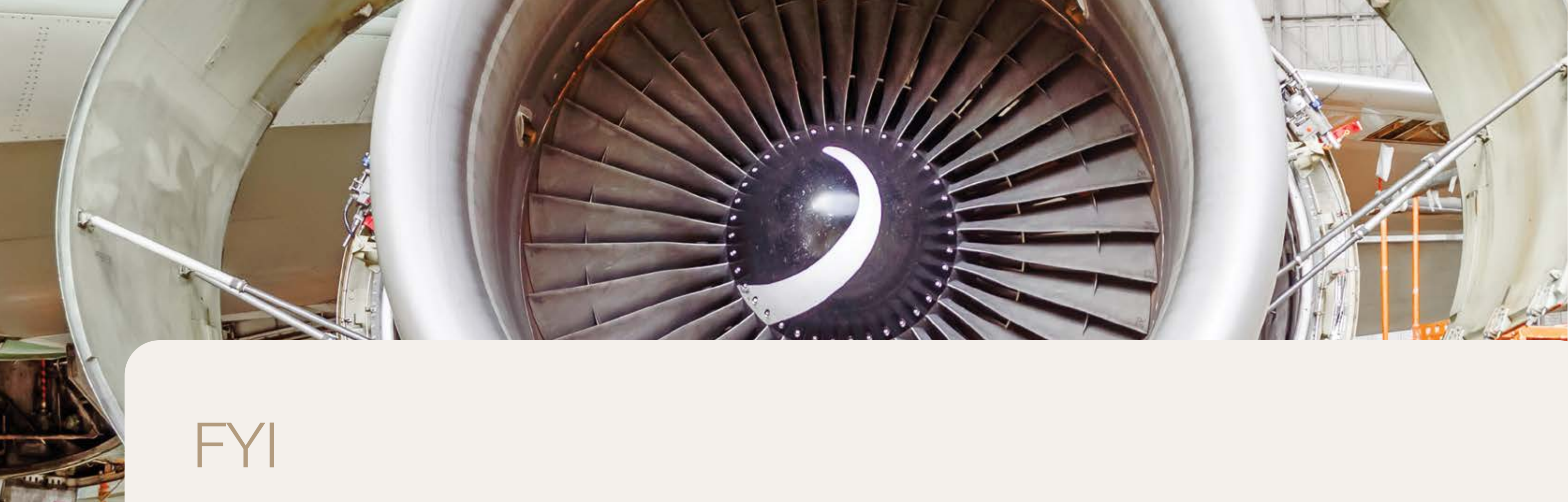

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An Overview of Digital Radiography for the Aerospace Sector

by Lennart Schulenburg

Radiographic testing (RT) is a widely adapted nondestructive testing (NDT) method used for quality control of industrial products in many sectors. Safety-relevant parts in the aerospace sector, in particular, are subject to comprehensive tests. This article will focus on the aerospace sector and its special requirements for the implementation of digital radiography (DR) systems.

The growing aerospace market needs fast, process-reliable testing solutions to ensure product quality, whether for the inspection of parts coming from legacy production techniques or new production methods like additive manufacturing. Many companies are therefore switching from film to digital X-ray imaging because it requires shorter exposure times, eliminates harmful chemistry, simplifies evaluation procedures, and increases the potential for automation. A broad and sometimes confusing palette of international, industry, and company-specific quality standards and requirements must be closely followed to pass the demanding audits stipulated by Nadcap and original equipment manufacturers. Additional challenges present themselves due to the constant technology evolution in DR equipment and software. The quality and variety of digital detector arrays (DDAs) is increasing at a faster pace than ever, allowing their usage in more and more applications. Figure 1 shows an operator inspecting a turbine blade using DR.

At the same time as quality requirements increase, companies must achieve a high cost efficiency to remain competitive in a globalized world. In many cases, the only solution to this dilemma is digitizing and streamlining the inspection process through film replacement and several forms of automation. Therefore, companies and NDT managers all around the world are analyzing available solutions, which often pose a long-term capital investment.

When implementing digital systems, it is important to realize that this effort requires procedures and techniques to be rewritten, adapted, and of course qualified again. It is seldom possible to simply transfer the film techniques because with digital X-ray technology, variables like magnification, exposure times, and even X-ray energies can be optimized beyond what was possible before. Digital systems also require some additional work like regular performance evaluations. This article will introduce the main performance metrics and explain the underlying procedures. The performance values of a DR system are described by the spatial resolution, contrast, signal-to-noise ratio (SNR), and other parameters. One major takeaway from this article is that it is a good strategy for organizations to not just migrate film techniques to DR, but to optimize the procedures so that a better inspection quality can be achieved in less time. This is the only way to unlock the full potential of modern DR systems.

