MONTE CARLO SIMULATION OF NEUTRON RADIOGRAPHY 2 (NUR-2) SYSTEM AT TRIGA MARK II RESEARCH REACTOR OF MALAYSIAN NUCLEAR AGENCY

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To my wonderful family, thanks for the prayers and support

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ABSTRACT

The imaging properties namely the edge spread function (ESF) and line spread function (LSF) of the Neutron Radiography 2 (NUR-2) system at Triga Mark II Reactor at Malaysian Nuclear Agency were investigated via simulation and experiment. The simulation of radiographic image was performed by using the Monte Carlo N-Particle codes version 5 and the real neutron radiographic images were collected from experiment done at NUR-2 facility. The simulation used Flux Image Radiograph (FIR) tally while for the experiment the direct method using film was used to detect the transported neutrons. The ESF of the system was measured using cadmium foil with thickness of 1 mm, 2 mm and 3 mm which blocked half of the neutron beam. Demineralized water was used as a scattering material to study the neutron scattering effect inside the material where it was placed between the cadmium foil and the detector. The differentiation of the ESF gave the LSF of the system and the full width at half maximum (FWHM) was estimated. From fast Fourier transformation of the LSF, the modulation transfer function (MTF) of the system was obtained. The results showed that the simulated neutron patterns without scattering material were similar to those found in experiment but with the presence of scattering material, the simulation and experimental data showed great differences. Cadmium with thickness of 1 mm gave the best spatial frequency response followed by 2 mm and 3 mm thick of cadmium. The range of spatial frequency for MTF at 20% was 1.0 to 2.5 cycle/mm, while the range of FWHM was 0.3 to 0.5 mm. The FWHM and MTF obtained in this study are valuable for the characterization of imaging properties of the neutron radiography system.

ABSTRAK

Sifat-sifat pengimejan iaitu fungsi taburan pinggiran (ESF) dan fungsi taburan garis (LSF) bagi sistem radiografi neutron di Reaktor Triga Mark II di Agensi Nuklear Malaysia telah dikaji menerusi simulasi dan eksperimen. Simulasi imej radiografi dilakukan dengan menggunakan perisian ‘Monte Carlo N-Particle’ versi 5 dan imej sebenar radiografi neutron telah diperolehi daripada eksperimen yang dijalankan di kemudahan NUR-2. Simulasi menggunakan gundalan fluks imej radiografi (FIR) manakala bagi eksperimen kaedah terus menggunakan filem digunakan untuk mengesan neutron yang dipindahkan. ESF sistem diukur menggunakan kepingan kadmium dengan ketebalan 1 mm, 2 mm dan 3 mm yang menutup separuh daripada alur neutron. Air ternyahmineral digunakan sebagai bahan penyerak untuk mengkaji kesan serakan neutron di dalam bahan di mana ia diletakkan di antara kepingan kadmium dan pengesan. Pembezaan ESF terhadap jarak memberikan LSF sistem tersebut dan lebar penuh pada separuh maksimm (FWHM) dianggarkan. Dengan mengambil jelmaan Fourier bagi LSF, fungsi pemindahan modulasi (MTF) sistem tersebut telah diperolehi. Keputusan menunjukkan bahawa corak simulasi neutron tanpa bahan penyerak adalah hampir sama seperti yang diperolehi daripada eksperimen tetapi dengan kehadiran bahan penyerak, data simulasi dan eksperimen menunjukkan perbezaan yang besar. Kadmium dengan ketebalan 1 mm memberikan sambutan frekuensi ruang yang terbaik diikuti oleh kadmium dengan ketebalan 2 mm dan 3 mm. Julat frekuensi ruang untuk MTF 20% ialah 1.0 hingga 2.5 kitar/mm sementara julat FWHM ialah 0.3 hingga 0.5 mm. MTF dan FWHM yang diperolehi dalam kajian ini adalah berharga untuk pencirian sifat pengimejan sistem radiografi neutron.

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LIST OF SYMBOLS AND ACRONYMS

eV	-	Electron volt
kW	-	Kilowatt
R	-	Röentgen
n	-	Neutron
cm	-	Centimetre
mm	-	Millimetre
µm	-	Micrometre
s	-	Second
I	-	Transmitted intensity
I_0	-	Incident intensity
Σ	-	Macroscopic absorption cross section
d	-	Thickness of the sample
Sb-Be	-	Antimony Beryllium
Am-Be	-	Americium Beryllium
Cf-252	-	Carlifornium-252
Gd	-	Gadolinium
MCNP	-	Monte Carlo N-Particle
FIR	-	Flux image radiograph
PScF	-	Point scattered function
$l(x)$	-	Line spread function (LSF)
$e(x)$	-	Edge spread function (ESF)
$h(x,y)$	-	Point spread function (PSF)
M(u)	-	Modulation Transfer Function (MTF)
$f(x)$	-	Input function
F(u)	-	Fourier Transform

