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Alternative method of diffraction-enhanced imaging

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Abstract

Diffraction-enhanced imaging (DEI) is a radiographic technique that derives contrast from an object's X-ray absorption, refraction gradient and small-angle scatter properties (extinction). The DEI imaging system prepares the incident beam by diffraction from highly perfect crystals and then subsequently analyzes the beam transmitted through the object being imaged with another crystal. To apply DEI, two images are acquired with the analyzer crystal set on each side of the rocking curve. The low-angle side and the high-angle side images were combined to obtain refraction angle and apparent absorption images. An alternative method of obtaining those images of the object is presented in which the analyzer is fixed and the object is rotated. The resultant images verify the new analysis method and are compared with the images obtained by the original method of DEI. This method may be useful in situations where it is important to keep the analyzer fixed in angle which may improve the angular stability of the system.

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1. Introduction

Diffraction-enhanced imaging (DEI) [1] utilizes the sensitivity of the diffraction properties of perfect crystals to introduce new sources of imaging contrast to X-ray imaging. A perfect crystal will prepare an X-ray beam with an intrinsic collimation on the microradian scale [2]. This range of collimation allows subtle angular deviations of X-rays created by an object to be observed as intensity variations when the prepared beam is passed through an object and subsequently analyzed by another crystal. Such an arrangement is shown in Fig. 1. This type of system is also referred to as an analyzer-based imaging (ABI) system [3,4].

These types of systems develop contrast from X-ray refraction and ultra-small-angle scatter rejection (extinction) [3,5,6] in addition to absorption contrast which is the sole contrast mechanism of conventional radiography. This method has shown great promise for a variety of imaging applications [7–16] and especially for soft tissue imaging. The DEI method to extract refraction and an absorption-based image (apparent absorption) requires that two images be taken at different angular settings of the analyzer [1]. This can be done serially or simultaneously using two analyzers [17]. The key point is that the analyzer is set to introduce a steep reflectivity or transmissivity as a function of incidence angle to the analyzer. The DEI method has been extended to include methods to independently extract all of the contrast mechanisms [5,6,18], but these methods require the acquisition of multiple images.

2. The DEI method

To implement DEI with a reflection type analyzer, two images are taken at nearly symmetric points on the rocking curve [1]. These two settings introduce sensitivity to the gradient of the projected mass density within the object (or more accurately, the projected electronic density) [19]. The two images contain both absorption information

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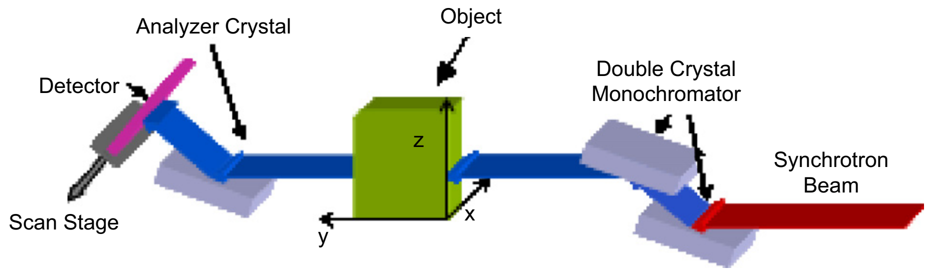

Fig. 1. Schematic arrangement of the diffraction-enhanced imaging or analyzer-based imaging system. The beam is monochromatized by a perfect crystal pair (monochromator), is passed through the object, and then is analyzed by a matching crystal.

(apparent absorption) and refraction information. If the two images are taken at exactly symmetric points on the reflectivity curve of the analyzer, they contain the same absorption information, but opposite refraction information. Technically it is difficult to take images at symmetric points; however, the lack of symmetric images is simply dealt with by scaling the images to the same background value. This is allowed since the slope on each side of the rocking curve is nearly identical though opposite in sign.

