Thin-film Approximate Point Scattered Function and its Application to Neutron Radiography

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Abstract

A simpler and improved approximate point spread function for thin-film converters in neutron radiography devices is proposed as a correction method to produce clearer, more realistic images. The model' s validity was demonstrated through simulation experiments. Based on the results, an error analysis was conducted, certain corrections were applied to the original model, and the final model achieved a very low relative error in the simulation experiments. The model can also be optimized for quantitative neutron radiography analysis using iterative algorithms to obtain realistic neutron radiography images more efficiently. At the end of the article, the model is extended to consider energy spectrum hardening by introducing a temperature correction parameter.

Full Text

Preamble

Thin-film Approximate Point Scattered Function and its Application to Neutron Radiography

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We propose a simpler and improved utility approximate point scattered function for thin-film converters currently used in neutron radiographic devices as a correction method to produce clearer, more realistic images. The validity of the model was demonstrated through simulation experiments. Based on the results, an error analysis was carried out, certain corrections were made to the

original model, and the final model achieved a very low relative error in the simulation experiments. The model can also be optimized for quantitative neutron radiographic analysis using iterative algorithms to obtain realistic neutron radiographic images more quickly. At the end of the article, the model is extended to consider the case of energy spectrum hardening by introducing a temperature correction parameter.

Keywords: Neutron radiography, Point scattered function, Image processing

Introduction

Neutron radiography is a method for surface or internal diagnosis of a sample using the properties of neutron attenuation and scattering. Compared to other radiographic techniques, neutrons interact with nuclei in a more complex manner, and the macroscopic cross section does not have a definite relationship with nuclide species. These properties give neutron radiography unparalleled advantages over other radiographic techniques, making it currently invaluable for diagnosing a wide variety of industrial materials and of great importance in the metal and aerospace industries [**?**, **?**, **?**]. Simply put, neutron radiography takes advantage of neutron transmission and absorption by the sample being evaluated. By comparing detector images with and without the sample, the physical condition of the sample can be determined. However, inherent errors exist in this technique, mainly due to neutron scattering by the sample, absorption by the detector material, and attenuation during transmission.

In response to this problem, two main correction methods have been proposed. The first modifies the energy spectrum of the neutron source to produce more realistic final detection results [**?**, **?**], while the second introduces various functions to correct for scattering effects in neutron radiography [**?**, **?**]. Energy spectrum correction is proposed primarily to counter the neutron energy spectrum hardening problem, which becomes more significant as sample thickness increases to the point where correction becomes necessary. However, in a broader context, the scattering effect is more direct and important than the energy spectrum hardening effect. Therefore, this paper discusses energy spectrum correction as a secondary correction after scattering correction. For example, 14 MeV fast neutron radiography (FNR) [**?**], which has been extensively studied in recent years, shows promising applications with high contrast sensitivity and other features. However, it has difficulty dealing with scattering effects, which reduces its effectiveness and restricts practical applications. Two popular methods exist for energy spectrum correction: the maximum-likelihood expectation-maximization (MLEM) method and the quantitative neutron radiographic analysis (QNPA) method. The MLEM method performs statistical correction based on least squares and maximum-likelihood estimations [**?**], whereas the QNPA method uses neutron decay characteristics to iteratively correct the neutron distribution. For scattering correction, the "point scattered function" has been proposed [**?**], which is essentially the probability density distribution function of scattered neutrons detected after the neutron beam passes through the sample. However,

direct application is difficult due to its complex form and numerous parameters. Therefore, scattering correction models based on various approximate point-scattered functions have been proposed [?, ?]. In recent years, materials science has advanced rapidly, and an increasing number of neutron detectors can use very thin detection layers as converters to optimize neutron radiography [?, ?, ?]. Thus, we propose a new approximation called the "thin-film approximate point scattered function."This model offers significant computational advantages while maintaining sufficiently low error for practical applications. Below, we derive the thin-film approximate point scattered function from the conventional point scattered function and perform numerical simulations using software such as Monte Carlo N-particle transport (MCNP) and Mathematica to evaluate model accuracy and perform error analysis.

