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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Design of a divergence and alignment indicator

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Abstract

The divergence and alignment indicator (DAI) is an extension of the ASTM E803 *L/D* thermal neutron radiography *L/D* device that allows the user to determine both the beam centerline and the beam divergence. The DAI was made using aluminium plate and rods, and incorporated cadmium wire for contrast. Circular symmetry was utilized to simplify manufacture. The DAI was placed with the five posts against the film cassette or radioscopic imaging device in the physical center of the beam. The DAI was perpendicular to the selected beam radius when the front and back center Cd wire images overlap. The degree of misalignment was indicated by their image positions. After the DAI was aligned, analysis of the cadmium wire "+" image spacing yielded the beam divergence. The DAI was tested in a neutron beam which has an *L/D* of 30 but a small degree of divergence. The DAI was also imaged using an X-ray source. The point source predictions of Cd wire image locations showed good agreement with those measured from the X-ray radiograph. The neutron radiographic locations could be predicted using the point source equations, even though the neutron beam was a complex distributed source.

Keywords: Divergence angle; Alignment; Neutron radiography; Beam characterization

1. Introduction

Traditional neutron radiography image quality devices have been designed for use with high intensity, low divergence thermal neutron beams emanating from research reactors where the design of the collimator is well known [1]. Thus, the neutron beam can be characterized by its physical dimensions, the *L/D* ratio, and image quality indicators such as the ASTM sensitivity indicator and beam purity indicator [2]. With the increased use of portable neutron sources, low intensity beams which are more divergent than those typically used in reactor-based neutron radiography are being proposed and in some cases used for neutron radiography applications. Additionally, the portable nature of such a system may lead to uncertainty of the alignment of objects in the beam. Neutron computed tomography is an example where it is important to know with some precision both the beam's centerline and the degree of beam divergence, especially if the beam does not closely approximate a parallel beam. The divergence and alignment indicator (DAI) described in this paper is an extension of the ASTM E803 *L/D* thermal neutron radiography *L/D* device that allows the user to determine both the beam centerline and the divergence [3].

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2. Experimental method

The DAI was made using aluminium plate and rod and incorporated cadmium wire for contrast. Circular symmetry was utilized to simplify manufacture and assembly of the device. The DAI is illustrated in Fig. 1. The dimensions of the device's features are shown on the figure. An important feature of the DAI is flexibility to adapt the "as-built" dimensions into the analysis. Therefore, a high degree of dimensional accuracy is not required in either the cadmium wire or the machined parts. The degree of accuracy in the alignment and calculated divergence depends on the accuracy of measurement of the "as-built" dimensions and the features observed in the radiographic image of the DAI.

A 22-cm diameter 0.31-cm thick aluminium plate was machined with concentric circular grooves (0.32-mm radius by 0.32-mm deep) as illustrated in Fig. 1. Eight radial square grooves (0.32-mm wide by 0.32-mm deep) at 45° angles were machined across the same face of the plate. Five 1.3-cm diameter by 5-cm long aluminum rods were fastened to the plate on the side opposite the grooved face using aluminum screws. These formed the five stand off posts of the DAI. A 0.64-mm diameter by 2-mm long cadmium wire was placed in a drilled center hole in each rod at the end away from the plate and in a hole at the center of the front plate. The front center Cd wire was

