Performance of imaging system at Reactor TRIGA Mark II PUSPATI

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Abstract. The neutron radiography facility in TRIGA MARK II PUSPATI reactor (RTP) was successfully upgraded to obtain higher image quality as well as reducing exposure time. The major improvement is the implementation of a new neutron detector for neutron imaging. In this work, the implementation of a new neutron imaging system based on CCD camera and LiF/ZnS scintillator is presented. This article focuses on the qualitative and quantitative results obtained by using the new imaging system. The characteristics of this new imaging system were investigated in terms of spatial resolution.

1. Introduction

Reactor TRIGA Mark II PUSPATI (RTP) is a swimming pool-type light water research reactor with enriched uranium-zirconium-hydride fuel and graphite reflector (1 MW). The reactor has three radial beam ports, one tangential beam port and one thermal column.

The neutron imaging facility at RTP has been developed since the late 1980s and is located at one of the radial beam ports. The film-based technique was established at this facility. However, this facility produced low neutron intensities at the sample position, and this led to very long exposures. To overcome this limitation, an upgrade plan for the neutron facility was initiated in 2015. This upgrade was essential as there was an urgent need for a modern imaging system at this facility. Three years after the start of the upgrade plan, the newly designed collimator was successfully installed [1] [2]. Recently, extensive experiments using film have been carried out to characterise the new neutron beam setup [3].

A major step in the improvement of the neutron radiography activity at this upgraded facility is the implementation of a digital neutron detector for real time neutron radiography. The CCD camera-based detector is a key component in the new neutron imaging system. The common modern detector for a neutron imaging system is a CCD camera optically coupled to a scintillator screen. This digital detector offers some very explicit advantages over the conventional film-based technique. Generally, the chain of components in a CCD camera scintillator detector consists of: scintillator-mirror-lens-CCD camera-interface-PC-software. The most common scintillation screen for neutron imaging consists of zinc sulphide (ZnS) mixed with lithium fluoride (6LiF), doped with silver (Ag) for blue light emission or copper and gold (Cu, Au) for green light emission.

The objective of this work is to characterise the performance of the new imaging system at RTP in terms of spatial resolution.
2. Experimental

2.1. Neutron imaging system

All experiments in this work were performed at the upgraded neutron radiography facility at RTP. The facility is a new well-shielded concrete construction (bunker). Figure 1 shows a simplified view of the neutron radiography facility at RTP. It consists of a 232 m long divergent collimator, a 3 cm diameter aperture, mechanical beam shutter and an external beam trap. The imaging test station is located 130 m away from the beam port exit. Between the beam port exit and imaging equipment a horizontal moveable beam trap is installed. It is a sandwich construction consisting of several 10 cm thick borated polyethylene and 15 cm thick lead. To perform neutron radiography, the sample is positioned at a 100 cm distance from the beam port exit between the beam trap and imaging equipment (L/D ratio ~110). Due to the limited space in the bunker, the maximum L/D ratio is ~120. The thermal neutron flux at the sample position is 10^4 n s^{-1} cm^{-2} at 750 kW reactor operating power. This leads to a long exposure time at this low flux position for better image quality.

Figure 1. Layout of neutron radiography facility at RTP.

Figure 2 shows the present status of the installed imaging equipment at RTP. The detection system consists of a scintillator converter screen, a mirror and a commercial CCD camera. The scintillator screen is 0.1 mm thick and has a 20 cm*20 cm field of view based on 6LiF/ZnS co-doped with Cu and Au. The camera is a Peltier cooled (-27 °C) low intensity CCD sensor comprising of 2759 x 2200 pixels (4.54 x 4.54 µm² size) and a quantum efficiency of ~75%. A 45° front-surfaced aluminium mirror and a 50 mm f/1.2 high-performance manual focus lens is used to project the greenlight from the scintillator onto the CCD sensor. The detector is housed within an L-shaped light-tight camera box and a small additional shielding (lead plate plus a B4C layer) was used to protect the CCD unit from the direct beam. However, this shielding of the detection system was insufficient. High-energy gammas from the radial beam port may hit the CCD chip directly. Hence, an additional 2 cm lead shielding was fabricated to minimise the camera’s gamma exposure.

Figure 2. The present setup of the neutron imaging equipment inside the bunker at RTP.
2.2. Modulation transfer function

The modulation transfer function (MTF) is a fundamental tool for assessing the performance of imaging systems. In neutron imaging particularly, MTF is one of the most useful tools to evaluate the performance of an imaging system on a quantitative basis. There are several approaches to obtain the MTF.

The most common method is use a slit to determine the modulation transfer function of the detector system. This approach is less sensitive to noise. However, the disadvantage is that the slit must be polished or extracted with very high precision and must be very well aligned with the beam.

