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Evaluation procedures for spatial resolution and contrast standards for neutron tomography

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Abstract

Digital neutron imaging (radiography and tomography) is a powerful non-destructive analytical tool and has demonstrated its importance in industrial and research application worldwide. The standardization process, to certify digital neutron imaging as a standard practice in industry, entails standardized test phantoms to be evaluated. Through the evaluation of the phantoms the spatial resolution and contrast of a neutron digital imaging system can be determined in a controlled and standardized manner by accepting good practice in terms of scanning, data processing, data visualization and evaluation. Standard test phantoms are objects with physical features designed to test the capability of an imaging setup to reveal these features without any ambiguity. The good practice enables the acceptable assessment of different international digital neutron imaging facilities for spatial resolution and contrast abilities. The purpose of this contribution is to establish good practice for the experimental setup, acquiring of 2-D digital projections and the reconstruction process of the 3-D digital images of standard test phantoms for spatial resolution and contrast. Results obtained from applying this suggested good practice on contrast standard test phantom will be discussed.

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1. Introduction

Digital neutron imaging is a powerful non-destructive analytical tool and has demonstrated its importance in industrial and research application worldwide [1]. Yet, quality assessment standards for this analytical technique do not exist. Standardization is an essential in science and technology in that it establishes and enforces precision and accuracy in measurements, as well as to create a basis for industrial- and commercial measurements [2]. As part of the standardization process for 3-D neutron tomography, test phantoms for spatial resolution and contrast are under development, and good practice in terms of scanning, data processing, data visualization and evaluation is required. Standard test phantoms are objects with physical features and designed in such a way to test/determine facility capabilities to reveal these features without any ambiguity. The good practice enables the common acceptable assessment methodology for different international digital thermal neutron imaging facilities to obtain characteristics about their spatial resolution and contrast abilities.

This paper provides the standardized analytical procedure for projection acquisition and post processing of neutron projections to images in three-dimensional space (tomogram and slices in X-, Y-, and Z planes). This procedure is being discussed in the context of spatial resolution and contrast and complements another work conducted within the same topic at PSI [3]. One test sample for contrast, the Neutron Tomography Contrast (NTC), and two for spatial resolution with positive and negative contrast, called Neutron Tomography Spatial Resolution (NTRS) PLUS and -MINUS are defined and introduced for adoption as standards.

2. Samples

All Schematic diagrams of standard samples adopted for contrast and spatial resolution assessment are shown in Figure 1.

![Schematic diagrams of standard samples](image)

Fig. 1. (a) Design of the NTC standard proposed by KAERI. (b) Side view of the NTRS standard design proposed by PSI.
2.1 NTC (Neutron Tomography Contrast) Standard

The NTC standard sample shown in Figure 1(a) was design by the Korean Atomic Energy Research Institute (KAERI). This NTC sample consists of 6mm diameter cylinders of Al, Cu, PE, Ni, Pb and Fe embedded in an Al cylinder of 30mm in diameter.

2.2 NTSR (Neutron Tomography Spatial Resolution) Standards

A set of samples designed and manufactured by Neutron Imaging and Activation group located at the Paul Scherer Institute (PSI) in Switzerland were made available for testing of spatial resolution of neutron tomography facilities through visualizing different sizes of an inclusion and/or a void in a solid piece of material. Each sample is made of two solid blocks of dimensions 10mm x 20mm x 40mm fixed together by a set of screws, one at the bottom and another at the top. The NTSR MINUS is based on matrix of Fe and the Al foil (Neutron transparent material – illusion of a void) between the two blocks, while the NTSR PLUS is based on Al matrix and Cu foils. The space between the two blocks can be varied by inserting a number of 20-micron thick foils between the blocks. The side view of the general design of the phantoms is shown in Figure 1(b).

