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Determination of a neutron beam divergence after the rocking curve concept using Richardson–Lucy's unfolding algorithm

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ABSTRACT

Thermal neutron radiographs acquired under high beam divergences suffer the impact of intense penumbrae degrading their final quality. As a divergence reduction is not always feasible, one possible alternative is an *a posteriori* treatment to restore the degraded images, such as the *Richardson–Lucy — RL* unfolding algorithm. Such a procedure requires the characterization of the spoiling agent *Point Spread function – PSF* in order to apply it in the inverse way. It can be deduced from the blur in the radiograph of a shielding blade edge. This blur depends upon the *beam divergence* and the *object–detector gap*. Due to the complex scattering of neutrons along a reactor channel, it is usual to express this divergence as the inverse of an *L/D ratio*. A novel approach based on the concept of *Rocking Curve – RC*, a term borrowed from the X-ray diffraction field, has been recently proposed which yielded slightly better quantitative results. After this concept, every sub-element of a surface source emits neutrons *anisotropically* following a bell-shaped profile. The RC angular semi-width incorporating neutron scattering and geometrical blur, is assigned as the beam divergence. The present work aims at its assessment through a quantitative determination ratified by a qualitative evaluation of radiographs unfolded by the RL algorithm. Its main purpose is an additional ratification of the soundness, consistency and robustness of the RC concept by comparison with formerly obtained quantitative results. In spite of the utterly different approaches and techniques, the outcome has corroborated the novel concept. All data treatment is simple and performed by an ad hoc written Fortran 90 program embedding the required algorithms.

1. Introduction

Radiographic images acquired with thermal neutrons are *infested by plagues* such as beam divergence, poor detector resolution, neutron scattering, statistical fluctuation and electronic noise which degrade their final quality. All of them are impossible to eliminate or at least hard to mitigate at their origin due to their fundamental features or technological and engineering constraints. Yet, although not possible to restore the primordial image, it is feasible to improve them through a *post-acquisition* treatment such as an unfolding with the *Richardson–Lucy — RL* algorithm [1,2]. This treatment requires however the characterization of the spoiling agent *Point Spread Function–PSF* in order to apply it in the inverse way.

The PSF is the response of an image acquisition system to a point-like input. For isotropic systems it has an intensity distribution with a radial symmetry engulfing all the spoiling agents. Although hard to characterize, it can be fairly expressed by the rotation of a Gaussian around its epicenter, and its standard deviation deduced from the blur cast on a detector by the straight edge of shielding blade. This blur depends upon the *beam divergence w*, being amplified by the *object-detector gap g*.

As for the beam divergence itself, it is worthwhile to define its meaning within the scope of this work as follows. A flat surface source emitting only in the perpendicular direction, should not produce any penumbra at the detector, independently of the object-detector gap or its thickness. As early stated by Berger [3] – quoted in *Domanus* [4] – "*. . . the present state of art is such that parallel beams are definitely preferred*". This assertion was later on refuted by Barton [5] who concluded that a divergent collimator produces better images.

This disagreement seems to be a matter of misinterpretation. Perhaps Berger had in mind an *ideal flat source* as above described and not a real one where each source sub-element would emit neutrons isotropically. Or perhaps he was actually referring to *quasi-parallel* beams, as those tied to high *L/D ratios*. Under such a circumstance, a divergent collimator would naturally produce a better image, as stated by Barton, because in this case, the ratio of the source–detector clearance *L* to source size *D*

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would increase towards that exhibited by an ideal point source, where the L/D ratio would obviously raise to infinite. An *ideal point-source* as well, would not blur the image, and thus is treated in this work as *non-divergent*, in spite of its conical beam.

In a *real* neutron acquisition system however – where a *virtual* flat source could be visualized *somewhere* in the reactor neutron channel – scattering causes some neutrons to hit the detector at different angles, as if they were delivered from several sources at different distances and intensities.

The overall impact on the quality of final image is equivalent to that caused by a single source of *unknown* size *D* located at an as well *unknown* distance *L* from the detector. As comprehensively addressed by Domanus [4], other techniques e.g., [6–10] rather than simple length measurements should be carried out to measure the *effective* L/D, which is always lower than the purely *geometric* one and rules the quality of the final image. Hence, disregarding the specific geometric arrangement at any facility, the images would exhibit equivalent qualities if they were acquired under the same effective L/D.

The approach condensing the spoiling agents into a single L/D parameter overcomes the complex task of dealing with them, mainly with neutron scattering. Recent works have been proposed [11,12] positing the concept of *Rocking Curve – RC*, a designation borrowed from the X-ray diffraction field. It assumes that the source emit neutrons *anisotropically* with intensities ruled by a 3D-Gaussian distribution, and the beam divergence expressed by its angular half width at half maximum – HWHM designated as *w* in this work.