Basic Spatial Resolution (SR_b)

Image resolution is one of the most important values for the performance evaluation of an X-ray system. Simplified, it can be said that the spatial resolution describes what level of detail can be resolved in an X-ray image. This metric is comprised of two main factors. The first one is the image unsharpness (consisting of pixel pitch and scintillator resolution). The second one is geometric unsharpness. The latter is dependent on the focal spot size of the X-ray tube and the geometric magnification being used. The geometric magnification is the quotient of the focus detector distance (FDD) and the focus object distance (FOD). Typical minifocus systems (0.4 mm focal spot) operate in the 1 to 2× magnification range, while microfocus systems can operate at a much higher magnification. For minifocus X-ray, geometric magnification,

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Figure 1. Digital inspection of a turbine blade.

which increases detail perceptibility, has to be balanced with geometric unsharpness. Due to the cone beam nature of industrial X-ray tubes, a higher magnification literally magnifies the object and increases the detail perceptibility. If an operator magnifies beyond a certain point for a certain focal spot, the geometric unsharpness causes fuzzy edges (similar to when you move your hand too close to a light projector). This is the point when the geometric unsharpness exceeds the image unsharpness and, therefore, further magnification results in worse resolution.

The electronic photo diodes of the digital detectors (DDA, matrix detector, or flat panel detector) determine the pixel pitch and thereby the image unsharpness. Modern detectors have pixel sizes between 25 and 200 µm. The thickness and type of the so-called scintillators (the X-ray excitable light-emitting top layer on the detector) also determine the resolution of flat panel detectors. Thicker scintillators have a better X-ray photon conversion efficiency and there is more light generated within the luminescent layer. Thinner scintillators typically provide sharper images. It is therefore very important to choose the right scintillator for each detector and application. There are two prevailing scintillator materials, Gadox (gadolinium oxysulfide) and CsI (caesium iodide). As a rule of thumb, it can be said that Gadox has approximately 120 to 150 µm resolution and CsI approximately 80 to 100 µm. Then, there are many special scintillators with values in between that can be chosen depending on the application. Most detectors operate on the amorphous silicon technology, but there are also options with TFT (thin film transistor), CMOS (complementary metal oxide semiconductor), and IGZO (indium gallium zinc oxide) sensors. Due to the high variety of options, it is advisable to obtain a recommendation by a DR solution provider based on your inspection requirements.

The spatial resolution is typically measured using a double-wire image quality indicator (IQI), a test specimen with smaller and smaller wire pairs where the diameter of the wire is the same as the gaps between the wires. The ability to distinguish between them is measured using a line profile of image gray values; if you cannot distinguish the wires anymore, you have reached the resolution threshold of the system. The task is to find the first wire pair where the modulation of the histogram between two wires is less than 20%, as can be seen in Figure 2. The associated resolution can be read from a table that is found inside the ASTM standard (ASTM 2015), but modern software is able to locate the IQI and calculate the resolution automatically by using the diameter of the smallest pair with >20% modulation of the line-profile signal and diameter of the largest wire pair with <20% modulation of the line-profile signal.

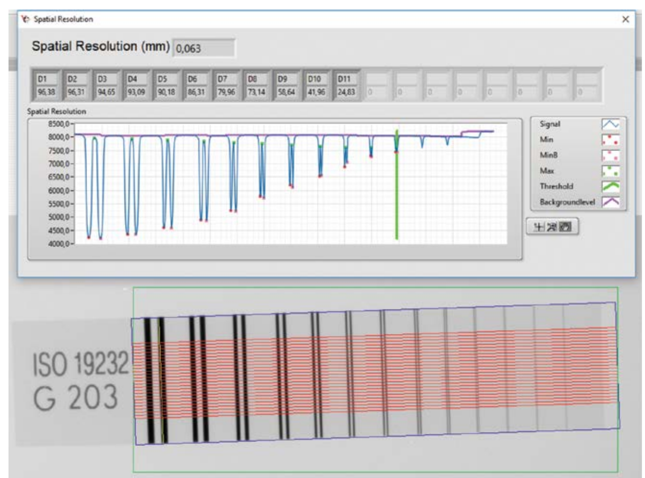

Figure 2. Spatial resolution measurement with double-wire IQI.

Contrast-to-Noise Ratio (CNR)

The contrast of a radiograph is by far the most important image quality metric. While the spatial resolution determines the resolution in the X-Y plane of the image, the contrast determines the amount of depth information (very simplified!) of a single pixel in the digital radiograph. Effectively, *contrast* refers to the difference in intensity (or gray values) between neighboring areas or pixels of an image. Contrast sensitivity can be defined as the smallest difference in intensity that can be resolved between a defect (void) and its immediate surrounding and relates to the percentage of material thickness change that can be resolved. This is so crucial, as X-ray is a penetration technology and information about the internal structures of the inspected object is "summed up" along the X-ray beam traveling through the object. The existence of two different resolutions (special and contrast) is also a common source of confusion around the DR technology.

