Resolution analysis of thermal neutron radiography based on accelerator-driven compact neutron source (Postprint)

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Abstract

Owing to the immobility of traditional reactors and spallation neutron sources, the demand for compact thermal neutron radiography (CTNR) based on accelerator neutron sources has rapidly increased in industrial applications. Recently, thermal neutron radiography experiments based on a D-T neutron generator performed by Hefei Institutes of Physical Science indicated a significant resolution deviation between the experimental results and the values calculated using the traditional resolution model. The experimental result was up to 23% lower than the calculated result, which hinders the achievement of the design goal of a compact neutron radiography system. A GEANT4 Monte Carlo code was developed to simulate the CTNR process, aiming to identify the key factors leading to resolution deviation. The effects of a low collimation ratio and high-energy neutrons were analyzed based on the neutron beam environment of the CTNR system. The results showed that the deviation was primarily caused by geometric distortion at low collimation ratios and radiation noise induced by high 1 energy neutrons. Additionally, the theoretical model was modified by considering the imaging position and radiation noise factors. The modified theoretical model was in good agreement with the experimental results, and the maximum deviation was reduced to 4.22%. This can be useful for the high-precision design of CTNR systems.

Full Text

Resolution Analysis of Thermal Neutron Radiography Based on Accelerator-Driven Compact Neutron Source

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Abstract

The immobility of traditional reactors and spallation neutron sources has driven rapidly increasing demand for compact thermal neutron radiography (CTNR) based on accelerator neutron sources for industrial applications. However, recent thermal neutron radiography experiments conducted by the Hefei Institutes of Physical Science using a D-T neutron generator revealed a significant resolution deviation between experimental results and values calculated using the traditional resolution model, with experimental results up to 23% lower than theoretical predictions. This discrepancy hinders the achievement of design goals for compact neutron radiography systems.

To identify the key factors causing this resolution deviation, we developed a GEANT4 Monte Carlo code to simulate the CTNR process and analyzed the effects of low collimation ratios and high-energy neutrons based on the neutron beam environment of the CTNR system. Our results demonstrate that the deviation is primarily caused by geometric distortion at low collimation ratios and radiation noise induced by high-energy neutrons. We subsequently modified the theoretical model by incorporating imaging position and radiation noise factors. The modified theoretical model showed good agreement with experimental results, reducing the maximum deviation to 4.22%. These findings provide valuable guidance for the high-precision design of CTNR systems.

Keywords: Neutron radiography, Spatial resolution, Accelerator-driven neutron source, Geant4, MTF, ESF

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1 Introduction

Neutron radiography has emerged as an important non-destructive inspection method and quantitative measurement tool [1]. Thermal neutrons provide strong contrast for elements that are close to one another in the periodic table and can even distinguish isotopes of the same element, making neutron radiography complementary to X-ray and gamma-ray radiography [2]. This capability has led to widespread applications in aerospace, national defense, materials science, energy, biological archaeology, and other fields. Currently, thermal neutron radiography (TNR) represents a critical area in neutron radiography development [3]. However, conventional TNR relies primarily on expensive, bulky, and immobile reactor or spallation neutron sources, which severely limit its practical applications. Compact thermal neutron radiography (CTNR) offers a promising solution to these challenges [4,5].

Unlike conventional TNR, CTNR typically employs a compact accelerator as the neutron generator. Accelerator-driven neutron sources (such as D-D or D-T neutron generators) require complex moderator and collimator configurations to produce neutron beams with suitable radiographic properties [6]. Their intensity is 2–3 orders of magnitude lower than that of reactors or the neutron beams available from spallation sources. Consequently, moderation and collimation are significantly less effective than in conventional neutron radiography, manifesting primarily as a low collimation ratio (L/D) (Table 1) and low thermal neutron content (Fig. 1) [5,7]. Both factors adversely affect imaging resolution but have received limited consideration in conventional TNR systems. Against this background, this paper presents an in-depth study of resolution in CTNR systems.

