Phase Effects on Mesoscale Object X-Ray Attenuation Radiographs

We are investigating the nondestructive characterization (NDC) of mesoscale objects—objects that have mm extent with μm features. Here we confine our discussions to x-ray digital radiography and computed tomography methods.

Project Goals

The goal is object recovery algorithms including phase, to enable emerging high-spatial resolution x-ray radiographic methods to "see" inside or image mesoscale-size materials and objects. To be successful, our characterization effort must be able to recover the object function to 1 μm or better spatial resolution over a few mm field-of-view, with very high contrast.

Relevance to LLNL Mission

Specific LLNL programs that would benefit from this new capability include the study of explosive samples for DoD and DOE; high-energy-density physics for DNT; novel sensors for NAI; and inertial confinement fusion experiments for NIF.

FY2005 Accomplishments and Results

Our approach includes the research, development and validation of algorithms to model phase-contrast effects observed in x-ray radiographic systems, and to use these algorithms for quantitative object recovery. This requires three tasks. First, we are modifying HADES to model x-ray phase contrast and are investigating whether multi-slice techniques within the object are needed to fully capture the physics seen in x-ray data. Second, we are developing object recovery approaches. Third, we are validating these simulations and object recovery

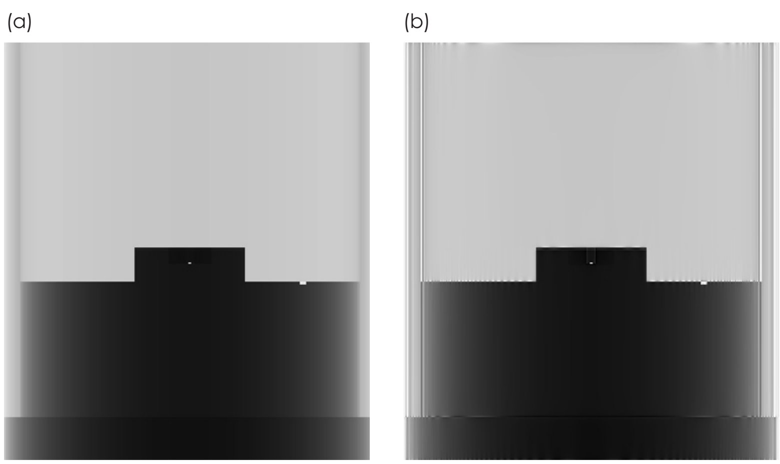

Figure 1. HADES simulated radiographs of cylindrical reference standard: (a) without and (b) with x-ray phase. Note x-ray phase effects create the well-known bright and dark edges.

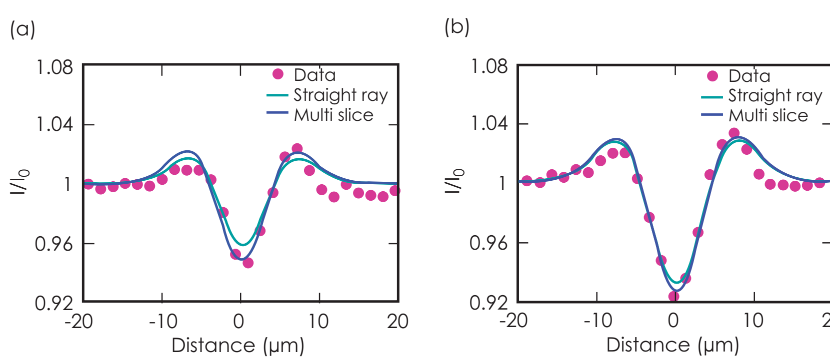

Figure 2. Transmission profiles of the (a) single and (b) double C fiber projections. The measured data (dots) were collected by a Cu-anode source and a direct detection CCD camera. The simulated straight ray (green curve) and the multi-slice (dark blue curve) profiless have been convolved with a single Gaussian line-spread function with a Gaussian sigma value of 3.6 and 4.0 for the single and double fiber data, respectively. Note the very good agreement between both simulated results and the empirical data.

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approaches against x-ray systems using well-known objects.

