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TOWARD COMPREHENSIVE INDUSTRIAL CT IMAGE QUALITY ASSESSMENT: I. PHANTOM DESIGN

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ABSTRACT

When comparing the performance of different industrial X-ray CT systems, reconstruction algorithms, or scan protocols, it is important to assess how well the required inspection and measurement tasks can be performed. Furthermore, it can be very informative to quantify image quality (IQ) metrics that can provide insight into the IQ characteristics that lead to the resulting inspection or measurement task performance.

Inspection and measurement task performance is determined by basic characteristics such as spatial resolution; feature contrast, size, and shape; random noise; and image artifacts. In this report, we describe a modular phantom set that enables robustly quantifying these characteristics and also enables assessing the performance of the inspection or measurement tasks themselves. The phantom set includes two phantom bodies and several insert types that can optionally be installed in the bodies. Phantom body extensions can optionally be included to increase scatter. The phantom bodies combined with the available insert types can comprehensively evaluate all important IQ metrics and measurement tasks. The precisely-known phantom body geometry and insert location, geometry, and orientation supports automatic analysis of large, complex experiments of multiple variables. This phantom set, with associated image analysis software, could potentially serve as a general evaluation method for NDT CT.

Keywords: modular phantom, insert, image quality, inspection and measurement, industrial X-ray CT

1. INTRODUCTION

X-ray CT systems are one of the essential tools in industry for inspection and measurement of industrial parts. Performance of these measurement tasks ultimately depends on the scanner hardware, scan protocol, and reconstruction algorithm, as well as the scanned object and its features of interest. When developing and evaluating scanner hardware, scan protocols, or reconstruction algorithms, it is difficult to evaluate the performance of each specific task over a wide range of part geometries for each combination of the many variables. The problem becomes more tractable with a phantom that represents a "typical" part for the intended application, especially if the phantom enables automated image analysis. With this in mind, we developed a methodology, including a modular phantom set and associated image analysis software, to produce rigorous, repeatable, quantitative measurements of basic CT image quality (IQ) characteristics and to assess the ability to perform measurement tasks and defect detection. By assessing both basic IQ characteristics and measurement tasks, we can understand the factors that affect the system's ability to perform these tasks.

Image quality characteristics that affect inspection or measurement task performance include spatial resolution, contrast, random noise, and artifacts. Well-designed phantoms can be useful tools to access the basic IQ characteristics to predict how well the tasks can be performed. In an ASTM standard, a simple uniform disk is suggested to access the modulation transfer function (MTF) and contrast discrimination function (CDF) [1]. It can evaluate MTF and CDF in the transaxial direction ("in-plane"; "slice"). However, the system might have different spatial resolution in different directions (for example, transaxial or longitudinal, and radial or azimuthal within a slice). The proposed phantom enables evaluation of MTF in all directions. Image resolution can also be object dependent when using iterative reconstruction (IR) algorithms. For example, the resolution might be different for small and large feature sizes within iteratively reconstructed images. Although the "limiting" spatial resolution is independent of image contrast and noise, the ability to precisely measure spatial resolution can be limited by contrast and, especially, noise. Our phantom bodies provide for inserts of 0.5" (12.7 mm) diameter and 1.0" (25.4 mm) long. This enables use of stock rod material to produce versatile inserts: cylinders with different materials (to provide contrast of interest), inserts with wires, pores, balls, etc. to fully access the image resolution. Spatial resolution is also location dependent for most modern CT systems; the proposed phantom can provide spatial resolution measurement at different locations. The phantom body can be any shape; our designs include an annular phantom body to represent parts with an aspect ratio of approximately unity. Image noise is usually calculated as the standard deviation in a uniform region of the scanned part. However, in industrial CT images where the image could suffer severely from beam-hardening and scatter artifacts, the measurement of statistical noise cannot be simple standard deviation calculation in a uniform region because artifacts also contribute to the variations of the image. The proposed phantom concept is longitudinally uniform; therefore, the fixed pattern from artifacts can be averaged, suppressing statistical noise. Therefore, an artifact “score”, independent of statistical noise, can be obtained from the averaged image. The average image can then be subtracted from each slice, leaving only statistical noise in multiple slices. Artifacts are significantly affected by scatter and beam hardening, which are prominent in industrial CT images, especially for large parts. However, it is difficult to distinguish between artifacts that are due to beam hardening and those due to scatter. The proposed phantom concept can include extensions to assess dependency of artifacts on scatter. Realistic aviation parts, such as airfoils, can also suffer from significant streak and shading artifacts even after scatter and beam-hardening artifact reduction[2]. Therefore, we also designed a versatile airfoil phantom body.