2.1 The Traditional Resolution Model of Neutron Radiography

The modular transfer function (MTF) is a classical resolution analysis method based on frequency domain analysis derived from the Fourier transform of a point spread function (PSF). Compared with PSF and other spatial domain methods, the MTF approach offers higher accuracy in resolution calculation. The MTF is defined as the ratio of output modulation to input modulation and can be calculated using the following equation [15]:

$$MTF = \frac{(I_{max} - I_{min})/(I_{max} + I_{min})}{(I'_{max} - I'_{min})/(I'_{max} + I'_{min})}$$

where I_{max} and I_{min} are the maximum and minimum grey values of the input image, while I'_{max} and I'_{min} are the maximum and minimum grey values of the target area in the output image. According to the Rayleigh criterion, the spatial resolution of an image is defined as the spatial frequency corresponding to 10% MTF [16]. Furthermore, the MTF method can be used to analyze the effects of various system elements on spatial resolution.

A resolution model is essential for designing TNR systems to ensure that realistic resolution goals are established and achieved. The traditional theoretical resolution model focuses on the TNR system structure, which comprises a collimator, converter screen, and imaging system [15]. Assuming that the effects of these components on imaging resolution are independent, the total MTF of a digital thermal neutron imaging system can be expressed analytically through Fourier transformation [17]:

$$MTF_{total}(u) = \left|\frac{\sin(\pi ud)}{\pi ud}\right| \cdot e^{-(\pi u\delta)^2} \cdot \left|\frac{\sin(\pi u\Delta s)}{\pi u\Delta s}\right| \cdot \left|\frac{\sin(\pi u M_{CCD}\Delta s)}{\pi u M_{CCD}\Delta s}\right|$$

where u is the spatial frequency of imaging, d is the distance from the converter screen to the sample, D is the diameter of the neutron aperture, L is the distance from the aperture to the sample, δ is the optical diffusion response of the converter screen, Δs is the sensor sampling interval, M_{CCD} is the scintillator-to-CCD magnification, and $\Delta s/M_{CCD}$ represents image sampling on the converter screen. The MTF describes the magnitude of the system's frequency response, and the theoretical resolution model is valuable for depicting and quantifying system resolution.

2.2 Deviation of the Theoretical Resolution Model Applied to CTNR

Based on the traditional theoretical resolution model, we analyzed the factors affecting imaging resolution in a TNR system driven by a typical accelerator neutron source (Table 1). Fig. 2 [Figure 2: see original paper] shows the relationship between resolution and L/D for different optical diffusion responses and image samplings on the converter screen. When the L/D ratio is less than 12, the curves for each parameter coincide, indicating that the influence of the converter screen and image sampling is minimal in resolution analysis at low L/D ratios, making the L/D ratio the dominant factor affecting resolution.

To verify the applicability of the theoretical model, we performed neutron radiography experiments using a standard line-pair sample (Fig. 3b [Figure 3: see original paper]) based on the TNR terminal with a D-T fusion neutron source (Fig. 3a) built by the Hefei Institute of Physical Science (HFIPS), Chinese Academy of Sciences. The iron sample measured 50 mm × 100 mm × 10 mm and contained seven line pairs at 0.5, 0.62, 0.83, 1.0, 1.67, and 2.0 lp/mm. A schematic of the system is shown in Fig. 3c, and Table 2 lists the characteristics of the neutron beam emitted by the moderated collimator and the imaging system parameters.

Neutron radiography experiments were conducted using L/D values of 6.3, 7.4, 8.8, 10, and 12, with an imaging exposure time of 300 s. Fig. 4 [Figure 4: see original paper] shows the radiography results for line pairs at different L/D ratios, with the center of the imaging field of view (FOV) coinciding with the center of the neutron beam. Fig. 4a shows the neutron radiograph at L/D=7.4, where the red box indicates the sampling area of the line-pair image from which the corresponding gray curve was obtained. Gray curves for images with other L/D ratios are shown in Fig. 4b. The MTF value for each line-pair image was calculated by substituting the gray values into Eq. 1, and the image resolution was determined using interpolation at MTF=0.1 (Fig. 5a [Figure 5: see original paper]). Theoretical resolution results under the same conditions were calculated using Eq. 2, and a comparison between experimental and theoretical resolution curves is shown in Fig. 5b. Both experimental data and theoretical calculations show that image resolution improves with increasing L/D.

