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TITLE: COLLIMATION TECHNIQUES FOR DENSE OBJECT FLASH RADIOGRAPHY

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Collimation techniques for dense object flash radiography

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In explosively driven experiments, flash radiography can record a wealth of information about material densities and boundaries. Obtaining accurate quantitative data from these radiographs requires careful design of the experiment so that one can control and measure the scattered radiation background that is a part of any experiment.

We have used collimators at the x-ray source to match the incident x-ray flux to the transmission of the object, thereby reducing the production of scattered radiation while still preserving a complete view of the object. Multi-hole collimators (at the film plane) with a length-to-diameter ratio of $\sim 20:1$ have been used to measure the scattered radiation field with several exposure geometries and with various shielding methods.

Introduction

Explosively driven hydrodynamic experiments can present a formidable set of constraints and/or problems if one wishes to use flash radiography as a diagnostic tool. A high-energy (10-30 MeV) flash x-ray machine capable of producing 100 rad at 1 m in 100 ns from a 3-mm-diam spot, is typical of the parameters one must work with in order to minimize motion blur and penetrate thick metallic assemblies. The challenge is to image features in all regions of an experiment where the dynamic range of the scene is $\sim 10^4$, and to do it in such a way that quantitative information about material boundaries and densities is not lost.

With maximum material path lengths of 200 gm/cm², it is clear that scattered radiation is a major problem. The image of interest is formed by the differential attenuation of the primary beam by the experimental object. At the multi-megavolt energies needed to penetrate such thick objects, there is a strong flux of energetic secondary (scattered) radiation that can overwhelm the primary beam. Under infinite plane conditions, the buildup factor (the ratio of scattered to direct radiation plus 1) would be 3 or more for this energy and maximum areal mass,^{1,2} and our problem is much worse because we want to image the thin portions as well as the regions of maximum attenuation.

Our goal, therefore, is twofold:

- 1) Reduce the dynamic range of the information presented to the detector (a film pack in our case) and restore the original scene in a post-exposure process.
- 2) Reduce the magnitude of the scattered radiation reaching the detector and characterize the spatial distribution of the residual scattered radiation field, so that it can be included in subsequent analysis.

Method and experimental setup

Our approach has been to use collimation at the source that illuminates the object with just enough radiation to form an image. This overcomes the dynamic range problem and also reduces the generation of scattered radiation within the object. A narrow beam and broad beam measurement (at many points) of radiation reaching the detector plane allows one to obtain an estimate of the scattered and primary radiation intensity. Finally, we have employed beryllium shielding at the detector to attenuate secondary radiation (in the form of electrons), while having a minor effect on the primary (image forming) x-ray beam. In all of our test images, the final judgment on the quality of the radiographic results was made by performing a least squares fit to the data and comparing the fitted parameters to the known dimensions and densities of the materials. Examination of the residuals in the fitting procedure revealed any systematic deviations between the model and the data and proved to be a sensitive test.

Machine and setup

While our goal is to develop techniques for flash x-ray work, we have employed a betatron for the work to be presented here. The energy of the betatron (24 MeV) is very close to that of our flash x-ray machine, PHERMEX,¹ so there are no differences in the x-ray spectrum. The time scale of the exposure at the betatron differs from that at PHERMEX by a

factor of 10^9 ; however, the direct recording films we have employed do not show any sign of reciprocity failure. Other work has shown that radiographic magnifications between 1.5 and 2.0 yield near optimum resolution for our experiments, so only these geometries were investigated. We have used as a standard film pack a double emulsion direct recording film intensified by 1-mm-thick front and back lead screens. All films were developed in a Kodak Industrex M X-Omat processor.

Test object

With axially symmetric objects, one can make quantitative measurements using only one view provided the axis of symmetry is perpendicular to the beam.⁴ While a cylindrical object satisfies these requirements, a spherical test object was chosen to simplify the problem of manufacturing the collimators. Our test object consisted of three nesting hollow spheres with dimensions as follows:

Table 1.

	Inner Diameter (cm)	Outer Diameter (cm)	Density (g/cm ³)	Maximum Density-Length (g/cm ²)
uranium (238)	2	9	18.9	165.8
copper	9	13	8.9	36.5
foam	13	45	0.5	16.0

The last column gives the areal mass along a path tangent to the void in the uranium sphere.