In this work, a simple method for obtaining the MTF of neutron imaging detectors from edge images is implemented. From the digital edge image an edge spread function (ESF) is generated. ESF is measured using an opaque object with a straight edge. Figure 3 shows the test object used to measure the MTF.

The cadmium plate was chosen to obtain significant different intensities. The triangle slits were fabricated in order to produce slanted pattern edges between the air and the plate. The test object was positioned at close contact to the scintillator screen and scanned at 750 kW reactor operating power with 5 minutes exposure time. All neutron images were 16-bit grayscale images and all white noise were suppressed in a pre-processing step before the MTF calculation process to avoid noise amplification.

Figure 3. Test object

The calculation of the MTF was implemented in the following steps:

(1) Acquisition of an image of a slanted edge. A small region of interest (ROI) surrounding the edge was manually extracted. The ROI was selected for a high contrast sharp edge that is homogenous on both sides.

(2) Construction of an ESF. The ESF of a system is the image of an ideal step function. ImageJ software was used to extract the step function from the ROI by taking 1D line profile cross section (cross-sectional plots).

(3) In order to avoid noise from differentiation, the edge profile was fitted using curve fitting. Therefore, in this work a curve fitting using Arctan (Equation 1) was selected in fitting the ESF. The reason for selecting Arctan fitting is due to close contact measurement.

\[
 f(x) = a \arctan \frac{(x-\mu)}{\sigma} + \frac{1}{2}
\]

where \(a\), \(\mu\) and \(\sigma\) are the amplitude, position of edge, and width, respectively.

(4) The differentiation of fitted ESF was performed in order to obtain the LSF.

(4) The LSF was then converted to the frequency domain using a fast Fourier transform (FFT) to the LSF to obtain the MTF.
2.3. Qualitative method
The most rapid way to investigate the performance of a neutron imaging system is by visual inspection with the PSI Siemens Star test pattern. The test device developed by [5] at PSI consists of a metallic gadolinium-based star pattern which measures resolution in microns. Another test device uses the American Society for Testing and Materials (ASTM) standard objects: Beam Purity Indicator (BPI) and Sensitivity Indicator (SI).

3. Results and discussion

3.1. Quantitative results
A close contact radiography of the test object in Figure 3 is shown in Figure 4. As previously explained, the edge was detected using ImageJ software as display in Figure 5(a) and then the ESF was fitted using the Arctan function given in Equation (1). Figure 5(b) display the corresponding ESF using Arctan function. Error! Reference source not found. shows the LSF pattern. The LSF, calculated by differentiating the fitted ESF, shows visible ‘spikes’. In this work, the real LSF and Gaussian fitted LSF are plotted. To calculate the MTF from the LSF, the fast Fourier transform (FFT) is applied. From the result in Figure 5(c), the measured MTF is 50% at 8 lp/mm and 10% at 14 lp/mm corresponding to MTF resolutions of 6.25 μm and 35.7 μm.

Figure 4. Contact radiography of test object.
Figure 5. Measurement of Modulation transfer Function (a) Edge line profile using ImageJ software, (b) the corresponding ESF using Arctan function, (c) The LSF pattern and (d) MTF of the edge.
3.2. Qualitative Results

Figure 6 shows the image of the Siemens star structure acquired with a 0.1 mm LiF/ZnS scintillator screen. The image of the PSI-Siemens star spatial resolution test object shows that individual features of about 400 µm can be resolved. Figure 7 shows the image of the ASTM standard objects. Clearly visible in the image of BPI are the BN disks, the cadmium wires and the density difference between the Teflon block and the open region in the centre. From the image of SI, only two aluminium shims are clearly visible. However, all the holes are not visible. From the images in Figure 6 and Figure 7, it can be observed that small structures in micrometre scale cannot be detected. In both cases, the L/D ratio becomes the major limiting parameter for the resolution, and blurring can be seen in the image.

![Figure 6. Resolution measurement performed with the Siemens star structures on 0.1mm LiF/ZnS scintillator screen.](image)

![Figure 7. (a) Conventional photograph of Purity Indicator (BPI) and Sensitivity Indicator (SI) and (b) Neutron image of (a).](image)
4. Conclusion
A simplified edge-based MTF measurement method to determine the MTF of the neutron imaging system at RTP from an edge image has been described. The measured MTF using the method is 50% at 8 lp/mm and 10% at 14 lp/mm corresponding to MTF resolutions of 6.25 μm and 35.7 μm. However, this edge-based slanted method is prone to error and the MTF results can be improved by means of a slit or pre-sampled MTF machine fabricated edge. The results show that this new imaging system at RTP provides enough resolution for neutron radiography applications where such capability is needed but resources are limited. The implementation of the new neutron digital detector has a high impact on the neutron radiography activities at RTP.

5. References
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