However, all experimental points lie above the theoretical calculation curve, with a maximum deviation of 23.1%. This significant deviation between the theoretical model and experimental results warrants further investigation.

3 Analysis of Main Parameters Affecting Spatial Resolution and Resolution Deviation

This section discusses the effects of low L/D ratios and high proportions of non-thermal neutrons on imaging resolution to elucidate the reasons for the observed deviation, based on Monte Carlo simulation numerical analysis performed using the GEANT4 framework [18]. The G4TENDL database [19], which has demonstrated high computational accuracy in previous studies [20], was employed for the Monte Carlo calculations.

3.1.1 Geometric Distortion

We developed a GEANT4 Monte Carlo calculation model based on the theoretical resolution model. As shown in Fig. 6 [Figure 6: see original paper], the model consisted of three modules: a surface neutron source with a diameter of 9 cm, a converter screen with an area of 20 × 20 cm^2, and a position-sensitive detector. The surface neutron source replaced the accelerator neutron source and moderator to simulate neutron beams emitted from an ideal neutron aperture. The converter screen material was 6LiF/ZnS with specific parameters listed in Table 2 [21]. Photon-emission spectra and other scintillation parameters were set according to previous studies [22]. The position-sensitive detector was affixed to the back of the converter screen with a single pixel sampling area of 0.2 × 0.2 mm^2, consistent with the projection of CCD camera pixels on the converter screen. This detector recorded information about the number and position of photons produced in the converter screen [23], generating grayscale images for comparison with experimental results. Based on this model, the effect of neutron beam characteristics on resolution could be analyzed for arbitrary L/D parameters.

The edge-spread function (ESF) method was used to extract resolutions at different locations in the simulated image [24]. In this method, an opaque sample with a straight edge serves as the imaging object, and the curve of grey-level change perpendicular to the image edge is called the ESF curve. Spatial resolution is defined as the distance between the 10% and 90% points on the ESF curve [25]. A schematic of the resolution measurement simulation using the ESF method is shown in Fig. 7 [Figure 7: see original paper], where the red box represents the imaging sampling area centered on the sample edge. The relative distance between the sample edge and imaging center was defined as d_c. The experimental sample was a 1 cm-thick rectangular iron block, and different images were obtained in simulations by adjusting the edge positions. Grey value curves extracted from simulation images were used to calculate resolution at each position via the ESF method.

Simulation results were compared with experimental images to verify accuracy. The yellow boxes shown in Fig. 4 (L/D=7.4) were selected as sampling areas with d_c=1.0 cm and d_c=5.0 cm. Fig. 8a [Figure 8: see original paper] presents the grey images extracted from the experimental image alongside simulated images with the same d_c parameters. Fig. 8b compares the corresponding grey curves, showing good agreement between simulated and experimental curves with a calculated resolution deviation of less than 4.5%.

Using this validated simulation method, we first calculated imaging resolutions at different positions for L/D=7.4. Fig. 9a [Figure 9: see original paper] shows the results, where the black line represents spatial resolutions at different positions and the red line represents deviations between simulated and theoretical resolutions. The resolution curve exhibits a symmetrical structure, with deviations increasing linearly with d_c. To further investigate the influence of d_c on resolution under different L/D conditions, we simulated images with five different L/D ratios and obtained resolutions at various imaging positions. Fig. 9b presents the variation in deviations between simulation and theoretical calculation results at different d_c positions, showing that deviations increase with d_c but gradually narrow as L/D increases. Notably, simulation results are consistent with theoretical model predictions at the image center (d_c=0), with a maximum deviation of less than 2.7%.

Experimental data analysis yielded similar results to the Monte Carlo simulations. Fig. 9c presents ESF curves derived from experimental data for L/D=7.4 and L/D=12, showing significant deviation between imaging locations at d_c=1 cm and d_c=5 cm, with larger deviations observed at smaller L/D ratios. These experimental results intuitively demonstrate the impact of geometric distortion on imaging resolution.

Based on this analysis, we conclude that geometric distortion is a critical factor causing resolution deterioration. Under low-collimation conditions, resolution degradation due to geometric distortion increases linearly with d_c.