The contrast in X-ray images can be determined by using either a single-wire IQI or hole-type IQI. In aerospace environments, hole-type plaques according to ASTM E1742 and E1025 (ASTM 2018a, 2018b) have mainly prevailed. These specimens have a defined thickness and three holes, wherein most cases the diameter of holes corresponds to the single (1T), double (2T), and quadruple (4T) of the IQI's thickness. The appropriate IQI is selected depending on the thickness of the inspected part and material. In the example shown in Figure 3, a 4T hole is selected for the evaluation of the contrast-to-noise ratio (CNR), so therefore the mean value of the ROI (region of interest) adjacent to the 4T hole on the IQI is subtracted from the mean value of the ROI inside the 4T hole, and then this value is divided by the standard deviation of the ROI adjacent to the 4T hole.

To fulfill most aerospace standards, the resulting value must be at least 2.5 to 1 or above to obtain a sufficiently contrasting image. It is advisable to have at least a 20% buffer beyond that value. The contrast sensitivity (CS) can be additionally calculated from the CNR value using the procedure described in ASTM E2597 (ASTM 2014).

When we talk about contrast, it is also important to look closely at the detector. First, most detectors have a CS of 1% to 2%. This means that the maximum contrast difference that can be resolved is between 1% and 2% of the total material thickness. This clearly shows the difference between contrast resolution and spatial resolution and might lead to situations where the spatial resolution is sufficient to resolve a defect, but not enough contrast can be achieved. And vice versa—there are situations where an excellent CNR can compensate for less spatial resolution. In any case, the scintillator plays an important role for contrast. Typically, it can be said that thicker and lower resolution scintillators (like Gadox) have a better conversion efficiency and contrast. This is a balance that must be carefully managed.

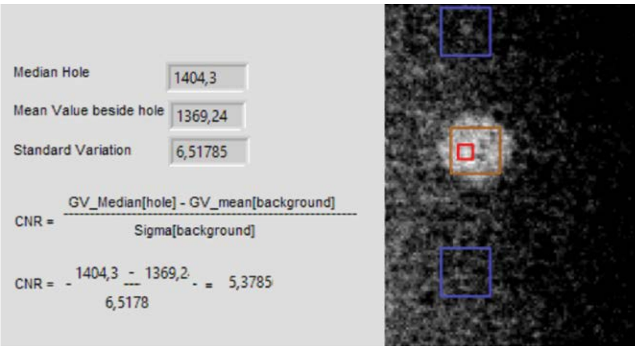

Figure 3. Contrast-to-noise ratio (CNR) measurement in the 4T hole.

Signal-to-Noise Ratio (SNR)

The SNR describes the relationship between the measured signal and the baseline noise. The SNR should be increased to "lift" the desired signal out of the image noise. In extreme cases, if the SNR is too low the desired signal caused by the modulation of object features cannot be kept apart from the background noise, which results in a loss of those features on the radiographs. A very common issue is that the modulation caused by small discontinuities is below the noise baseline. Those discontinuities will not be visible to the inspector, even though the spatial resolution is sufficient to capture them. Image noise is typically caused by several sources: X-ray photon noise (the random manner in which the photons are distributed within the image), scatter radiation from the object or manipulator, and artifacts caused by the metallographic structure of the object. It can also come from more trivial sources like the surface roughness of the part introducing some kind of noise.

The SNR is calculated from the mean gray value divided by the standard deviation in a homogenous, defined range. Many standards require the SNR to be normalized with the spatial resolution of the image to achieve the normalized SNR, also called SNR_N. Higher SNR values allow greater visibility of the image features, and the images are visibly smoother. The most common ways to improve SNR are to increase image integration time (frame averaging), reduce scatter radiation, and utilize beam collimation. As the very important CNR measurement is denominated by the SNR, it is crucial to optimize the SNR as much as possible to obtain better CNR values. As a rule of thumb, it can be said that detectors with a smaller pixel size and higher resolution have a higher noise level than detectors with larger pixels.

