Mobile X-Ray Inspection of Light Weight Materials

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Abstract: Digital detectors such as phosphor imaging plates (IP) and digital detector arrays (DDA) allow radiographic inspection with higher efficiency and improved image quality in comparison to the classic film technique. Mobile X-ray flash tubes are used routinely for veterinarian and security applications. New high sensitive IPs and DDAs enable to apply them for inspection of light materials with low X-ray attenuation as in aluminium, plastics and composites. A versatile computed tomography (CT) system was developed for in situ inspection of large aircraft components under production conditions. A gate based planar computed tomograph was developed and tested for inspection of integrity of the stringer incorporation. Successful test trials were performed to prove the detection rate of cracks in embedded stringers. Honey comb structures of aircrafts have to be inspected for water inclusions during in-service inspections. Thermography is a powerful method for in house inspections when variations in temperature caused e.g. by sunshine can be excluded. A new X-ray diaphragm was developed for mobile back scatter measurements of large components. This method is insensitive to heat alterations in the field and thus can be applied also outdoors.

1 Introduction

The new digital detectors such as phosphor imaging plates (IP) and digital detector arrays (DDA) allow radiographic inspection with higher efficiency and improved image quality in comparison to the classic film technique. The application range of mobile flash tube inspection up to mobile computed tomography and back scatter inspection paves the way for new applications which could not be performed with classical film based radiography and other methods.

Portable X-ray flash generators of less than 10 kg weight have been introduced in veterinarian and security applications. The photon flow of these tubes is low and insufficient for radiography with NDT-films. New high sensitive phosphor imaging plates (IPs) and digital detector arrays (DDAs) enable their application for light materials with low X-ray attenuation such as aluminium, plastics and composites. Due to the small controlled area and short exposure times several operator teams can work simultaneously in a rather close distance.

The application of computed tomography (CT) increased fast during the last years, since DDAs were available which permit exact and fast reading of multiple radiographic projections. More and more industrial CT systems have been introduced in different NDT departments in casting and automotive industry as well as in research institutes and for materials development. Most units are stationary and require transferring and adjusting the test object into the CT device. A flexible CT system was developed for in situ inspection of
large aircraft components under production conditions. Flat fibre composite structures of aircrafts of up to 3 x 9 m size were inspected. Imbedded stringer structures in carbon fibre reinforces plastic (CFRP) panels have to be manufactured stress free to avoid stress cracking. A gate based planar tomograph was developed and tested for inspection of integrity of the stringer incorporation. Successful test trials were performed to prove finding parameters and results for cracks in the imbedded stringers.

Honeycomb structures of aircrafts have to be inspected for water inclusions during in-service inspections. Thermography is a powerful method for in house inspections as long as heat alterations caused e.g. by sunshine can be excluded. A further prerequisite is a direct contact of the honeycomb structure to the surface. A new X-ray diaphragm has been developed for mobile back scatter measurements of large components. This method is independent from in field heat conditions and can be applied independently of environmental temperature alterations. Water inclusions could be detected as proven by classical radiography. New developments of back scatter units with large area detectors and flying spot exposure for security applications enable fast back scatter imaging of large areas. Diaphragm based and flying spot techniques are compared.

2 Mobile Radiography with Flash Tubes and Digital Detectors

2.1 Technology available

Portable X-ray flash generators have been introduced originally for veterinarian use to examine e.g. sprained ankles in big animals on site. The standard imaging device was a Polaroid film that could be developed immediately on the spot without any darkroom. Soon af-
ter, security enforcing operators responsible for rendering safe procedures found this kind of equipment essentially useful to inspect suspected objects which could be e.g. improvised explosive devices (IEDs). Nowadays, inspecting putative IEDs is the predominant application of X-ray flash generators. They come usually with maximum energies of 150 kV (see Fig. 1) and 270-300 kV. All commercially available generators have their predefined energy that cannot be adjusted.