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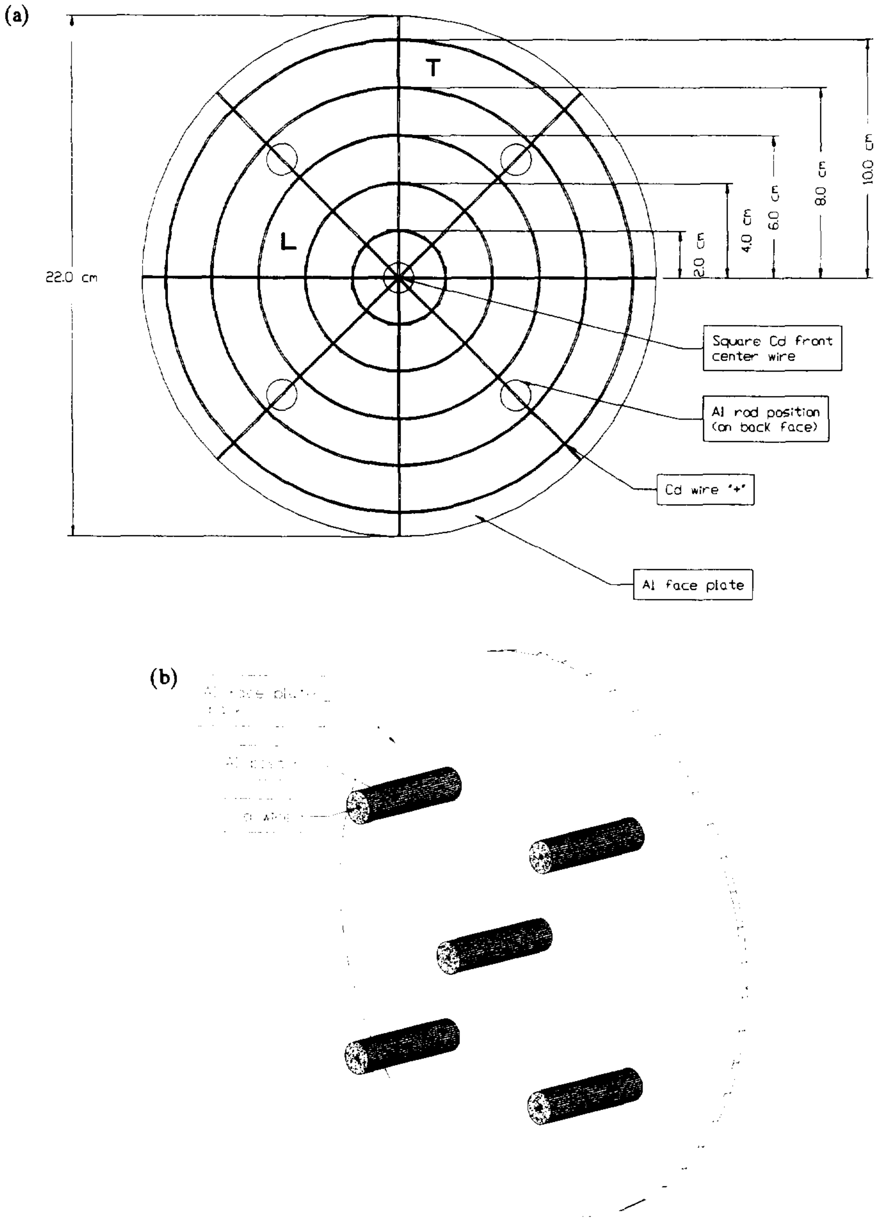

Fig. 1. The DAI device with cadmium shown in solid black; (a) front view showing machined grooves and design dimensions in cm and (b) back view illustrating Al post positions and the Cd wires in the bottom of each post.

placed with a square shaped piece of Cd cut from Cd sheet to help distinguish front from back images. A "+" made from 1-cm long cadmium wires was placed at the intersection of each radial and circular groove. A cadmium "L" and "T" were placed on the face plate as illustrated in Fig. 1.

The DAI was mounted such that the center of rotation was the center square Cd piece in the front of the DAI face plate. The DAI was placed in the physical center of the beam. The X-ray or neutron film cassette was placed against the five posts in the back of the DAI. In the resulting radiograph, the images of the cadmium wires at the bottom of each post gave a set of fixed reference points. It was important to know the offset of the DAI from the film plane to determine some of the beam characteristics, as is discussed below.

3. Theory

The DAI is centered on and perpendicular to the selected radius of the divergent beam when the cadmium wire images at the front and back of the center post overlap. The degree of misalignment will be indicated by the image positions of the front and the back cadmium wires, in the face plate and center post, respectively. After the DAI is aligned, the positions of the "+" images and the posts' cadmium wires can be measured and these radii used to determine the beam divergence for a given beam diameter using the simple relationship developed below for a point source.

The geometry for the DAI and a point source is illustrated in Figs. 2a and 2b. For a point source, the center Cd images will be superimposed when the DAI is perpendicular to any radius. Thus, it is necessary to select the central radius by placing the device in the desired imaging position, usually the physical center of the beam. The rotation angle "A" can be used to determine the amount of rotation about the front center wire needed to make the face plate of the DAI perpendicular to the selected radius using the simple geometric relationship:

$$\tan A = d/j\,, \quad (1)$$

where "j" is the distance separating the front and back center post Cd wires and "d" is the separation between the Cd wires images in the x or y direction. Since the plate can be misaligned in two rotational axes, it is necessary to measure the offset in both the x and y directions. For example, if the center rod back and front Cd wire images were separated by 1 mm at a 45° angle in the first quadrant, it would be necessary to rotate an equal amount around both axes of rotation.

To align the device to a specified radius, a translational motion is required. Fig. 2b illustrates the offset from the selected radius. Now in addition to the center post Cd wire images, the location of the Cd wire "+" images must be utilized. The relationship between the images and the amount of translation motion required to move the center of the DAI to the selected radius, x, is given by:

$$x = cd/(d_1 - d)\,, \quad (2)$$

where c is the "as-built" radius of the DAI "+" Cd wire, d_1 is the difference between the measured "+" Cd wire image radius and c. In most cases the DAI will be placed so close to the desired radius that only rotational motion will be necessary to achieve perpendicularity.