Performance Evaluation

To ensure reliable inspection results and a repeatable baseline system performance, it is essential that the performance levels achieved after installation of a new system are documented and closely evaluated over time. This must be checked daily (or even before each shift) and must be carefully documented as required by industry standards like Nadcap. For this reason, a best practice is to work with so-called test phantoms. There are several types of phantoms:

- Duplex plate phantom according to ASTM E2737 (ASTM 2018c): This is a two-stage phantom. One plate corresponds to the thinnest part thickness, and the other plate corresponds to the thickest part thickness to be tested. On its surface there is a double-wire IQI and two ASTM hole-type test plaques according to the thickness of the plates. The test parameters (kV/mA, focal spot size, pre-filtering, geometric magnification, detector mode, number of image integrations, and exposure time) should be the same as those used later during the actual inspection process. This phantom can be made individually according to the specific inspection needs (size, thickness, and material). An example of such a phantom can be seen in Figure 4.
- Five-groove wedge according to ASTM E2737 (ASTM 2018c): This is a standardized specimen. There are two versions: heavy metal or light metal. Using the milled grooves, it is possible to determine the different thicknesses, the resolution, and the CS. Even though it is carefully described in the standard, it is not as commonly used as the duplex plate phantoms.
- TAM phantom: This is a special-made phantom that covers the testing of titanium and Inconel parts up to 0.25 in. (6.35 mm). To achieve this, the phantom has two step wedges with thicknesses of 0.05 to 0.25 in. (1.27 to 6.35 mm); the respective test specimens are in accordance with TAM ASTM E1742 (ASTM 2014). The resolution is determined by two double-wire IQIs in a 90° orientation. It is required to use two IQIs (one positioned horizontally and one vertically), as many X-ray tubes have an asymmetric focal spot and therefore the spatial resolution of X-ray images differs. In the center is a BAM snail (an IQI in the form of a snail that helps to position objects in the central beam) that is used for proper placement of the phantom inside the central beam.

Figure 4. Image quality evaluation toolbox with duplex plate phantom.

By using CNC-controlled digital X-ray systems, these daily image quality tests can be completely automated, while modern software solutions are taking care of the image performance evaluations. Values such as SR_b, CNR, SNR_N, CS, SR (spatial resolution), and SL (signal level) can be evaluated and saved as a fully automated report. This phantom is not yet commonly used, but highly recommended.

Another complication is that detectors are electrical devices with deviations and therefore must be standardized regularly. Each digital detector must have a dark image (offset) calibration and white image (gain) calibration. In addition, there can be so-called bad pixels on the detector. A classification of bad pixels is given in ASTM E2597, and there is also a standardized procedure to identify and classify them. Bad pixels are not a problem per se, although depending on the application an accumulation of bad pixels can lead to the detector having to be replaced. This is the case if a pixel has more than five underperforming neighboring pixels and is called a cluster kernel pixel. In that case, a correction using the neighboring pixels is not allowed anymore, and the detector (or at least that section of the detector) shall no longer be used for aerospace-grade inspections. With modern-day detectors these cases happen rarely. Most modern interpretation software also offers simple tools with the ASTM E2597 dead pixel detection tool to detect and classify bad pixels and to generate a report with one click.

DICONDE

The storage of digital images is based on a standard that was originally developed for the medical world, DICOM. By saving DICOM (or for the NDT industry, DICONDE) images as a .dmc file, we can store not only the compressed or uncompressed X-ray image but also process the metadata. These files can later be displayed again with a DICOM/DICONDE compatible image viewer. This can be done directly over the file system or network on locations spread all over the world. In other words, DICOM defines not only a file storage format—it also defines the protocols and the whole framework to exchange data between image sources, storage, and communication servers. This way companies can eliminate film archives that consume large amounts of space and energy and ensure their equipment fulfills modern interoperability requirements. Nadcap and other standards require the usage of DICONDE, and the company's responsible Level III has to ensure that the storage and network system they use is DICONDE capable. Contemporary digital X-ray interpretation software should be fully compliant to read and write DICONDE files.

Figure 5. Automation using robotics.

Outlook and Summary

DR has developed into a mature RT technique that is already widely adapted throughout several industries. With growing volume and cost pressure, the aerospace industry is transitioning more and more applications from film to digital. This shift is also the enabler for automation, robotics, computed tomography, and automated defect recognition. Figure 5 shows an example robot system that allows high-volume inspection with very short cycle times.

The implementation of a DR system is not trivial as it requires reworked techniques and processes. Also, the effort in employee certification (NAS 410 nonfilm) and qualification (Nadcap) is not to be underestimated. But typically, companies see a return on those investments very quickly. It is highly suggested to reach out to a reputable solution provider early in the process. It is crucial to also look at the economic aspects of automation (Schulenburg 2021).

This article should give NDT technicians an overview about the most important factors that have to be considered when implementing a DR system in an aerospace environment. Obviously, it only scratches the surface of this complex technology, and there is much more to consider during the implementation phase.

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