The Polaroid film previously used by veterinarians and rendering safe operators has been replaced by digital technologies today. In general, two types of devices can be applied in combination with X-ray flash generators, digital detector arrays (DDA) and phosphor imaging plates (IP, see Fig. 1). Both systems require accessory equipment, which is also available in mobile versions, in some cases even portable. DDAs require a control unit which is linked to the detector either by wire or by wireless data transmission. IPs consist of a flexible plate with an X-ray sensitive layer that can be handled very much like a film, i.e. placed in a cassette and brought to the exposure site. Afterwards it will be read by a specially designed reader unit linked to a computer, compiling a digital image from the reading results (“computed radiography”). In difference to the classical film, IPs do not need any wet developing procedure, but are simply scanned by the plate reader unit and are reusable after erasure of the previous image. Erasing is simply completed by exposing the plate to visible light. For more details about the IP technology see [1]. Nowadays, nearly any accessory device can be operated by means of a portable computer (laptop).

2.2 Applications on Light Structures

The 150 kV X-ray flash generator (XR 200) was applied for inspecting a test specimen, a former flap of an aircraft with several inclusions invisible from outside (see Fig. 2). It consisted of a 7 to 9 cm thick polymer foam layer between aluminium plates of 6 mm and 6.5 mm thickness, respectively, and containing test inclusions. Both image detectors were
used, the digital detector array (DDA, see above) and the phosphor imaging plate (IP, see above) in larger formats (35 cm x 43 cm) to cover a larger area. The sensitive area of the DDA was comparable in size with the IP. Due to the limited beam cone of the generator, a focus – detector distance of 1 m was necessary to ensure a workable illumination of the detector area. This was partly compensated by emitting two series of 99 X-ray flashes each (the usual distance is about 60 cm where up to 99 flashes are sufficient with an exposure time of less than 10 seconds).

The radiographic images, taken both with the DDA and with the IP technology, did not differ virtually and were of comparable quality; therefore only one of the results is shown here in Fig. 3. They equally unravel several details from the interior of the test specimen: a stinger, cables, tubes and honeycomb structures partly filled with a material. Also the image quality indicators (IQI) attached on the surface can be located: the cross mark for position (on the left at the pipe wall above the cables) and the wire type IQIs. All the wires of the 6 Al EN IQI were visible at least on the filtered image. Due to the cone beam characteristics of the X-ray flash generator the radiographs were affected with significant shading that was compensated by high pass filtering.

![Fig. 3: Radiographic image obtained by the DDA, original image (left) and after digital filtering (right)](image)

3. Planar Computed Tomography for Inspection of Large Flat Composite Structures

3.1 TomoCAR

One of the key tasks of NDT and especially of in-service inspection (e.g. welds) is the detection of planar defects and its sizing. The depth, length and kind of the indications are essential features for the decision about acceptance or rejection. For this purpose, the new system for mechanised Tomographic Computer Aided Radiometry (TomoCAR) [2-3], was developed and qualified according the ENIQ (European Network of Inspection and Qualification) standard during the last years [4]. This system was designed to scan the test sample (e.g. girth seams of pipelines) using a digital detector (e.g. line camera, flat panel detector) and an X-ray tube in a numerically controlled geometry.

The recent TomoCAR design [3, 4] was modified for inspection of large planar CFRP panels (see Fig. 4). An X-ray tube and a digital detector array were mounted on a mechanical manipulation system, so that a region of interest was scanned by the movement...
of the X-ray tube running parallel to the surface of a digital detector array. The scan resulted in a 3-dimensional (3-D) radiometric digital image after numeric reconstruction. In general, the functional principle corresponds to that of digital coplanar translational laminography also known as planar tomography. The image evaluation of the inspected area of interest requires a 3-D digital image processing.

All planar defects (like cracks, insufficient glued surfaces, lack of fusion) are detected with maximum contrast, if they are oriented within the observation angle. This observation angle depends on the distance of X-ray tube to the detector and the length of X-ray tube movement (Fig. 4). The larger the length of movement (scan length) and the smaller the detector tube distance, the larger the observation angle will be and the better the quality of the reconstructed 3-D images. The continuous change of radiation angles during a scan increases the probability of detection of planar defects and reduces the false detection rate. Furthermore, this multi-angle technique provides sufficient information for a 3D-reconstruction of the structure to be tested.