Most neutron beams do not emanate from a point but rather from a distributed source. Although the distributed source geometry causes a geometric unsharpness in the front plate Cd wire images, the center of the blurred front Cd wire image can be used as the imaged wire location. This approximation is justified because the angle of divergence is small and the dimension of the blurred image is small. If this location is used, the simple point source equations can be applied to determine the rotational or translational motion required to align the DAI.

After the DAI is aligned in the beam, the angle of divergence at a selected beam radius can be determined. The distance between the center post Cd wire images and the Cd "+" images is measured, using the center position of all images, as illustrated in Fig. 3. The difference

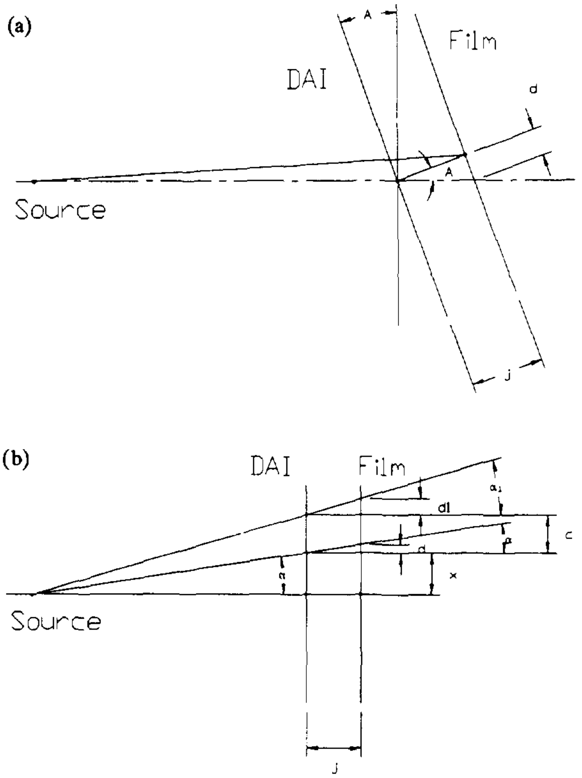

Fig. 2. Simple point source geometry illustrating (a) the center of rotation at the selected beam radius but with the DAI rotated and (b) the DAI perpendicular to the selected radius but translated off axis.

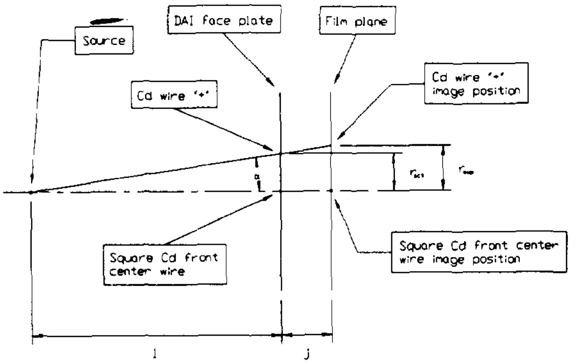

Fig. 3. Illustration of the DAI and the resulting Cd wire image positions using a point source at a distance l from the DAI front plate.

between the image radii measured from the radiograph, r_{exp} and the "as-built" radii r_{act}, and the offset between the DAI front face plate and the imaging plane, j, can be used to determine the beam divergence:

$$\alpha = \tan^{-1}[(r_{exp} - r_{act})/j] . \quad (3)$$

Alternatively, the distance between the source point and the center of DAI face plate, l, can be used to determine the angle α:

$$\alpha = \tan^{-1}[r_{exp}/(l + j)] . \quad (4)$$

If l is unknown, it can be calculated from:

$$l = (r_{exp}/\tan \alpha) - j . \quad (5)$$

The position of the front and back center Cd wires was predicted by assuming the view from the source looking at the DAI. Positive tilt about the horizontal rotational axis was defined to be rotation which moved the top of the DAI away from the source. Positive rotation about the vertical axis was defined to be rotation which moved the right hand side of the DAI toward the source. Motion of the center Cd wire upward and to the right was defined as positive.

4. Results and discussion

The DAI was first imaged using an X-ray source with a 0.3-mm spot size, at a distance of 92 cm, to study the radiographic image in a high divergence beam emanating from a point source. The DAI was then tested in the University of Virginia Nuclear Reactor Facility neutron beam, which has an L/D of 30 but a small degree of divergence. The beam port configuration is a convergent/divergent arrangement using lead and bismuth gamma filters and a boron aperture. The distance from the aperture to the imaging end of the beam tube is 220 cm.