3. Procedure- good practice of neutron tomography

The procedure suggests good practice for neutron tomography with regard to experimental setup, scanning protocol and data post processing. The following image quality indicators for neutron tomography are incorporated in the test procedure; signal-to-noise ratio, contrast-to-noise ratio and spatial resolution and are discussed below. See appendix A for a step by step procedure for spatial resolution and contrast.

3.1 Signal-to-noise ratio

This quality indicator is affected by data acquisition and post processing. The best way of optimising the signal amidst noise is by acquiring single radiographs such that the flat field part of the image is 70% of the total dynamic range, and scanning at least five radiographs at each step angle. In cases where it is not practical to do so, one radiograph per step angle may be acquired and noise removed by means of a digital filter. The signal-to-noise (SNR) ratio is calculated in imaging using equation 1, this equation applies with the neighbourhood pixels not a total image [4][5].

\[
SNR = \frac{E[signal] - E[background]}{s[background]} \tag{1}
\]

Types of noise involved in neutron imaging (radiography and tomography) are systematic and random noise. Factors contributing to systematic noise are dark current (electronic noise), detector texture and radiation background scattering; while those contributing to the random noise are gamma ray spots (zingers) and some component of background scattering. The dark current is eliminated by pixel wise subtracting of the average dark current radiograph obtained by acquiring at least five radiographs without the neutron beam. Background scattering is modelled by placing a neutron ‘blackbody’ with the same dimensions as the sample at the sample position and acquiring several radiographs. Random noise is
relatively difficult to eliminate from radiographs. The best way is through signal amplification by ensuring optimum neutron dose and averaging at least five radiographs at each step angle. When it is not practical to do this, electronic methods through filtering is being applied. Electronic filters mostly degrade the spatial sharpness of the image and threshold and Fourier filters are recommended. Threshold electronic filters do not smoothen the entire image but targets the outliers, i.e. the gamma spots and dead pixels. Fourier filters though they smoothen the image but allows for selection of the degree of discarding the high frequency component of the image signal.

3.2 Spatial resolution

Spatial resolution requires a good choice of the detector, the object-detector-distance (ODD), collimation ratio (L/D), image processing and sampling of the object (Nyquist-Shannon theorem) [6]. It is important to ensure the implementation of the recommendations for good signal-to-noise ratio to obtain good spatial resolution, while other recommendations to obtain good spatial resolution are:

- High L/D
- Shorter ODD (sample as close as possible to the detector)
- Preferably no electronic spot filtering unless the filter doesn’t smoothen the image.
- Applying a thin coated scintillator
- Good sampling of the object, Nyquist-Shannon theorem in 180°, as shown in equation 2

\[ N_{\text{projections}} = \left( \frac{\pi}{2} \right) \times \text{object's dimension}_{\text{pixel}} \]  

Where

Object’s dimension_{\text{pixel}} is defined by the number of pixels that constitutes the widest horizontal dimension of the object to be imaged.

N_{\text{projections}} is the number of projections in 180°.

3.3 Contrast

It is important to implement the recommendations of sections 3.1 & 3.2 if small features (twice the pixel size or less) and materials with low attenuation coefficient for neutrons are to be observed; image sharpness and good signal to noise ratio are important in this case. The former recommendation is important for a case where materials with little differences in attenuation coefficients are investigated. Where the above requirements are not important, relatively less number of projections may be acquired and the even 50% of the dynamic range may be used. The other recommendation is interpolation of data and Fourier filtering at the reconstruction stage for smooth images without much of random noise. Interpolation at the reconstruction stage is mainly to fill gaps in the data set as a result of insufficient sampling of the object under investigation.