![Fig. 4: Principle of Tomographic Computer Aided Radiometry (TomoCAR) for large and flat samples.](image)

The developed planar TomoCAR technique was based on a continuously shift of an X-ray tube parallel to the sample in a radiation angle range of about ±45° to the detector normal. During the movement of the X-ray tube usually more than 400 two dimensional projections were acquired. Each single scan represented a defined angle of incidence of the X-ray beam in relation to the detector and sample. The detector was not shifted during the scan of the x-ray tube.

The reconstruction technique used here, was based on a modified filtered back projection. The reconstructed data set from these projections represented a cross section of the sample as a three dimensional image in which the indications could be evaluated in relation to their shape and depth (Fig. 6). This technique, as a typical analysis method, was applied for quantitative evaluation of the different indications and structures, including depth. With the classical radiography, depth is not accessible.

### 3.2 Moving Gantry Bridge Construction for Flexible Planar TomoCAR

According to the principle in Fig. 4 a moving gantry bridge was constructed and mounted for the tomographical testing of a spherical CFRP panel of a vertical tail plane. The gantry bridge carries the X-ray equipment, the digital detector array (DDA) and the digitally controlled linear axis for the positioning and the movement of the X-ray tube.
The test sample was a spherical panel of a vertical tail plane. The size of the sample amounted to 9 m x 3 m. At both ends of the sample, 87 positions were defined and measured. The total length of all measured areas amounted to about 14 m. All technical parameters are summarised in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray energy</td>
<td>maximal 73 kV</td>
</tr>
<tr>
<td>X-Ray current</td>
<td>maximal at 640 W</td>
</tr>
<tr>
<td>Source detector distance</td>
<td>400 mm</td>
</tr>
<tr>
<td>Focal spot size</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Exposure time for single projection</td>
<td>1 sec.</td>
</tr>
<tr>
<td>complete data set</td>
<td>11.7 min.</td>
</tr>
<tr>
<td>reconstructed voxel size</td>
<td>0.1 x 0.2, x 0.2 mm</td>
</tr>
<tr>
<td>total number of voxels</td>
<td>750 x 900 x 900</td>
</tr>
<tr>
<td>total reconstruction time</td>
<td>8 min.</td>
</tr>
</tbody>
</table>

Tab. 1: Parameters of the measurement and reconstruction

The reconstruction was executed on a multi-processor computer with 8 kernels and fast RAM-memory. The software was adapted for parallel processing of pre-processing of measured data and of the 3-D image reconstruction. The total reconstruction time amounted to approximately 8 minutes per measured tomogram. The X-ray tube was a modified 225 kV (MXR-225/21FB) of Comet with reduced target angle and an extended tube window of ±45° perpendicular to the tube axis. The DDA was a Perkin Elmer XRD 0820C N15 with a carbon fibre window of 0.75 mm and 200µm pixel size.

Fig. 5: Moving Gantry Bridge.

a) The detector and the X-Ray tube were positioned on the left and right side of the sample. The X-Ray tube was moved on the linear axis, which was oriented perpendicular to the stringer.

b) The spherical shell of the vertical tail was located between the X-ray tube and the detector. The size of the panel amounted to 9 m x 3 m. The gantry bridge could be moved parallel to the sample.
3.3 Inspection of Embedded Stringers in Carbon Fibre Composite Shells

Fig. 6 shows the result of two planar reconstructions and fig. 6A a 30% embedded stringer. The black/white lines mark the geometrical shape of the T-stringer and the embedding CFRP environment up to its surface. The white stringer part was outside the CFRP panel and the grey one inside, that means embedded. The two black lines show the adhesive connection of the stringer to the CFRP panel. Horizontal adhesive connections were not highly resolved as indicated with the method applied. The stringer foot was visible as a “roughness” indicating a horizontal line with white end points. For qualification of the TomoCAR method, several embedded stringer components were manufactured with high stress. These test samples showed stress cracking which had to be found. Fig. 6B shows such a cracked embedded stringer (60% embedded). The crack shape and length could clearly be seen and the dimension and shape could be measured. The qualification of the TomoCAR technique was successfully performed by destructive cross sectioning.