The results from the X-ray beam test agreed with those predicted for a point source. The DAI was placed in the beam at a position which was thought to be in the center of the cone beam and perpendicular to the beam's central radii. The first radiograph indicated the center post front and back wires were not in alignment. The x and y axis deviations were measured and the amount of rotation about the vertical and horizontal axes calculated using Eq. (1). The DAI was rotated by the calculated angle about the horizontal axis, and the subsequent radiograph showed the front and back wires aligned with the horizontal axis. The DAI was then rotated about the vertical axis by the angle calculated to bring the wires into alignment with the vertical axis. The degree and direction of movement were as predicted by Eq. (1) and by the simple geometry.

The ability to predict the effects of DAI rotation and translation movement was demonstrated by a series of tests as shown in Table 1. The theoretical and experiment image positions agree within ±8.4%, with most of the error attributed to measurement error. Rotating by the same degree in both vertical and horizontal axis resulted in the image of the wires separating along a 45° line in the predicted quadrant. The 40-mm horizontal movement to the right with respect to the source caused the front and back wire images to separate as predicted.

The tests were repeated using the distributed neutron source. Measurements were more difficult due to the degree of geometric unsharpness of the front wires at an L/D of 30. However, using the center of the blurred image, the degree of rotation in each axis required to align the DAI was calculated using Eq. (1). After rotating in both axis by the angles predicted using the point source geometry equation, the DAI was aligned. The amount and direction of the front and back center post Cd wires were measured following rotational and translational motion of the DAI. In all cases the measured value agreed with the calculated value.

After the DAI was aligned in the X-ray and neutron beams, the radiographic images of the Cd crosses were measured. The results for the X-ray and neutron beams are presented in Table 2. Note that the "as-built" radii differed slightly from the design values. The "as-built" radii must be used in the calculations. The angle of beam divergence was calculated using a measured l for the X-ray beam, α_1, and by using only the data from the DAI and the

Table 1
Comparison of measured "d" from X-ray radiograph of DAI

Movement	Angle or distance	d theoretical [cm]	d experimental [cm]	Error [%]
Tilt	+1.0°	0.0873	0.080	8.4
	+2.0°	0.1746	0.170	2.6
	+4.0°	0.3496	0.360	−2.9
	−4.0°	0.3496	0.350	0.01
Tilt and rotate	−1°, +1°	0.123	0.115	−6.5
	+2°, +2°	0.247	0.240	2.8
	+4°, +4°	0.494	0.490	0.8
Horizontal	+40 mm	0.217	0.230	−6.0

Table 2
Comparison of X-ray and neutron beam results

As-built radius [cm]	X-ray image radius [cm]	X-ray α_1 [a] [deg]	X-ray α_2 [b] [deg]	X-ray l [cm]	Neutron image radius [cm]	Neutron α [deg]	Neutron l [cm]
9.91	10.5	6.127	5.798	97.59			
7.914	8.385	4.900	4.640	97.51			
5.99	6.34	3.709	3.447	99.43			
3.915	4.19	2.453	2.710	82.71			
1.943	2.065	1.210	1.208	92.13			
0	0	0	0		0	0	
−1.99	−2.12	−1.242	−1.282	88.92	−2.03	−0.432	264.17
−4.025	−4.29	−2.511	−2.612	88.23	−4.09	−0.701	328.81
−6.043	−6.425	−3.758	−3.767	91.77	−6.17	−1.375	251.65
−7.958	−8.455	−4.941	−4.894	92.93	−8.11	−1.645	277.08

[a] Angle calculated using measured radius and measured $l = 92$ cm and $j = 5.81$ cm.
[b] Angle calculated using Eq. (1).

radiographic image of the aligned DAI, α_2. The effective l was calculated for both the X-ray (using α_2) and neutron beams using Eq. (5). However, the calculated l values vary by as much as 10% from the measured l. This is due to the error in measuring the difference between $(r_{exp} - r_{act})$ and in measuring the exact location of the imaging plane. The value of l is not known for the neutron beam, but the average value of 280 cm is reasonable, since the aperture to imaging position separation was approximately 290 cm.

5. Conclusions

The DAI was successfully used in determining the alignment of the imaging plane perpendicular to a radius of a divergent beam. The DAI was also useful in predicting both the angle of divergence at a selected beam radius and the source to DAI center of rotation distance. Two DAI design features may be useful. First, the use of locating holes and pins in the DAI and DAI holder were very helpful in realignment of the DAI after removal from the beam. Second, the front center Cd wire image was difficult to detect in the $L/D = 30$ neutron beam due to the loss of the umbral shadow. Additional Cd wire was added to "point" to the front center wire. This was not needed on the X-ray radiographs, as both the front and back Cd wire images were in focus.

The DAI needs additional testing in other neutron beams with higher L/D ratios and with different degrees of divergence. Following this testing, assessment of the utility of the DAI may lead to its proposal as a neutron radiographic characterization device.

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