Inserts were designed to comprehensively evaluate all important IQ characteristics. We also designed inserts with known features that we can perform inspection and measurement tasks on. Note that the possible insert designs are not limited to those presented in this paper.

In summary, the proposed phantom design allows for comprehensive evaluation of imaging systems in terms of resolution, noise, artifacts, and different object features. The proposed design is discussed in more detail below.

2. Phantom Design

The proposed modular phantom design includes representative phantom bodies and removable inserts for assessment of IQ and inspection and measurement tasks.

2.1 Phantom Body Design

The phantom body can be any shape. Our designs include phantom bodies with symmetric and asymmetric cross sections. An annular phantom body, shown in Figure 1, is designed that represent symmetric phantom bodies. It has 4-inch outside diameter (OD), 2-inch inside diameter (ID) and includes twelve ½-inch-diameter holes for inserts. The size of the phantom body represents a medium part size in NDT applications. We also designed an airfoil-shaped phantom body that represents a specific part of interest in NDT applications, shown in Figure 2. It is approximately 2.5 inches x 6 inches in cross-section, which represents a medium-sized airfoil. It includes 6 internal gussets. There are twelve ½-inch-diameter holes distributed at 12 external-wall and internal-gusset locations and three extra ½-inch-diameter holes inside the body. Its asymmetric shape can produce cupping, shading and streak artifacts. Both phantom bodies allow assessment of IQ metrics and detection or measurement tasks by using certain inserts. We will talk about different families of inserts in the following subsection. The 1/2-inch-diameter insert can be scanned with micro-CT to obtain high-resolution images of features inside the insert. Each insert is precisely located in position and angular orientation within the phantom body using covers (shown in Figure 1 on the right and Figure 2 on the bottom) with holes that provide for selecting one of 8 orientations (at 45º increments). Each insert, shown in **Error! Reference source not found.**, has a dowel pins and a slot on one end; the pin mates with holes in the phantom cover and the slot facilitates pin-to-hole alignment during assembly. The phantom body is 1 inch thick and has a longitudinally-uniform cross section. The uniformity in the longitudinal direction can be helpful in estimating the artifact pattern and getting statistical results by using multiple slices within 1 scan rather than using multiple scans. One inch is thick enough to obtain 50-100 image slices; it is also thin to produce relatively low scatter in the longitudinal directions.

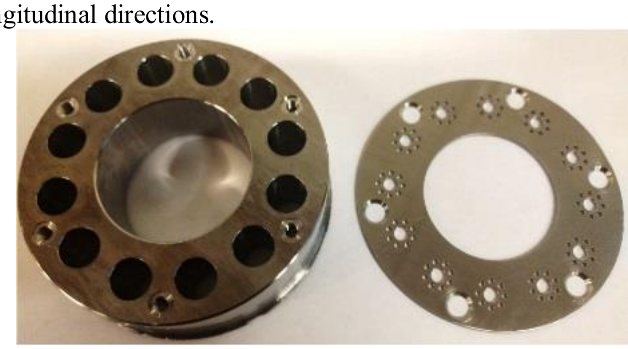

Figure 1. Photograph of the annular phantom body (left) and cover.

Figure 2. Photograph of an airfoil phantom (top) and cover.

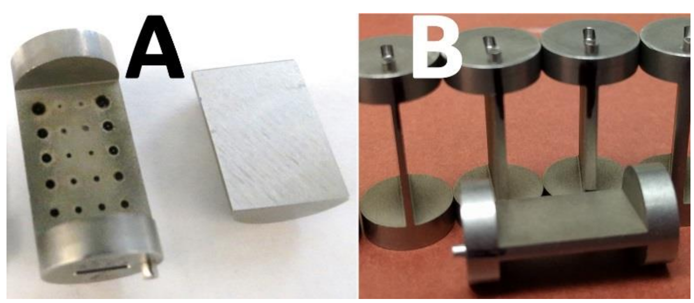

Figure 3. Photographs of (A) a semi-circle insert with EDM pores and cover; (B) gusset inserts. Pins in the ends of the inserts mate with holes in the phantom cover; a slot provides for rotation to facilitate assembly.