Fig. 7: Embedded stringers in carbon fibre composites shells. In the middle of the sample is visible the impact

The TomoCAR was also utilised for the inspection of impact damages of aircraft components. A test sample was cut and exposed to an impact hammer for damaging the surface with defined energy. The sample was obtained of FhG, IZfP, Dresden. The TomoCAR was tested for determination of impact damages as function of depth. The sample consisted of a cover plate of 1 mm with brass mesh reinforcement. The core structure was manufactured of carbon reinforced foam of 27 mm thickness and the second (lower) surface (opposite to the impact) consisted of a fibre reinforced polymer plate of 3 mm (see Fig. 7). Fig. 8 shows the radiographic cross sections in three layers after impact: upper plate with mesh, reinforced foam (centre of test object) and lower plate. The impact could be clearly seen in the metal mesh area. The advantage of the TomoCAR design was the ability to inspect also in-service damages in field.

4. X-Ray Back Scatter Inspection of Honey Comb Structures

4.1 Back Scatter Imaging with Flying Spot Technique

The Flying Spot technology has been mentioned already in the seventies [6] and has
been patented in the eighties [7]. The very principle is to scan an object with an X-ray pencil beam and to determine the scattered radiation either in direction of the beam but outside the primary beam direction or on the same side of the specimen in large area detectors adjacent to the source. Particularly the latter regime has been found to be useful in scanning for objects hidden behind thin material layers such as cloth. Rather soon this approach has been found suitable for security purposes and even to scan persons without concern about the radiation dose which is rather low due to the nature of the pencil beam [8].

A scanner of this type is currently installed in a few airports and is offered to being scanned alternative to a strip search in cases of suspected contraband or clandestine weapons. In larger setups, even vehicles can be scanned for hidden objects [9].

4.2 Diaphragm Based Back Scatter Technique

The diaphragm based technology follows the pinhole camera principle with the difference that a pinhole does not exist for high energy radiation that penetrates the shielding material itself. Penetration of radiation only can be prevented by sufficiently thick walls. A hole in such a wall forms a collimator rather than suiting a pinhole camera setup. This problem is solved by a diaphragm consisting of a twisted slit instead of a plain hole [10]. Since this is an emerging technology, it is currently only available in an experimental setup. The diaphragm is inserted into a cabinet of lead bricks that can house various types of image detectors (see Fig. 9, 10).

In this case, an IP was used of the same size as for the radiographic image (s. a.), but the whole setup could be designed definitely smaller depending of the size of available detectors. In this experiment, the specimen was irradiated with 350 kV in a 1 m distance for half an hour. The exposure time might be significantly reduced by smaller setups of the camera with the diaphragm and bringing the X-ray tube closer to the sample.
The resulting images, corrected for the distortions due to the internal structure of the diaphragm, high pass filtered and smoothed with automatic noise determination, are shown in Fig. 11. Several details unravelled previously by direct radiography (s. a.) could be also recovered in these back scatter images, the pipes and part of the wires, the stringer and all filled parts of the included honeycomb structures.

As referred to thermography it should be noted that the honeycomb structures inserted here did not necessarily have a contact with the surface layer. Also, the plasticine used for attaching the lead cross mark (visible as white rectangle in Fig. 11, left) had pronounced backscattering properties. In addition, the metallic label of the 6 Al EN IQ1 on the right side appeared as dark spots indicating an absorption of the backscatter radiation from the inside of the object. Furthermore, the hole visible from the outside reappeared in the backscatter image while it was covered by the inside walls in the direct radiograph due to the bevelled incident angle of the radiation (see Figures 3 and 11). Further details could be detected when carefully comparing this backscatter image with the radiograph (Fig. 3).

Fig. 10: Experimental setup for backscatter radiography by the diaphragm based technology together with the X-ray tube and the test specimen. The diaphragm itself is incorporated into the wall of the lead brick cabinet (open lid in this photo) facing the specimen. The cassette with the IP is placed inside the cabinet which will be closed by lead plates for exposure. Source and detector are situated on the same side of the specimen.