σ	-	Standard deviation
δ(x)	-	Delta function
ROI	-	Region of Interest
FWHM	-	Full Width at Half Maximum

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CHAPTER 1

INTRODUCTION

1.1 Background study

For more than 60 years, neutron radiography has existed as a testing technique and as a research tool especially in non-destructive testing. Neutron radiography is an imaging technique which provides images similar to X-ray radiography. The ways that neutrons interact with matter are very different from the way x-rays interact with matter. X-rays interact with the electron cloud surrounding the nucleus of an atom while neutrons interact with the nucleus itself. This property allows neutron radiography to image objects which are invisible to X-ray. The attenuation coefficient of X-ray is directly dependent on atomic number of material but the attenuation coefficient of neutrons is not a function of the atomic number of material. Neutrons are efficiently attenuated by only a few specific elements especially material that have high hydrogen content. Organic materials or water for example are clearly visible in neutron radiographs while many structural materials such as aluminium or steel are nearly transparent.

Since early 1960s, imagings with neutrons have been widely used in industrial research and non-destructive testing applications. Berger in the first book in 1965 published on neutron radiography had suggested three main areas of applications of neutron radiography which is reactor technology, rocket and missile technology and general applications (Berger, 1965). A short review of neutron radiography applications in the *Nondestructive Testing Handbook* include in general, explosives, turbine blades, assemblies, contrast agents, metallurgy and nuclear industry field was published in later (Paul, 1985).

There are several components that tend to degrade the image and thus limit the resolution of neutron radiography (Park, 2000). According to Harms and Wyman (1986), the five major sources of image degradation in neutron radiography are converter unsharpness, scattering degradation, geometric unsharpness, motion unsharpness and noise degradation.

Limitations in the imaging and processing systems, such as converter-film unsharpness and noise degradation are well defined, and image degradation due to the system is easily obtained through a simple experiment (Lindsay, 1983). Geometric unsharpness associated with lack of collimation in the beam can be ignored if the length of the collimator is large compared to the diameter of the source size. Motion unsharpness which is due to object motion during the exposure can be ignored if the object is static during the exposure. However, if the object has a large scattering cross section, the scattering degradation caused by the neutrons scattered in that object cannot be ignored. Therefore, removing object scattering from the image is important in order to improve the image quality for the highly scattering material (Park, 2000).

In this research, we will determine the edge spread function (ESF), line spread function (LSF) and the resolution of the Neutron Radiography 2 (NUR-2) facility at TRIGA MARK II reactor of Malaysian Nuclear Agency via Monte Carlo simulation and the experimental confirmation will be made to verify the simulation results. The modulation transfer function (MTF) for the system will be estimated. The MTF is useful for the enhancement and restoration of neutron radiographic image.

1.2 Historical Review of Neutron Radiography

Radiography with neutrons began shortly after the discovery of the neutron by Chadwick in 1932. The first investigation on neutron radiography was performed in Germany by Kallman and Kuhn. This study initiated in 1935, resulted in a great number of German, French and American patents, most of them filed in the late 1930’s and early 1940’s. Kallman and Kuhn used neutrons produced by an accelerator to make radiographs but the quality was not very good due to the weak and ill defined beam (Domanus, 1992). Although the actual radiography produced by them was not of high quality, these efforts indicate some of the possible uses of the neutron radiography and also yielded a great deal of information concerning many of the characteristics of neutron sources and image detection methods (Berger, 1965).

A similar study on neutron radiography was being conducted by Peter in 1946, also in German. While the neutron source used by Kallmann was of relatively low intensity, Peter used a more powerful accelerator to produced radiographs of useful quality with only a few minutes of exposure. According to Berger (1965), Peter only took 1 to 3 minutes to obtain radiograph with his source whereas a scintillator detection method which is the fastest technique developed by Kallmann and Kuhn required four hours of exposure with their smaller source. The radiographs published by Peter were of fair quality and could be obtained in a reasonable time (Berger, 1965).

In 1956, the first neutron radiographs were produced by Thewlis and Derbyshire in England. They carried out their work with the BEPO reactor at Harwell, and its intense neutron beam allowed them to produce radiographs of much better quality than those of Kallman and Peters (Von Der Hardt and Röttger, 1981). They produced good quality images having specific non-destructive testing application such as voids in uranium and in “Boral”, a neutron shielding material fabricated from boron carbide and aluminium (Domanus, 1992).

The spread function approach that uses Monte Carlo simulation to determine the shape of the point spread function (PSF) of object to detector distance, object thickness, and various scattering and absorption cross section was attempted by Segal et. al., (1983). Since then some researchers have tried to use PSF deconvolution method to restore the neutron radiographic images, but the computational requirements and the necessity of a priori knowledge have made this option unattractive as a formal method for removing the object scattered neutron contribution from radiographic image (Syh et. al., 1990; Mora and Bernizer, 1992).