To explore the underlying mechanism, we calculated the neutron beam emission angle distribution using our Monte Carlo simulation model. Neutron emission angles were recorded on the front surface of the converter screen at different d_c intervals. Fig. 10a [Figure 10: see original paper] presents results for d_c intervals of 0–1 cm, 1–2 cm, 3–4 cm, 5–6 cm, 7–8 cm, and 9–10 cm under L/D=10 conditions, while Fig. 10b shows results for the d_c range of 4.5–5.5 cm with five different L/D ratios. The results indicate that when only d_c increases, the Gaussian widths of the neutron emission angle distribution do not change significantly, but the average neutron emission angle gradually increases. When d_c is fixed, the average neutron emission angle decreases with increasing L/D.

These findings suggest that image resolution degradation is related to the average neutron emission angle, which can be derived from the parameter d_c.

Based on these considerations, we performed a theoretical derivation. Fig. 11 [Figure 11: see original paper] shows the geometric layout of the collimator, object, and converter screen. The offset distance d_g between original and actual positions can be calculated using simple trigonometry:

$$d_g = d_c \cdot \frac{d}{L}$$

where d_c is the distance from the object to the imaging center, L is the distance from the aperture to the object, and d is the distance from the object to the screen.

An oblique-incidence neutron beam also causes geometric distortion on the converter screen. Fig. 12 [Figure 12: see original paper] illustrates this process, where the offset distance can be calculated as:

$$d_s = t \cdot \frac{d_c}{L}$$

where d_s is the offset of light output on the converter, t is the thickness of the converter screen (as effective photon yield is generated mainly by neutrons reacting at the bottom of the screen), and L is the distance from the collimator aperture to the converter screen. The offset is proportional to t and inversely proportional to the L/D ratio. Fig. 13 [Figure 13: see original paper] shows simulation results of light spots generated by a neutron beam under L/D=10 conditions, demonstrating that d_s moves proportionally with d_c.

Both offsets blur the object edge image and deteriorate resolution. Geometric distortion arises from the physical characteristics of the beam emission angle and can also be observed in traditional TNR and other optical imaging systems [26]. However, unlike CTNR systems where L/D is typically very large, the effect of geometric distortion is usually insignificant in these other imaging modalities.

Effect on Converter Screen Characteristics

The characteristic parameters of a converter screen include photon yield and optical diffusion response [27]. We performed a series of calculations to study these characteristics. In neutron radiography systems, the optical diffusion response (δ) of the converter screen can be calculated as [16]:

$$PSF(x,y) = \exp\left[-\pi\left(\frac{\sqrt{x^2+y^2}}{\delta}\right)^2\right]$$

where $PSF(x,y)$ is the light output distribution induced by a single neutron beam from the converter screen. Fig. 14a [Figure 14: see original paper] shows Monte Carlo simulation results of photon output behind the converter screen, which conform to the Gaussian distribution of Eq. 5. The Gaussian widths of photon distribution with large L/D ratios are significantly smaller than those with small L/D ratios, while the neutron light yield at the spot center decreases with deteriorating L/D.

Fig. 14b compares δ fitted from Fig. 14a with the total neutron light yield, showing that δ exhibits a negative relationship with the L/D ratio, consistent with the analysis in Fig. 14a. However, under different L/D conditions, the total photon yield of neutrons remained approximately constant, indicating that the L/D ratio does not affect the light output of the converter screen. Fig. 14c shows the variation of optical diffusion response with screen thickness under different L/D conditions. When L/D=100, the curve shows little correlation, but the other two curves exhibit evident positive correlations, with the effect of converter screen thickness on δ increasing significantly as the collimation ratio decreases.

In an ideal neutron radiography model, different components are considered independent. However, our analyses reveal that under low L/D conditions, changes in the L/D ratio affect δ of the converter screen, representing one factor potentially contributing to experimental resolution deterioration. When the converter screen thickness is set to 100 m as used in the experiment, δ is 6.32 m at L/D=10 and 3.49 m at L/D=100. In this case, the MTF change caused by δ is only 0.89% on the limiting resolution of devices (1 lp/mm), indicating that while δ changes under different L/D conditions can affect image resolution, the effect is not significant.

