones, such as integrated closed boxes and sandwiches. By increasing the level of detectability of defects in composite structures, as well as by detecting defects invisible to standard industrial non-destructive testing methodologies, the novel method will play a major role during the whole life cycle of composite components, reducing their inspection cost and increasing their reliability.

Acknowledgments

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