Recent advances in computer processing power and speed have made the Monte Carlo technique a powerful tool for image formation formulation simulations. Monte Carlo techniques have been used by several investigators to model various aspects of image generation in neutron radiography and in computed tomography (Mora and Bernizer, 1992; Yanch et. al., 1992; Wallin, 2005, Hassanein, 2006). Most researchers have used Monte Carlo simulation to calculate the scattering contribution of neutron in the radiographed object for different cases to be applied for the restoration of radiographs (Park, 2000; Kardjilov et. al., 2005; Hassanein et. al., 2005; Hassan, 2009).

The MTF can be used to characterize the resolution performance of a digital radiographic system (Samei et. al., 2005). The MTF technique could be applied to determine the image degradation components of the imaging system. The removal of blurring effects due to scattered neutron has been attempted by several investigators either mathematically, experimental methods or by using a combination of experimental data and Monte Carlo simulations. However, mathematical formulation cannot be used to characterize the unsharpness due to the object scattering accurately (Park, 2000).

In order to remove the effects due to scattered neutrons valid for various geometries, Park (2000) tried to develop the neutron scattering functions for neutron radiographic images through the solution of the neutron transport equation. The analytic solution was verified through Monte Carlo simulations and the experimental method but the algorithm obtained is limited to two-dimensional radiographic images. There are limitations in the scattering correction algorithm obtained for example the scattering LSF was estimated with a given knowledge on the scattering material. Furthermore, there are many uncertainties in the measurement of the neutron radiographic images which should be evaluated in detail.

Most recently scattering correction in neutron radiography was studied by Hassanein (2006) from Swiss Federal Institute of Technology Zurich for the application to the thermal neutron tomography. Similar to Park (2000), Hassanein also used spread function method and Monte Carlo simulation to calculate point scattered function (PScF). The PScF calculated were used successively to correct the scattering effect in the three other thermal neutron radiography facilities with different beam characteristic. The correction algorithm has been tested successfully not only for NEUTRA facility at PSI where the algorithm has been developed, but also for neutron radiography facilities at ANTARES (FRM II, Technische Universität München), CONRAD (Hahn-Meitner-Institute Berlin) and well as SANRAD (Necsa Pretoria). The algorithm yield accurate quantitative results for any facility if the neutron energy spectrum and the properties of the detector are known and the experimental recommendations are realized (Hassanein, 2006).

1.3 Research Objectives

The aim of this study is to analyze and compare the neutron radiographic images produced by NUR-2 system available at Malaysian Nuclear Agency via simulation and experiment. The objectives are;

(a) To determine the edge spread function and line spread function of neutron imaging system and estimate the full width at half maximum.
(b) To determine the resolution property of the neutron radiography system via the modulation transfer function.

1.4 Rational for Research

The MTF is a basic measure for characterizing and quantifying the performance of an imaging system. When an imaging system is to be characterized, a straightforward approach to measure the MTF is to image a known input, such as a point source, a slit or knife-edge, which corresponds to PSF, LSF and ESF respectively. In this research, the knife-edge method was used to determine the spread function of the system in order to estimate the FWHM. The effect of the scattered neutron in the material was also considered in this study since the blurring effects due to scattered neutron could contribute to the degradation of the image. The value of MTF and FWHM obtained could be used in future work for image restoration codes. This research will contribute to the development of a neutron scattering correction algorithm for the enhancement of neutron radiographic images peculiar to the NUR-2 facility at TRIGA MARK II reactor of Malaysian Nuclear Agency.

1.5 Research Scope

The aim of this research is to determine the ESF and LSF of neutron radiography system at NUR-2 facility. Cadmium with thickness of 1 mm, 2 mm and 3 mm was used as a sample in order to obtain the ESF. To study the neutron scattering effect, demineralized water was used as a scattering material. This scattering material was placed between the sample and the detector. The resolution properties of neutron radiographic images are also to be determined via MTF. This research only covers the used of NUR-2 facility although there have other neutron radiography facilities using tangential beam port and thermal column. The simulation was done by using Monte Carlo n-particle transport code version 5 (MCNP5).

1.6 Organization of Thesis

This thesis details the work, results and analysis from the study of neutron radiographic system. The introduction chapter describes the basic of neutron radiography and indicates some factors that contribute to the degradation of the image. Chapter 2 describes the principle of neutron radiography broadly, the transfer system for imaging system and the Monte Carlo technique. Research methodologies are discussed in Chapter 3 which detailed the simulation and experimental confirmation of the simulation results. Further in Chapter 4, the result and discussion of each method are presented. Finally, the conclusion of the research and suggestion for other improvements are presented in chapter 5.

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