Source collimation

The imaging objectives are confined to the metallic components of the test object, so the first step in collimating the source was to build a lead wall 0.6 m $\times$ 0.6 m $\times$ 0.2 m thick with a conical hole in the center.⁵ The taper of the cone originates at the source. Figure 1 shows this collimator and the geometry of the experiment. Dimensions were chosen so that

Figure 1. Experimental arrangement.

the field of view at the object plane was about 40% larger in diameter than the copper sphere. The primary radiation in the annulus between the edge of the copper sphere and the collimator boundary was about 5000 times the intensity of primary radiation along the path tangent to the inner void. The scatter field from this annulus was so intense and varied so rapidly in position, that it was impossible to obtain meaningful results, even when a special film pack with a 100:1 range in film sensitivity was used. There may also have been effects caused by spectral differences in the beam at the edge and center of the image.

Step collimation

The obvious solution to too much radiation at large radii is to add an insert to the basic collimator that provides partial (0.6%) transmission between some intermediate radius and the maximum radius of the main collimator (see Figure 1 for details). This step collimator transmission function is shown in Figure 2a. A densitometer scan across the center of the image obtained with this collimator is shown beside the function in Figure 2b. The film was digitized using 0.3-mm $\times$ 0.3-mm picture elements (pixels) for all scans, and the figures show the average of 10 lines.

In this situation the dynamic range has been reduced to manageable proportions, and we can see the outer boundary of the copper as well as the void in the center, all on one film. Scattered radiation does not appear to be a major problem. With the abrupt change in source strength at the collimator step, we have reduced the signal to nearly zero for a portion of the scan and have lost some information. The imbalance in exposure from one side of the image to the other is attributed to a decentering of the beam profile relative to the object/collimation center. The radius of the free opening and transmission percentage could be adjusted to give a better result, but for dynamic experiments such fine tuning is not very practical.

Graded collimation

To avoid the abrupt change in transmission associated with the step collimator, we have employed a conical collimator whose taper originates near the object (Figure 1). The radius of the opening and the taper angle can be adjusted to cover many situations and are not as critical as for the step collimator. The path length through the collimator for any given radius on the image plane is given by

$$P_L = \frac{\tan \alpha}{\cos \theta} \left(\frac{L_1 \tan \theta - R_C}{1 + \tan \alpha \tan \theta} \right) \text{ for } \tan \theta > \frac{R_C}{L_1}$$

and

$$P_L = 0 \quad \text{for } \tan \theta < \frac{R_C}{L_1}$$

where the variables are defined by Figure 3. The transmission falls exponentially with increasing angle beyond $\theta_C = \tan^{-1} R_C/L_1$ (see Figure 4). A densitometer scan of the image obtained with this collimator shows a reduced dynamic range, a rather clean central image, and sharp peaks at the uranium and copper outer boundaries.

Figure 2. The transmission function of the step collimator (a) and a densitometer scan of the resulting image (b)

Figure 3. The geometry of the graded collimator

Figure 4. The transmission function of the graded collimator (a) and a densitometer scan of the resulting image (b)

Reconstruction process

In the case of both the step and graded collimators, we know the transmission functions and the geometry, so it is possible to reconstruct the image that would have been recorded in the collimator were removed. Several assumptions are made in performing the restoration. First, we assume the net optical density on the film is linear with absorbed x-ray dose (numerous experiments support this assumption). The fog plus scatter background on the film is treated as a constant. This is clearly too simplistic, but as we will see, it is correct to first order. Under these assumptions, each picture element (pixel) in the digitized image is restored using

$$D_{\text{restored}} = \frac{1}{T} (D_{\text{original}} - D_{\text{fog}}) + D_{\text{fog}}$$

where T is the computed transmission through the collimator along a ray from the source to the pixel in question. The ideal collimator transmission function is blurred by a function that correctly represents the radiographic system resolution, so the transmission function at the image plane correctly models reality. A correction is also made for the source beam intensity profile. With a uniform incident beam, the ideal transmission function of the object is shown in Figure 5.

Figure 5. The ideal transmission function of the object (computed) corresponding to the line scans of figures 2b and 4b. An expanded view of the central data is shown on the right.

Step collimator

For the step collimator, the result of this reconstruction process is shown in Figure 6. Note the change in scale value that is still in film density units. The center of the beam profile correction was adjusted to balance the intensity at the edges of the image. An expanded view of the central portion of the data is shown to the right of the full scan and reveals the problems with this type of collimation. Because the original image is driven very near zero net density, very slight changes in the fog plus scatter background from one edge of the collimator to the other result in discontinuities in the restored data. Further, the abrupt change in the signal-to-noise ratio precludes meaningful measurement over a portion of the data. Nevertheless, the restoration process can produce a reasonable image with defects confined to a region near the step boundary.