3.2 Effect of High-Energy Neutrons on CTNR System

Effect on Converter Screen

In CTNR systems, a moderator is used to thermalize fast neutrons from the accelerator. To study the relationship between neutron energy and spatial resolution, we developed a CTNR system model shown in Fig. 15a [Figure 15: see original paper]. An 8 cm-thick lead layer served as the first moderator layer, followed by a 5 cm-thick polyethylene layer to obtain thermal neutrons, with a 15 cm-thick graphite reflective layer. This design significantly improves thermal neutron flux [28][29]. A 14 MeV neutron source was placed on the central axis before the moderator with a 1 cm-diameter beam spot.

This model enables study of thermal neutron flux, neutron beam energy spectrum, and photon yield from neutrons of different energies after passing through various moderation materials. Fig. 15b presents the energy spectrum of the neutron beam exiting the moderator, showing that the proportion of thermal neutrons was only 9.13%. After moderation, numerous non-thermal neutrons remained in the beam, making this model appropriate for studying non-thermal neutron effects on imaging.

Non-thermal neutrons interact with the converter screen through different cross sections. We first calculated the photon yield for neutrons of different energies (Fig. 16a [Figure 16: see original paper]), which was roughly consistent with the microscopic cross section of ^{6}Li. Fig. 16b shows simulation results of photon yield produced by the neutron beam exiting the moderator, where photons generated by thermal neutrons accounted for 95.79% and those from non-thermal neutrons for 4.21%. Based on these results, the effect of non-thermal neutrons on imaging resolution can be neglected in CTNR systems, even with a low proportion of thermal neutrons in the beam.

Effect on CCD

CTNR system shielding is limited by geometric dimensions, making complete shielding of high-energy neutrons and their secondary gamma rays difficult. When radiation particles reach the CCD chip, they deposit energy that generates electronic noise [30]. Noisy images obtained under different experimental conditions are shown in Fig. 17 [Figure 17: see original paper], demonstrating that white spot noise effects cannot be neglected even with shielding. The noise proportion in neutron radiography images was 2.07% with shielding and 7.09% without shielding.

Radiation noise presence is detrimental to quantitative resolution analysis. Both ESF and MTF methods rely on numerical analysis of gray curves in the sampling area. Due to limited sampling area, even a few random white spots significantly interfere with the grayscale curve, affecting resolution analysis results. Median filtering is sometimes used to eliminate noise in neutron radiography images, but it also causes an overall decrease in imaging resolution and cannot completely eliminate white spots [31]. The theoretical resolution model does not consider electronic noise and background radiation effects, which are negligible compared to radiation noise during short imaging times. The following section presents a quantitative study of radiation noise effects on image resolution.

4 Optimization of the Theoretical Resolution Model for CTNR System

4.1 Correction of Geometric Distortion

Geometric distortion deviates the projection position of the object, causing horizontal stretching of the ESF curve. Based on our analysis, the total stretch length of the ESF curve is the sum of spot position offsets D_g and D_s from Eqs. 3 and 4.

The ESF after geometric distortion can be calculated using Eq. 6:

$$ESF_p = ESF_0 + 0.8 \times (d_g + d_s)$$

where ESF_p denotes the actual resolution, ESF_0 is the resolution at $d_c = 0$, and 0.8 is the influence coefficient defined by the ESF method (the distance between the 10% and 90% grey values of the ESF curve). Table 3 compares resolutions obtained through experimental, simulation, and theoretical methods, showing good agreement (deviation within 3%).

In measurements, the MTF corresponding to a line pair was calculated using Eq. 1, with the input MTF (M_{in}) gradient fixed. Due to geometric distortion, the grey gradient of the line pair curve changed, but this did not affect I_{max} and I_{min} inputs for each line pair measurement. The MTF variation caused by geometric distortion can be expressed as:

$$MTF_p = \frac{(I_{max} - I_{min})/(I_{max} + I_{min})}{(I'_{max} - I'_{min})/(I'_{max} + I'_{min})}$$

where MTF_0 is the theoretical MTF unaffected by geometric distortion and MTF_p is the experimentally measured MTF. The image of a slit was obtained by subtracting ESF curves from the two edges of the slit. Due to the narrow slit width, the two curves are assumed identical, making the slope proportional to the ESF curve slope, which is inversely proportional to ESF resolution.