At the end of this R&D, we will have a set of validated x-ray forward modeling codes including the effects of phase, and an understanding of the current object recovery methods, applications, and limitations.

In the past year, we have fully integrated the Fresnel-Kirchoff diffraction theory into HADES modeling (Fig. 1). We have also merged into HADES the LBNL photoelectric absorption and phase cross-sections with the LLNL Evaluated Photon Data Library cross-sections for Compton and Rayleigh scattering, as well as pair production.

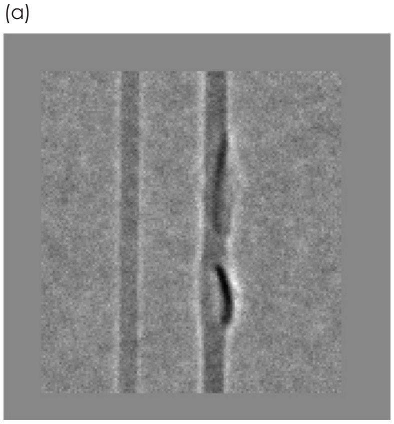
We have reached the point in x-ray imaging where the spatial resolution and object dimensions could theoretically result in the wave diffraction effects within the object becoming significant. We studied this possibility numerically using four simulation codes that incorporate x-ray phase effects. We refer to them as 1) the paraxial approximation multi-slice simulation code; 2) a Kirchoff propagation simulation code; 3) a Mie-type analytical simulation code; and 4) HADES.

We used the paraxial approximation code with and without a multi-slice method and the Kirchoff propagation code at worst-case x-ray energies of ~8 keV and compared these results to empirical data. The conclusion, based on the results of the validated simulation codes, is that diffraction effects within the object are insignificant for ≥ 8 keV x-ray data with ~1-μm spatial resolution, and for objects up to 10 mm (Fig. 2).

We have applied multi-grid techniques to both synchrotron and non-synchrotron data (Fig. 3). Comparisons with simulated data have shown the range of these techniques to be limited to cases of 90% transmission or better for simple geometric objects. Most of our data are on the order of 20% transmission for objects with complex geometry; thus, this object recovery method is not very useful for most of our data.

The "multi-slice" phantom is fabricated to contain either 5-μm diameter carbon fibers or 4-μm outer-diameter tungsten wires in various pre-selected configurations. The fibers or wires are attached to a base and slide that are adjustable in separation length from 2 to 10.2 mm. Three 5-μm carbon fibers are inserted into the multi-slice phantom and the phantom is oriented such that the fibers are vertical in the digital radiographs (Fig. 3a) and rotation can be used to align the two carbon fibers that are separated by 10.2 mm.

(a)



(b)

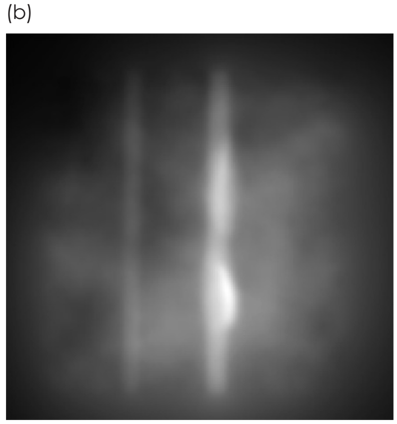


Figure 3. (a) digital radiograph of the two non-aligned C fibers acquired at 99 kV and 41 µA and pixel size of 0.6 µm at the object center; (b) electron density (related to x-ray phase) results from application of the weak absorption and uniform irradiance method on the digital radiograph shown in (a).

Related References

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2. Aufderheide, M.B., A. Barty, and H. E. Martz, Jr., "Simulation of Phase Effects in Imaging for Mesoscale NDE," *Review of Progress in Quantitative Nondestructive*, **24A**, AIP Proceedings 760, pp. 663-670, 2004.

3. Hau-Riege, S. P., "Extending the Size-Parameter Range for Plane-Wave Light Scattering from Infinite Homogeneous Circular Cylinders," *Appl. Opt.*, 2005.

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