3. DEI alternate method

By inspection of the imaging system in Fig. 1 it is clear that if the object being imaged were to be inverted (z of the object goes to $-z$) then the imaging system will sample the opposite gradient of the object while giving the same absorption image, though inverted. This simple observation now allows an alternate method to apply the DEI algorithm. An advantage of such an imaging scenario is that the analyzer remains fixed in this implementation. We have chosen in this discussion to focus on inverting the object by rotation about x-axis by 180°. This choice is shown in Fig. 2. An equivalent approach would be to invert the object by rotation about the y-axis.

Specifically, consider two images of the object being acquired, I_1 and I_2:

$$I_1(x,z) = I_{R1}(x,z)\left[R(\theta_1) + \frac{dR}{d\theta}(\theta_1)\,\Delta\theta_{Z1}(x,z)\right], \quad (1)$$

$$I_2(x,z) = I_{R2}(x,z)\left[R(\theta_1) + \frac{dR}{d\theta}(\theta_1)\,\Delta\theta_{Z2}(x,z)\right], \quad (2)$$

where I_R is the intensity of the transmitted beam, $R(\theta)$ is the analyzer reflectivity, $dR(\theta)/d\theta$ is the slope of the rocking curves at the angle θ, and $\Delta\theta_Z$ is the angle of refraction.

The images are taken with a specific setting of the analyzer, θ_1. The analyzer setting would be at or near the one half peak setting to give good intensity and good refraction sensitivity as shown in Fig. 3a.

The image can be assumed (as in the DEI analysis) to be composed of an apparent absorption image, I_R and a refraction angle image, $\Delta\theta_Z$. These images are acquired in the fixed laboratory system frame (x, y, z). The object frame will be chosen to be the primed frame (x', y', z') (see

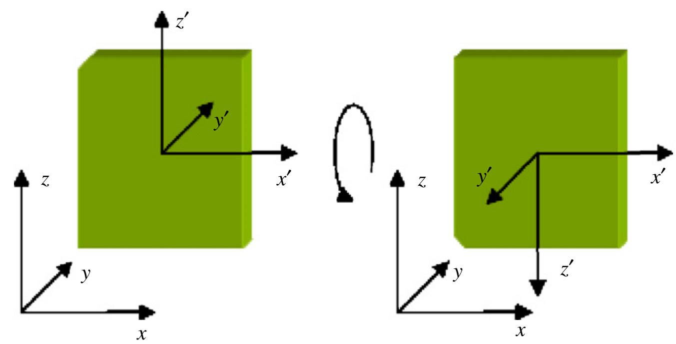

Fig. 2. Coordinate system of the imaging system (x, y, z), and the object system (x', y', z'). The orientation of the first image is shown on the left and the flipped orientation of the second image is on the right.

Fig. 2). The first image will be acquired with the same orientation as the lab frame ($x = x'$, $y = y'$, $z = z'$). The second image has the z-axis of the object frame inverted compared to the lab frame ($x = x'$, $y = -y'$, $z = -z'$) as in Fig. 3a. The inversion of the y-axis does not matter since we are dealing with projection images along the y-direction. The transformation of the images from the lab frame to the object frame leads to

$$I_R(x',z') = \begin{cases} I_{R1}(x,z), & \Delta\theta_{Z'}(x',z') = \Delta\theta_{Z1}(x,z) \\ I_{R2}(x,-z), & \Delta\theta_{Z'}(x',z') = -\Delta\theta_{Z2}(x,-z) \end{cases} \quad (3)$$

Note that the refraction angle image undergoes a change of sign in the transformation, which is due to the change in the sense of the angle as the image is inverted. This can also be understood in terms of the spatial gradient of the object's density along z; an inversion of z changes the algebraic sign of the refraction angle from a density gradient.

This change in frame modifies Eqs. (1) and (2) as

$$I_1(x',z') = I_R(x',z')\left[R(\theta_1) + \frac{dR}{d\theta}(\theta_1)\,\Delta\theta_{Z'}(x',z')\right], \quad (4)$$

$$I_2(x',z') = I_R(x',z')\left[R(\theta_1) - \frac{dR}{d\theta}(\theta_1)\,\Delta\theta_{Z'}(x',z')\right]. \quad (5)$$

These equations are very simple to solve for the apparent absorption image, I_R, and refraction angle