II. Thin-film Approximate Scattering Model

A. Thin-film Approximate Point Scattered Function

We first review the basic theory of the point scattered function, which is based on four basic assumptions:

1. The source and scattered neutrons have the same attenuation coefficient in the sample.
2. The sample width is large enough to ensure that scattered neutrons penetrate the sample and reach the detector.

These are reasonable assumptions. Because neutrons are electrically neutral, each should be homogeneous after scattering. The vast majority of neutrons also scatter only once in the sample, making multiple scattering corrections unnecessary.

[Figure 1: see original paper] shows a schematic of neutron radiography and the angular response of the detector. In the figure, r is the coordinate parameter of the detector, d is the thickness of the detector converter, θ is the scattering angle, D is the distance from the sample to the detector, T is the thickness of the sample, t is the location where scattering occurs in the sample, and R and l are geometric parameters. The following relationships exist between the geometric parameters:

$$\cos\theta = \frac{D+t}{R} = \frac{t+D}{\sqrt{(t+D)^2+r^2}}, \quad l = t+D$$

Then, for the detector coordinate r, the incident neutron flux $\Phi_{sc}(E)$ and the scattered neutron flux at the detector $\Phi_{st}(E)$ can be expressed as:

$$d\Phi_{sc}(E) = d\Phi_{st}(E) \cdot e^{-\Sigma_t(E)l}$$
$$d\Phi_{st}(E) = \Phi_0(E) \cdot e^{-\Sigma_t(E)(T-t)} \cdot \Sigma_s(E)dt$$

Here, $\Phi_0(E)$ is the neutron flux of the source, $\Sigma_s(E)$ and $\Sigma_t(E)$ are the scattering macroscopic cross section and total macroscopic cross section of the sample, respectively, and $\Sigma_{det}(E)$ is the absorption cross section of the detector material.

We must account for neutron attenuation, where a single neutron is detected with probability $P = 1 - e^{-\Sigma_d/\cos\theta}$. The neutron flux at the detector surface is:

$$dI_{det} = \int\int \Sigma_s(E)\cos\theta P \cdot d\Phi_{sc}(E)dE$$

According to the definition of the point scattered function, we have:

$$PScF(r) = \frac{I_{det}}{\int P \cdot \Phi_0(E)dE} = \frac{\int_{E,t} \Phi_0(E)\frac{D+t}{4\pi R^3}e^{-\Sigma_t(E)(\frac{tR}{t+D}+T-t)}\Sigma_s(E)dtdE}{\int_E \Phi_0(E)\cdot(1-e^{-\Sigma_{det}(E)\cdot d})dE}$$

This function is quite complicated and inconvenient to use. Many studies have attempted to approximate it. For a very thin detector, we can consider $d \to 0$. Because the series expansion of the exponential function $e^{-\Sigma d} = 1 - \Sigma d + O[2]$ involves a second-order infinitesimal term $O[2]$, we can use the approximation when the main and first-order terms occupy 99% of the exponential function (i.e., d satisfies $1 - \Sigma d = 0.99e^{-\Sigma d}$). This implies the following approximations:

$$1 - e^{-\frac{\Sigma_{det}(E)d}{\cos\theta}} \to \frac{\Sigma_{det}(E)d}{\cos\theta}$$
$$1 - e^{-\Sigma_{det}(E)d} \to \Sigma_{det}(E)d$$

The thin-film point scattered function $TPScF(r)$ can then be written as:

$$TPScF(r) = \frac{\int_E \Phi_0(E)\cdot\Sigma_{det}(E)\cdot\Sigma_s(E)\cdot F(E,r)dE}{\int_E \Phi_0(E)\cdot\Sigma_{det}(E)dE}$$

where

$$F(E,r) = \int_0^T \frac{1}{4\pi R(r,t)}e^{-\Sigma_t(E)(\frac{tR(r,t)}{t+D}+T-t)}dt$$