Graded collimator

Applying the same process to the graded collimator produces the data shown in Figure 7. The scale change is similar to the previous case, but the data at the edges of the image do not flatten out as expected. The expanded view of the central data look very good, and one is almost unaware of the effects of the collimation. There is a slow growth in the noise-to-signal ratio with increasing radius, and only the slightest hint of the collimator boundary.

The only real defect in the restoration is the behavior at the edges of the image. Examination of the original data reveals the low exposure in this region, and, consequently, the effect of a change in the fog-plus-scatter background is magnified. We believe we have identified the source of the problem--scatter from the edge of the graded collimator. The central portion of the image is shielded from this scatter source by the core of the object, while the edges are not. An additional scatter exposure of 0.15 density at the edge of the image is sufficient to produce the effects observed.

Nevertheless, the primary goal has been achieved. We have imaged an object whose transmission range is 10^4 to 1 while controlling scattered radiation to the extent that we have good quantitative data. Only minor artifacts have been introduced, and they appear confined to the extremities of the image where they have a minor effect.

Collimation at the image plane

To measure the intensity and spatial distribution of scattered radiation at the image plane, we have employed a collimator consisting of a 7×7 array of 6.35-mm-diam holes in a 12.5-cm-thick lead block. The holes are drilled on a square grid with 2.54-cm spacing and are angled to a focus at the source of the x rays (see Figure 1). The length-to-diameter ratio is sufficient to reject a large fraction of the scattered radiation generated within the object. By placing this multipoint collimator at the image plane and simultaneously exposing films in front of and behind this collimator, we can compute the magnitude and spatial distribution of scattered radiation on the front film. The key assumption is that the collimator array effectively rejects scattered radiation and that the back film is

Figure 6. Reconstruction of the data of Figure 2b - full view (a) and central portion (b)

Figure 7. Reconstruction of the data of Figure 4b - full view (a) and central portion (b)

exposed only by direct radiation. If the object is the source of all scattered radiation, this is a reasonably good assumption. Scattered radiation originating from points near the primary source will not be rejected and can cause problems with this technique.

The procedure consists of making measurements at homologous points on the front and back films. Net densities are computed for both films and then the readings on the back film are corrected to the front film position allowing for the increased distance from the source and the extra material penetrated by the beam. Under our assumptions, the difference between the two readings is the scattered radiation exposure on the front film.

Results

The results of a number of exposures using the multipoint collimator can be summarized as follows:

- 1) The intensity of scattered radiation from the object approximately obeys an inverse square law.
- 2) Over the central image area (the uranium shell) there is very little spatial variation in the scattered radiation from the object, and there is only a slight rise at larger radii.
- 3) The multipoint collimator itself can be a significant source of scatter if exposed to intense radiation.

4) Beryllium shielding (~1 cm thick) placed on the front and back of the film pack can reduce the exposure from scattered radiation (mainly electrons) by a factor of two, while attenuating the primary radiation (photons) by approximately 7%.

5) The central region of the image has a scatter exposure of $D_s = 0.05$ (diffuse density) for the step collimator, while the graded collimator yields $D_s = 0.07$. If the step collimator transmission is changed from 0.6% to .004%, all information in the outer portions of the image is lost, and the scatter exposure drops to $D_s = 0.01$ to 0.02. These values of scatter exposure are to be compared with the minimum exposure through the object of $D_{min} = 0.02$ and a maximum exposure at the outer edge of the copper of $D_{max} = 200$ (computed).

6) As mentioned earlier, the multipoint collimator does not reject scatter that originates near the primary source. The map of scattered radiation on the front film determined using the multipoint collimator failed to reveal the 0.15 rise in the scatter background at the edge of the copper shell in the graded collimator exposure. Independent measurements confirmed that there was another component to the scatter background and that it was of this magnitude.

Discussion

We have shown that source collimation can be used to control the dynamic range in a scene and that the original dynamic range can be restored in a post exposure process. The quality of the restoration is such that quantitative information about material densities and boundaries is preserved. The spatial distribution of scattered radiation from a test object has been measured and additional sources of scattered radiation have been identified. Further work needs to be done to properly characterize the total scattered radiation background and include it in our analysis.

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