According to Eq. 7, the measured MTF_p can be expressed as:

$$MTF_p = MTF_0 \cdot \frac{ESF_0}{ESF_p}$$

where ESF_p denotes the ESF resolution of the line pair and ESF_0 is the ESF resolution at $d_c = 0$. The relationship between ESF_p and ESF_0 is obtained using Eq. 6. Assuming the resolution corresponding to ESF_0 matches the theoretical resolution, the MTF at the line pair can be calculated as:

$$MTF_{total} = \frac{MTF_0}{1 + 0.8 \cdot \frac{d_g + d_s}{ESF_0}}$$

This equation was used to analyze experimental data for MTF calculation considering geometric distortion. Table 4 compares results with and without correction, showing that after accounting for geometric distortion, the maximum deviation was reduced from 23.1% to 8.82%, demonstrating that geometric distortion is a significant factor affecting CTNR system resolution.

4.2 Correction of Radiation Noise

The effect of radiation noise can be regarded as an independent factor due to the irregular scattering of fast neutrons. When noise effects are considered, the total MTF can be calculated as:

$$MTF_{total} = MTF_{system} \cdot MTF_n$$

where MTF_{total} is the total MTF value containing noise and MTF_n is the MTF of the noise. This treatment is appropriate because noise distribution is random.

Within a fixed imaging area containing n samplings, with noise proportion σ and average noise gray value g, random noise addition increases each column's gray value by σng. The MTF_n calculation formula is:

$$MTF_n = \frac{[(I_{max} + \sigma ng) - (I_{min} + \sigma ng)]/(I_{max} + I_{min} + 2\sigma ng)}{(I_{max} - I_{min})/(I_{max} + I_{min})}$$

The noise gray value in an image is constant for a given neutron radiography system. For single imaging, I_{max} and I_{min} are regarded as constants, allowing replacement of $ng/(I_{max} + I_{min})$ with constant r. Eq. 11 simplifies to:

$$MTF_n = \frac{1 - r\sigma}{1 + r\sigma}$$

This shows that noise proportion directly affects image modulation, with MTF negatively correlated with noise proportion. Experimental verification of Eq. 12 has been detailed in the literature [32].

In this study, white spot noise parameters were extracted from experimental images to correct theoretical calculations. White spot noise was identified based on abnormal gray gradients in the experimental image from Fig. 4, and average gray noise values and noise proportions were calculated for each image. MTF_n for each image was then calculated using Eq. 12. Table 5 lists the corrected theoretical and experimental results, showing that after considering both geometric distortion and radiation noise effects, the maximum deviation between the theoretical model and original experimental results was reduced to 4.22%. A small systematic deviation between the revised theoretical model and experimental values remains, primarily due to interference from non-fixed device factors such as neutron scattering by the experimental sample.

5 Conclusion

A significant resolution deviation between experiment and the traditional theoretical resolution model was observed in neutron radiography experiments performed by the Hefei Institute of Physical Science. To explain this phenomenon, we analyzed the effects of low L/D ratios and high-energy neutrons on imaging resolution using Monte Carlo simulations. The results indicated that the deviation was primarily caused by geometric distortion and radiation noise. Resolution deviation was effectively reduced by considering imaging position and introducing a noise factor. The following conclusions were drawn from theoretical model optimization:

1) When the imaging position is far from the imaging center, geometric distortion degrades image resolution in CTNR systems, with the effect becoming more significant as L/D decreases.
2) The optical diffusion response of the converter screen is not independent of L/D under low L/D conditions. However, changes in δ have minimal effect on resolution for thin converter screens.
3) The effect of non-thermal neutrons on spatial resolution can be neglected in CTNR systems, but radiation noise induced by high-energy neutrons and secondary gamma rays causes resolution degradation.
4) Considering both geometric distortion and radiation noise effects, the modified theoretical model agrees well with experimental results, reducing the maximum deviation from 23.1% to 4.22%.

This study analyzed factors affecting imaging resolution in low-L/D environments, representing the main difference between CTNR and traditional TNR systems. Currently, resolution degradation caused by geometric distortion and radiation noise has not been fundamentally resolved. Design improvements to the moderating collimator and performance optimization of imaging systems represent key directions for future research.

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

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