This integral can be calculated numerically using the Newton-Cotes method after the associated parameters are given. Using the geometric relations and adjusting the order, we obtain:

$$TPScF(r) = \frac{\int_{E,t} \Phi_0(E)\cdot\Sigma_{det}(E)\cdot\Sigma_s(E)\cdot g(E,t)dtdE}{\int_E \Phi_0(E)\cdot\Sigma_{det}(E)dE}$$

where

$$g(E,t) = \frac{e^{-\Sigma_t(E)(\frac{tR}{t+D}+T-t)}}{4\pi R}$$

B. Pre-processing of the Model

To better apply this model, we need to pre-process it as described in this section. We focus on the equation for $F(E,r)$ and apply the Newton-Cotes method to obtain a numerical solution:

$$F(E,r) \approx \frac{h}{3}\left[f(E,0) + f(E,T) + 4\cdot\sum_{n=1}^{m} f[E,(2n-1)h] + 2\cdot\sum_{n=1}^{m-1} f(E,2nh)\right]$$

where h represents the step size and m is obtained by solving:

$$(2m-1)h = T, \quad m = \left[\frac{T}{h}\right]$$

Here, $[x]$ represents the greatest integer function. The error from this approximation is:

$$Error(x) = \frac{(b-a)^5}{180n^4}\frac{\partial^4 f(\xi)}{\partial t^4}, \quad \xi \in (0,T)$$

This can be calculated quickly once the sample thickness T and absorption cross section $\Sigma_t(E)$ are known. In addition, the integration of $TPScF(r)$ is difficult, so we divide the integration interval into many small intervals:

$$TPScF(r) = \frac{\sum_{i=0}^{E_m}\Phi_0(E_i)\Sigma_{det}(E_i)\Sigma_s(E_i)F(E_i,r)}{\sum_{i=0}^{E_m}\Phi_0(E_i)\Sigma_{det}(E_i)}$$

where $E \in (E_0, E_m)$ is the range of the neutron source energy spectrum. Thus, we consider the model from a numerical perspective, making it less abstract and more computable. Next, we use examples to demonstrate the model' s validity and perform error analysis.

III. Application Example

A. Numerical Simulation of Scattering Correction for Water and Polyethylene

We construct a simple neutron radiography experiment. The neutron converter is made of 100 μm-thick ^{6}Li material, and cylindrical metallic aluminum with

a radius of 0.6 cm and height of 1.1 cm is used as the sample, located 0.8 cm from the detector. The experimental setup is shown in [Figure 2: see original paper].

As the neutron source, we use thermal neutrons ranging in energy from 0.01 eV to 1 eV with an energy spectrum satisfying Maxwell' s distribution. The neutron distribution on the converter is obtained by importing relevant parameters into MCNP. The results are represented as density maps for $PScF(r)$ and $TPScF(r)$ in [Figure 3: see original paper]. In the figure, r indicates the distance from the detection point to the center of the detector plane. Figure 3: see original paper shows simulation results using $PScF(r)$ as the point scattered function, while Figure 3: see original paper shows $TPScF(r)$ for comparison. Red areas indicate heavy neutron scattering, while blue areas indicate very light scattering. The boundary of the red area lies roughly at 0.6 cm, generally matching the actual sample dimensions. Note that the boundary between areas is not particularly clear due to idealization of the neutron energy spectrum and the stochastic nature of scattering in the sample. However, established methods exist to address this, primarily through energy spectrum correction and computer algorithms to sharpen edges, making neutron imaging more representative of actual experimental conditions [**?**, **?**].