The resulting images, achieved by the diaphragm based technology. Due to the currently limited coverage two separate images had been taken of adjacent areas corresponding to the penetrating inspection shown above (see Figure 3). Images processed by high pass filtering and automatically adapting noise suppression.

Fig. 11: Backscatter images achieved by the diaphragm based technology. Due to the currently limited coverage two separate images had been taken of adjacent areas corresponding to the penetrating inspection shown above (see Figure 3). Images processed by high pass filtering and automatically adapting noise suppression.
A honey comb test sample was used for testing of the detectability of water inclusions. Fig 12a shows the test sample, made from CFRP. Three holes were drilled and water was injected with a small syringe. Fig 12b shows the back scatter image with high contrast of the water inclusions. The honey comb structure was not visible due to the geometric unsharpness conditions. A conventional radiograph was taken with a DDA (DIC 100T of Ajat [5]) proving the exact water distribution in the honey comb cells (Fig. 12c). In two cases two cells were filled due to leaky connecting membranes.

4.3 Comparison between the Flying Spot and the diaphragm based technologies

The first obvious difference between the two technologies is that the Flying Spot one is well establishes since decades and already refined for various application purposes while the diaphragm based one is currently emerging [10]. Technically, the two approaches of radiographic inspection with single sided access differ in their radiation geometry and the compilation of an image. The first one thoroughly is a scanning procedure while the second one mimics the function of an optical camera together with an illuminated object. Basically, the camera does not have any moving components; the exposure currently is simply started and completed either by placing and removing an IP or by exposing a digital detector array, or ultimately by switching on and off the source. In other words, the camera is mechanically the simplest imaginable device as compared to the finely adjusted Flying Spot equipment. This could favour a further development towards future mobile diaphragm applications. However, the radiation loads are significantly different, so that the diaphragm based technology is not expected to be applied on humans (e.g. security applications). In case of non-destructive material testing, this difference does not matter really as long features can be detected by backscatter rather than with any other technology. As mentioned before, the diaphragm is a new approach that still needs further development towards technical application.
5. Summary

Low dose and low priced battery powered X-ray flash tubes can be applied successfully with imaging plates and DDAs as a film replacement. Images of sufficient quality were obtained from light alloys, plastics and composites. They potentially allow the inspection with high mobility. Due to the low exposure dose an inspection can be performed within a comparably small controlled area. Different NDT teams can work side by side without the typical interferences.

The basic design and working principle of the mobile CT system “TomoCAR” [3,4] was modified for the construction of a gantry bridge based planar CT system for inspection of large area CFRP panels of aircrafts. An X-ray tube, mounted on a linear manipulator, was positioned opposite to a DDA. Several hundred projections were taken during a single movement of the X-ray tube parallel to the detector surface, whereby the structure to inspect was located between detector and X-ray tube. Cracked stringer shafts could be distinguished from properly manufactured ones in the reconstructed CT images. 87 positions of a stringer reinforced CFRP panel of 3 m x 9 m were inspected by the developed TomoCAR based CT system. No cracks were found in the properly manufactured panels. Special panels were manufactured under stress for qualification of the system. Stress induced cracks were found and measured. Their dimensions were confirmed by destructive cross sectioning. The TomoCAR system was successfully applied for the inspection of impact samples. Principally, TomoCAR inspection can be performed for separate samples as well as for complete aircrafts or helicopters in service.

A special diaphragm was developed for back scatter imaging of aircrafts and aircraft components tolerating higher energies. High energy back scatter radiography (up to 400 keV) enabled the inspection with a better depth penetration as well as that of larger areas at a glance. This technology could be used together with highly sensitive imaging plates to reduce the exposure time. NDT-film based applications typically need high and uneconomical exposure times. Aluminium and foam based sandwich structures were inspected successfully. Even more, water inclusions were clearly detected in honey comb structures. The images proved suitable for inspection of internal structures with single sided access only. Pipes and structures were doubtlessly identified in light materials test objects.

6 References