For the sake of completeness, some features of those works including drawings, sketches and equations are shared by the present work. Although both earlier works share the same concept, they employ utterly different approaches and techniques. While Ref. [11] employs a position sensitive detector, a slit collimator and data treatment involving unfolding and extrapolation, Ref. [12] requires the neutron radiograph of a shielding blade edge, and an ad hoc written algorithm. Despite these differences, the results agree within 7% as follows:

Reference	[11]	[12]
RC HWHM (min)	75.91 ± 1.52	81.20 ± 1.18

Besides this fair agreement, the single blade required by Ref. [12], instead of an elaborated test-object to measure the L/D, makes the method affordable and attractive due to its simplicity. Furthermore, its basic algorithm used to measure the RC has been also used to measure the L/D agreeing fairly with Ref. [13] – based on neutron flux measurements – and exhibiting a lower uncertainty than the standard method presented in Ref. [6] as follows:

Reference	[6]	[12]	[13]
L/D ratio		20.14 ± 1.17	19.2 ± 0.71
L/D uncertainty %	12.5–16.7	5.8	3.7

The above data refer to the neutron port of the *Argonauta* research reactor at *Instituto de Engenharia Nuclear – CNEN*, Rio de Janeiro Brazil, where the measurements [11–13] have been done. In spite of the better uncertainty exhibited by Ref. [13], it is less employed due to its time-consuming.

Taking into account this performance, and considering that the RC concept has not been yet comprehensively and exhaustively cross-checked, it is an advisable policy to ratify its soundness, consistency and robustness by another approach. Within this frame, the present work addresses the determination of the beam divergence through unfolding of a neutron radiograph with the RL algorithm.

This is done by an analysis of radiographs unfolded with different PSF widths *s*, which selects the better amidst them. Its related PSF width s_x and the object-detector gap g_0 used to get the original radiograph constitute the coordinates [g_0, s_x] from which the related beam divergence w_0 will be inferred. To accomplish this task, a family of *synthetic* curves $s(w, g)$ is generated and the curve $s(w_0, g)$ hit by [g_0, s_x] is assigned as the searched one tied to the RC HWHM w_0. Further details are presented in Sections 2.4 and 2.5.

An illustrative concept of the RC is sketched in Fig. 1, where a high divergence corresponds to a broad Gaussian (large *w*) while a *zero* divergence would be expressed by an infinitely narrow one, emitting neutrons solely in the axial direction.

2. Materials and methods

The direct experimental determination of the PSF is very hard due to the low counting statistics imposed by its small size. Instead, it is replaced by the measurement of the *Line Spread function – LSF*, the response of a system to a line which can be obtained by differentiation of the *Edge Response Function – ERF.* This function is provided by the radiograph of a shielding blade edge. A Gaussian is then fitted to the LSF distribution and its FWHM assigned as the PSF width, since LSF and PSF share the same FWHM when the distribution follows a Gaussian profile [14] as depicted in Fig. 2. To overcome the related radiological burden, reactor operation costs and a cumbersome work, the family of curves $s(w, g)$ is obtained by an ad hoc written algorithm which generates synthetic radiographs and carries out the required treatments.

2.1. Generation of the synthetic images

To achieve this task a virtual 2D detector emulating a real one such as an imaging plate is positioned at the end of a neutron channel perpendicularly to its axis, as sketched in Fig. 3.

Somewhere in the neutron channel, a flat neutron source filling its whole cross-section would emit neutrons which could or not be intercepted by a shielding blade placed at a chosen distance *g* from the detector. Since its edge is aligned with the vertical axis dividing the image into two regions, the left region would be shielded while its right companion would be hit by the neutrons coming from the source. This ideal situation would occur only if the beam divergence or *g* were *zero.* For all other cases the penumbra would invade the neighborhood of the border line blurring the otherwise sharp edge. The intensity of the neutrons hitting the detector is assumed to depend upon the angle $\varPhi$ of their paths to the normal to the source as illustrated by the pictured bell-shaped surface.

Once a spatial detector resolution δ is defined, an *MxN* matrix is assigned to the image, so that δ.M and δ.N represent its width and height respectively. Each pixel intensity is obtained by the summation of all neutrons coming from the source subdivided like the detector into *KxH* square elements of size α. So, α.K and α.*H* represent the width and height of the neutron channel and its virtual source.

For a real source-detector set, the pixel intensity would depend upon the source intensity, detection efficiency and exposure time, but since that – for tiff images – it should not surpass the limit of 65,535, after summation, the pixel intensities as defined by Eq. (1) are normalized to this limit.

$$p(i,j) = \sum_{k=1}^{K} \varOmega(i,k).\sum_{h=1}^{H} \exp\left\{-0.5\left[\varPhi\left(i,j,k,h\right)/\varPhi_w\right]^2\right\} \tag{1}$$

$$\varPhi_w = w.][ln^4 \tag{2}$$

where:

$p(i,j)$ = Pixel intensity on the detector: $i = 1$ to M, $j = 1$ to N.
$\varOmega(i,k)$ = Bump function: *0* if the neutron hits the shielding, *1* otherwise.
$\varPhi(i,j,k,h)$ = Angle between the normal to the source and the straight line connecting the points (i,j) on the detector and (k,h) on the source.
$\varPhi_w$ = Angular standard deviation of the generatrix Gaussian, for the 3D Rocking Curve.
w = Angular Half-Width at Half Maximum – HWHM of the Gaussian.
K = No. of elements along the source width.
H = No. of elements along the source height.
M = No. of pixels along the image width on the detector.
N = No. of pixels along the image height on the detector.