Comparing Figure 3: see original paper and (b), $TPScF(r)$ gives overall smaller results than $PScF(r)$, indicating a systematic error between them. We therefore define the relative error function as:

$$\sigma(r) = \frac{|TPScF(r) - PScF(r)|}{PScF(r)}$$

For the experiment in [Figure 2: see original paper], the relative error function is mapped in [Figure 4: see original paper]. This result shows that the error is very small in the central area and larger near the edges, with an average error over the entire detection screen of approximately 0.306. Despite this, the model is valid due to the similarity between the two figures, which we further validate through error analysis below.

B. Error Analysis

The error function resembles an exponential function in the radial direction, so we introduce an exponential adjustment. First, we define a new approximate point scattered function:

$$NPScF(r) = TPScF(r) + Ce^{-ar}$$

By fitting the relative error data, we obtain the parameters C and a, yielding:

$$NPScF(r) = TPScF(r) + 8.7646 \times 10^{-5} e^{0.3980r}$$

To study the error relative to the original scattered function, the distribution is plotted in [Figure 5: see original paper]. The figure indicates that relative errors are at a very low level in most regions, with a maximum value of 17% and a mean value of 2.5% across the entire region. This demonstrates that further improvement to the approximation model is possible and validates that $NPScF(r)$ is a very effective point scattered function for the thin-film approximation.

IV. Neutron Imaging Correction

A. Quantitative Neutron Radiographic Analysis Method

Due to the nature of neutron-matter interactions, neutron imaging results are often inaccurate. We can reduce error through advanced experimental equipment and/or improve imaging techniques using correction algorithms. One such method, Quantitative Neutron Radiographic Analysis, uses algorithms to enhance imaging technology based on the exponential neutron decay pattern:

$$I_{sample}(i,j) = I_0(i,j)e^{-(\Sigma_A T(i,j))}$$

where I is neutron intensity, (i,j) is the pixel point in the image, and Σ_A is the attenuation coefficient. The sample thickness distribution can be determined using:

$$T(i,j) = -\frac{1}{\Sigma_A}\ln\left(\frac{I_{sample}(i,j)}{I_0(i,j)}\right)$$

This is the principle behind quantitative neutron radiographic analysis.

Numerous experimental studies have shown that quantitative neutron radiographic analysis is influenced by three main factors: (1) **Collimation Ratio**: The ratio of the distance from the neutron source to the sample relative to the output aperture diameter. Because neutrons are electrically neutral, they cannot be focused by electromagnetic fields, making full collimation impossible. (2) **Scattered Neutrons**: Substances with high scattering cross sections (e.g., water and polyethylene) cause many scattered neutrons to reach the detector, distorting and blurring the image. The solution is generally to increase the sample-detector distance. (3) **Neutron Energy Spectrum**: Since incident neutrons are not monoenergetic and different energy neutrons interact with matter via different cross sections, using a single cross section parameter can produce large errors. Additionally, the energy spectrum of neutrons scattered by the sample may differ from the source spectrum due to attenuation during propagation.

The focus of this study is neutron image correction through scattering correction. To investigate optimization of the proposed model for neutron imaging, the iterative algorithm for quantitative analysis of scattering samples is shown in [Figure 7: see original paper].

In the algorithm, I_{su} is the normalized neutron intensity, I_{sc} is the scattered neutron distribution function, and k is the iteration number. The convergence criterion:

$$\frac{\sum_{i,j} |I_{su}^{k+1}(i,j) - I_{su}^{k}(i,j)|}{\sum_{i,j} I_{su}^{k}(i,j)} \leq \epsilon$$

is used to select a convergence coefficient ϵ that terminates the iterative calculations. This criterion represents the relative change in transmitted neutron intensity between two adjacent iterations. As the algorithm converges, this value becomes increasingly smaller, gradually approaching zero. This algorithm has been tested extensively and is highly reliable, making it applicable to the thin-film point scattering function model developed above.