4. Results

4.1 NTSR samples

The procedure has been tested on the NTC sample, designed at KAERI and manufactured at PSI, using the SANRAD thermal neutron facility at Necsa with 0.0977mm spatial pixel size [7]. Figure 2 (a) shows the thermal neutron radiograph of the NTSR MINUS (top) & PLUS (bottom) samples and Figure 2 (b) shows the line profiles (in red) of the NTSR MINUS (top) & PLUS (bottom) samples. It is important to note that the 100micron Al foil cannot be visualised on the NTSR MINUS due to the scatter by the Fe.
The 100micron Cu foil could be clearly visualised within the NTSR PLUS even though the data is noisy and two peaks of gamma ray spots could be visualised as well, these gamma ray spots can be easily removed by a threshold filter. Cross-section slices of the NTSR PLUS (left) & MINUS (right), Figure 3, show a poor visibility of the 100micron Al foil within Fe blocks with a 10% difference in contrast between the Al and Fe.

![Image](image_url)

Fig. 2. (a) A thermal neutron radiograph (top) and a line profile (bottom) of the NTSR MINUS sample. (b) A thermal neutron radiograph (top) and a line profile (bottom) of the NTSR PLUS sample.
4.2 NTC sample

Figure 4 shows the effects of Fourier frequency filtering and Sampling on contrast resolution in thermal neutron tomography. The cross-sectional image of the contrast phantom is shown in Appendix A, Figure A.1. Figure 4 presents the Relative attenuation coefficients from a thermal neutron tomogram of the NTC standard obtained through a scanning protocol with 180 projections in 180° and without Fourier filtering.

Fig. 4. Relative attenuation coefficients from a thermal neutron tomogram of the NTC standard without Fourier filtering and 180 projections in 180°. Peaks from left to right: background noise and Pb, Cu, Fe, Ni and PE.
Fig. 5. Demonstration of the effect of the Fourier filter and effect of Sampling of the object during scanning.

The results in Figure 5 are obtained by applying the recommendations of the procedure in section 3.3. Figure 5(a) presents the effect of Fourier frequency filtering on resolution of Cu and Fe peaks from the scan of Figure 4. The NTC standard was then scanned to satisfy the Nyquist-Shannon sampling theorem in 180° and the results of that scanning protocol without Fourier frequency filtering is the resolution of Cu and Fe peaks, as well as the Pb peak from the Al and noise peaks (Figure 5(b)). Shown is Figure 5(c) is the effect both the Nyquist-Shannon sampling theorem in 180° and the Fourier frequency filtering. The standard was then scanned to satisfying the Nyquist-Shannon sampling theorem in 360° and Fourier frequency filtering was applied (Figure 5(d)). The results of Figure 5(a)&(b) show better resolution of the Pb peak from the Al and noise peaks.
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Appendix A.

1 Scanning parameters for NTC and NTSR standards

Scanning protocol for neutron facilities is divided into flexible and fixed components. This is due to that not all parameters can be fixed as these facilities are constantly under development and hence unique - allowing freedom of customizing for best performance.

Flexible parameters:
- Utilization of:
  - A neutron beam.
  - The highest available L/D ratio.
  - Smallest Field-of-View (FOV) on the scintillator screen for the standard to fit e.g. 5cm x 5cm.
  - Detector with highest number of pixels array which will be used for nondestructive testing of the component: e.g. 2048 x 2048 pixels.
  - Thinnest scintillator for optimum spatial resolution performance and a scintillator with high neutron efficiency for optimum contrast.

Fixed parameters:
- Number of projections: $\pi \times \#\text{pixels in 360 degrees}$, according to Nyquist-Shannon sampling theorem. #pixels are defined by the number of pixels that constitutes the widest horizontal dimension of the object to be imaged. Half the number of projections for 180 degrees rotation. Choose either 180 or 360 degrees rotation depending on your needs (see contrast results).
- Dynamic range: recommends not less than on flat field region 70% or more of valid capacity (results in acquisition time and neutron flux).
- Sample-detector distance: as little as practical from edge of sample to detector for parallel reconstruction.
- Number of “Dark Current” (dc) radiographs: minimum of 5 for enhancement of S/N.
- Number of Open beam (fl) radiographs: minimum of 5 for enhancement of S/N.
- Sample position is recommended not to be at the centre of the rotation stage if the sample shape is a cylinder, it might be mistaken for a ring artifact during reconstruction.