The most important feature of the phantom is its modularity. It can include versatile inserts that enable measurement of IQ metrics and represent different inspection and measurement tasks; it is also extendable in both axial and longitudinal directions. The annular shape phantom body could be nested in larger or smaller annular phantoms to provide different thickness of metal and produce different noise, scatter, and beam-hardening characteristics. Furthermore, additional 1-inch-thick sections can be stacked above and below the phantom bodies to produce different amount of x-ray scatter for cone-beam CT. This is of interest nowadays as the need for scanning large, heavy objects increases; the proposed phantoms are designed to work for these applications. To scan a large, heavy part, high-energy x-ray spectra in the MeV range are used to penetrate the object and Compton scattering is the dominate photon absorption mechanism. When fan-beam CT systems based on linear detectors are used, the scatter is minimal, but the time required to scan a large part using a fan-beam system is extremely long. Cone-beam CT systems are needed to reduce the scan time. However, high-energy cone-beam systems suffer from severe scatter artifacts. Various hardware and software solutions have been proposed to solve the scatter problem[3-6]. Being able to produce images with different scatter level will help evaluate different scatter reduction/correction methods.

The precisely manufactured phantom body and precise insert location and orientations enables automatic image analysis, which is especially useful for large datasets and experiments with multiple variables.

2.2 Inserts

The phantom bodies can include interchangeable inserts with known features. Inserts can be any shape as long as they fit within the 1/2-inch-dimater by 1-inch tall hole in the phantom: it can be cylindrical or prism-like. The insert can be from any material and any manufacturing process of interest: additive manufacturing, casting, or machining.

We designed some inserts to access basic IQ metrics. For example, a semi-circle insert can be oriented in different directions in the annular phantom body to access MTF in the radial or azimuthal orientations. A partial-height rod insert can be used to measure MTF in the longitudinal direction. Note that to have sufficient oversampling, the end of the rod has to be slightly tilted with respect to image planes. This can be achieved by tilting the entire phantom body or by using a rod with a slanted surface [7]. Because the MTF can be location dependent, a nested annular phantom body could be used to access transaxial MTF at different locations and rods with different heights can be used to access MTF at different longitudinal locations. Inserts can also be made from materials of lower or higher density; inserts can range from empty holes to solid rods of high-density material to fully evaluate image quality over a range of conditions.

Inserts can be designed to evaluate inspection or metrology performance. Such inserts can contain known defects such as cracks, pores, voids, or missing or surplus materials. Inserts with pores produced using electrical discharge machining (EDM) were fabricated with the pores on the face of partial-height rods and on the face of semi-circle inserts (Figure 3A). The pore diameters ranged from 10 mils to 53 mils (0.25 mm to 1.35 mm). These pores represent surface-breaking pores in a cast part; by mating the pore insert with a “cover” (a second partial-height rod or a second semi-circle), closed or “embedded” pores can be represented. We also designed an additively manufactured insert (AM) to evaluate internal pores in AM parts, potentially with residual metal powder entrapped in the pores. Those pore diameters are ranged from 6 mils to 64 mils (0.015 mm to 1.6 mm). The EDM and AM pore inserts permit evaluation of pore detection and measurement. We also fabricated “gusset” inserts (Figure 3B) to assess wall thickness measurement capability; these thicknesses ranged from 15 mils to 200 mils (0.38 mm to 5.1 mm). The dimensions of the insert features can be pre-measured by means of using high-spatial-resolution micro-CT, optical metrology instruments, precision micrometers, or other contact measurement means.

In addition to adding phantom extensions in the axial and longitudinal directions to generate different beam-hardening and scatter levels, different insert distributions also produce different noise and artifacts. Artifact correction algorithms could be evaluated using images from substantially different phantom configurations.

3. Conclusion

The proposed modular phantom can easily produce images to comprehensively access image quality in terms of resolution, contrast, noise, and artifacts and evaluate detection and metrology performance in industrial CT.

REFERENCES

[1] ASTM International, “E1695 Standard Test Method for Measurement of Computed Tomography (CT) System Performance.”

[2] “Unique tool for high quality scatter reduced industrial CT scans acquired in significantly shorter scan time,” GE Inspection Technologies. [Online]. Available: https://www.industrial.ai/sites/g/files/cozyhq596/files/2018-11/geit-31352_scatter_correct_en_0416.pdf.

[3] A. Peterzol, J. M. Létang, and D. Babot, “A beam stop based correction procedure for high spatial frequency scatter in industrial cone-beam X-ray CT,” Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms, vol. 266, no. 18, pp. 4042–4054, Sep. 2008.

[4] A. Miceli, “An experimental and theoretical approach to correct for the scattered radiation in an X-ray computer tomography system for industrial applications,” University of Bologna, 2008.

[5] D. Shedlock et al., “Refinement of Imaging Processing of Scatter Correction and Beam Hardening Tools for Industrial Radiography and Cone Beam CT.”

[6] B. Navnina, L. Jean Michel, T. David, and B. Fanny, “Scattering Correction in Cone Beam Computed Tomography.”

[7] B. Chen and E. Samei, “Development of a phantom-based methodology for the assessment of quantification performance in CT,” 2013, vol. 8668, p. 86681E.