B. Optimization Algorithm Based on Thin-film Approximation Models

In the iterative algorithm ([Figure 7: see original paper]), $PScF(r)$ is calculated based on sample thickness before iterative calculations begin. However, using $NPScF(r)$ instead of $PScF(r)$ can greatly accelerate convergence, as $NPScF(r)$ is equivalent to an approximate numerical integration of $PScF(r)$. When we applied this substitution to the experiments in Section III.A, only three iterations were required to obtain satisfactory results, as shown in [Figure 6: see original paper].

The results demonstrate both the reliability of the iterative algorithm and the faster correction achieved using $NPScF(r)$. Iterative calculations using $PScF(r)$ require five iterations to converge and take approximately three times longer than those using $NPScF(r)$. Comparing the result using $NPScF(r)$ with that using conventional $PScF(r)$, the latter produces poorer imaging results, slower convergence, and greater edge distortion, while the former produces good imaging results with only slight edge distortion.

Similar simulations for trapezoidal objects and cones showed that using $NPScF(r)$ instead of $PScF(r)$ for iterative calculations not only improved simulation quality but also increased algorithm speed. Moreover, recent years have seen the introduction of "3D detectors" for neutron radiographic techniques [**?**, **?**]. These add 3D microstructures such as trenches or holes to planar detectors and fill them with neutron converter material, significantly improving detection efficiency. The model proposed in this paper is also applicable to this class of detectors, and together with the algorithm in [Figure 7: see original paper], yields optimized results. However, the geometric parameter relationships must be recalculated for the 3D detector structure. A mathematically feasible approach is to use the symmetry of the 3D detector microstructure for piecewise solutions. For example, if the 3D microstructure is axisymmetric, it can be solved by radius using the center of symmetry,

determining the geometric relationship at a fixed radius, and then applying the method from Section II.

C. Effects of Energy Spectrum Hardening

For the thermal neutron spectra considered in this study, cross sections interacting with matter approximately obey the $1/v$ law. As neutrons penetrate the sample, low-energy neutrons decay more rapidly than high-energy neutrons, ultimately increasing the proportion of higher-energy neutrons in the spectrum—a phenomenon known as energy spectrum hardening.

The current solution defines an "effective neutron cross section"to correct for the energy spectrum. Considering that the macroscopic cross section is no longer constant, neutron transmittance is no longer simply exponential with sample thickness, even without scattered neutrons. Therefore, the detector' s energy response must also be considered. We define an effective cross section based on the ratio of incident to transmitted neutron intensity:

$$\frac{I_{su}}{I_0} = e^{-\Sigma_{eff}(T)\cdot T}$$

where $\Sigma_{eff}(T)$ represents the effective cross section for a sample of thickness T.

The intensity of neutrons detected by a detector is typically expressed as:

$$I_0 = \int \Phi(E)\left(1 - e^{-\Sigma_{det}(E)\cdot d}\right) dE$$

and the transmitted neutron intensity is:

$$I_{su} = \int \Phi(E) e^{-\Sigma(E)\cdot T}\left(1 - e^{-\Sigma_{det}(E)\cdot d}\right) dE$$

According to the $1/v$ law, which is approximately satisfied by thermal neutrons, the conventional neutron cross section can be expressed as:

$$\Sigma(E) = \Sigma_{th}\sqrt{\frac{E_{th}}{E}}$$

where $E_{th} \approx 0.025$ eV is the energy of a thermal neutron. Considering the detector energy response as a whole, $\varepsilon(E) = 1 - e^{-\Sigma_{det}(E)\cdot d} \approx \Sigma_{det}(E)\cdot d$, and combining the above equations yields:

$$\Sigma_{eff}(T) = -\frac{1}{T}\ln\left(\frac{\int_E \Phi(E) e^{-\Sigma_{th}\sqrt{E_{th}/E}\cdot T}\varepsilon(E)dE}{\int_E \Phi(E)\varepsilon(E)dE}\right)$$