2 Reconstruction parameters

The spatial resolution- and contrast needs for the reconstruction protocol for both the NTC and NTSR standards are different and are treated separately. This procedure describes application of the software package “Octopus” for reconstruction of cross-sectional slices from projections [8].

2.1 NTC STANDARD

2.1.1 Reconstruction of cross-sectional slices from projections.

Image processing module
- Enable automatic mode of spot filtering by inserting a -1 input.
- Normalize for beam fluctuation by selecting an AOI which is more 10 pixels thick and more than 100 pixels long in the open beam area – not to overlap with the sample.
- Enable automatic mode of ring filtering by inserting a -1 value input.
Check box to create sinograms.

**Reconstruction module**

**Scan geometry parameters**
- Choose last angle to be depending on your experimental settings.
- Insert pixel size input:  $\text{Pixel size} = \frac{\text{FOV dimension (mm)}}{\text{No. of pixels}}$.
- Right click on the rotation axis input space and click on “evaluate” under evaluation of parameters. Octopus will provide good results and select the best rotation axis automatically. Confirm if the chosen value gives the best image and select it, then click OK.

**Quality parameters**
- First choose the regular Fourier Filter and increase numerical input in the Noise Filter Percentage slot until the visualized noise, which mimics the shape of the sample (Figure A.1) around the sample’s cross-sectional image, is minimum or disappears. Fourier frequency filtering is used to get rid of statistical noise which is tricky to remove from the digital image data. This process requires transforming the intensity domain to frequency domain. The trick is to make and observe signal of the same frequency as the random noise incorporated in the image disappear to know that the noise is removed from the image signal.

Red line indicates the radius of the noise around the NTC phantom.

![Fig. A.1](image_url)

Fig. A.1. Demonstration of the visual effect of the Fourier filter on image noise. (a) Before and (b) after Fourier filtering.

- Uncheck the “Apply Scaling Factor” box to maintain sinograms scale from projections processing.
- Check the “Apply Logarithm” box to have the output numerical data on reconstructed image as integrated attenuation coefficient instead of transmission values.
- Choose no beam hardening correction under BHC method.
- Uncheck the “Vertical Smoothing” box.

**Output parameters**
- Choose after reconstruction option under scaling mode. The recommended output type should be 32bit. If 16 bit was selected minimum gray value= -1 and maximum gray value= 2.5.
- Crop the reconstructed data as desired as long as the entire NTC standard image is complete.

2.2 NTRS STANDARD

2.2.1 Reconstruction of cross-sectional slices from projections.

Image processing module
- Enable NO filtering.
- Normalize for beam fluctuation by selecting an AOI which is more 10 pixels thick and more than 100 pixels long. Octopus recommends a 10 pixels thick AOI.
- Enable automatic mode of ring filtering by inserting a -1 value input.
- Create sinograms.

Reconstruction module
Scan geometry parameters
- Choose last angle to be depending on your experimental settings.
- Insert pixel size input: Pixel size = \( \frac{\text{FOV\_dimension}}{\text{No. of pixels}} \).
- Right click on the rotation axis input space and click on evaluate under evaluation of parameters. Octopus will provide good results and select the best automatically. Confirm if the chosen value gives the best image and select it, then click OK.

Quality parameters
- First choose the regular Fourier filter and keep the percentage at zero for a spatially sharp image.
- Uncheck the “Apply Scaling Factor” box to maintain sinograms scale from image processing.
- Check the “Apply Logarithm” box to have the output numerical data on reconstructed image as integrated attenuation coefficient instead of transmission values.
- Choose no beam hardening correction under BHC method.
- Uncheck the “Vertical Smoothing” box.

Output parameters
- Choose after reconstruction option under scaling mode. The recommended output type should be 32bit. If 16 bit was selected minimum gray value= -1 and maximum gray value= 2.5.
- Crop the reconstructed data as desired as long as the entire NTRS standard image is complete.