However, due to difficulties in performing integration operations and obtaining relevant data, a simplified approximation is desirable. The approach in [**?**] applies a linear fit, but we believe this would produce large errors. Instead, we adopt a numerical integration approach as described in Section II.B. Applying the Newton-Cotes method:

$$\Sigma_{eff}(T) \approx -\frac{1}{T}\ln\left(\frac{4\cdot\sum_{n=1}^{m}\Phi((2n-1)h)e^{-\Sigma_{th}\sqrt{E_{th}/((2n-1)h)}\cdot T}\varepsilon((2n-1)h)+2\cdot\sum_{n=1}^{m-1}\Phi(2nh)e^{-\Sigma_{th}\sqrt{E_{th}/(2nh)}}}{4\cdot\sum_{n=1}^{m}\Phi((2n-1)h)\varepsilon((2n-1)h)+2\cdot\sum_{n=1}^{m-1}\Phi(2nh)\varepsilon(2nh)}\right.$$

where h is the step size, and note that $\Phi(E) = 0$ at both $E = 0$ and $E = \infty$. Introducing the effective cross section makes spectral decomposition lines more visible, so that sample edges or large density variations are more clearly reflected in the image.

However, further modifications to $NPScF(r)$ (Eq. 15) would improve energy spectrum correction. Maxwell' s spectrum can be formally defined as $\Phi(E) = aE\exp(-E/b)$. Energy spectrum hardening essentially represents excess retention of fast neutrons and excess depletion of slow neutrons, reflected in an increase in parameter b. Considering the specific form of Maxwell' s spectrum, an increase in b is equivalent to an increase in background temperature. We can therefore perform the following transformation:

$$\Phi(E) \to \Phi_\lambda(E) = \frac{2}{\sqrt{\pi}(kT)^{3/2}}\sqrt{E}e^{-E/k(T+\lambda)}$$

The temperature-corrected energy spectrum is then used in calculations. Parameter λ can be determined by fitting the specific energy spectrum to this equation. Substituting the corrected energy spectrum into Eq. 13 and replacing the mean scattering cross section with the effective scattering cross section yields:

$$TPScF(r) = \frac{\sum_{i=0}^{E_m}\Phi_\lambda(E_i)\Sigma_{det}(E_i)\Sigma_{eff}(E_i)F(E_i,r)}{\sum_{i=0}^{E_m}\Phi_\lambda(E_i)\Sigma_{det}(E_i)}$$

Subsequently, we can correct for error by applying error analysis as discussed in Section III.B, choosing a suitable exponential function based on the symmetry of the spatial distribution.

V. Conclusion

In this study, we investigated an approximate point scattered function for correcting neutron radiographic imaging. The modeling is presented in Section II.A, while Section II.B explains the algorithmic calculations. The simulation

experiment in Section III demonstrates the model' s validity through the results shown in [Figure 3: see original paper]. The model was then corrected based on the relative error results in [Figure 4: see original paper], reflected in the addition of an exponential error adjustment function (Eq. 15) with parameters determined by fitting to finally obtain Eq. 16, producing satisfactory simulation results. [Figure 5: see original paper] validates the correction, showing a mean relative error of 2.5% across the entire neutron converter.

In Section IV, we applied the model to the popular quantitative neutron radiographic analysis algorithm and found that replacing the conventional point scattered function with the proposed approximate version results in better neutron imaging, faster algorithm convergence, and significantly fewer iterations. Additionally, we investigated energy spectrum hardening effects on neutron radiographic imaging, concluding that hardening is equivalent to increasing the background temperature in Maxwell' s spectrum, and therefore a temperature correction parameter can be introduced (Eq. 26). After replacing the mean scattering cross section with the effective scattering cross section and including temperature correction, the new point scattering function is given by Eq. 27. Finally, we discussed the error analysis method applicable to the proposed model.

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Note: Figure translations are in progress. See original paper for figures.