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TITLE: FLASH RADIOGRAPHY AS A QUANTITATIVE TOOL

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Flash radiography as a quantitative tool

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Flash radiographs have long been useful for interpreting dynamic events. Such interpretation ranges from merely looking at a radiograph to aid in understanding the event to fully deconvolving film densities to reconstruct actual masses and positions. Between these two extremes are the possibilities of using trained observers to select features of interest or of using densitometers to aid in such descriptions. Several examples of these latter methods will be illustrated to indicate that reasonable precision can be obtained in this way and that flash radiography can indeed be a quantitative science. The examples will be from the field of shock-wave hydrodynamics.¹ The radiographs were taken at the PHERMEX facility,² a 25-MeV machine emitting about 30 R at a meter in a pulse of 100 ns for these examples. The first situation involves the selection of the position of a thin, low-density beryllium foil embedded in a moving high-density material, uranium. The second will involve the selection of the location or of the alignment direction of step mass discontinuities such as those found in shock waves or in interfaces between materials of different density. Such discontinuities may be slowly curving, and the problem is that of determining tangents at selected locations. Both spall in lead and multiple intersecting shocks in lead will be described. The third situation will involve the selection of the alignment of the head of a rarefaction wave--the problem of a density gradient with a discontinuous first derivative. The example will be oblique reflection of a detonation wave from an open edge in the explosive PBX-9404. The last situation will involve the problem of a material density gradient with continuous first derivative. The example will be low-density material ejected from a lead surface that has been shocked. In this last case the answer is not a single selection, but a variation as a function of location.

Introduction

The general problem in flash-radiographic interpretation of hydrodynamic phenomena is one of dealing with the film-density gradients. In flows of uniform or slowly varying density, contrasting mass markers such as wires or foils are often embedded in the flow to track particle movement. The analysis problem is to locate these peaked distributions in film density. At boundaries between different materials or at shock wave locations within a material, discrete jumps can occur in the mass density of the object. On film such jumps are blurred for a variety of reasons. The analysis problem is then to relate this blurred discontinuity in the film plane to a step discontinuity in the object. Characteristic film-density signatures of foils of lower-mass-density and higher-mass-density and of an edge of a higher-mass-density object are shown in Figure 1. This radiographic analysis for an observer can be simplified into two separate parts. The first is the position location for a foil or edge. In the second the need may be for the slope or angle of either a straight or slowly curving foil or edge with respect to some reference direction. Often only one of these determinations is required. The more general problem occurs when the object density is varying in a continuous fashion. This can result in a gradient in film density such as that also typified in Figure 1. The choice of a specific location by an observer is meaningless in this situation because there is no discontinuity in the object. However, the choice of the angle of such a variation may still be possible and even meaningful in analysing the flow. The method of analysing the position of the gradient is then to try to relate numerical values of film density variation directly to mass density. If the geometry and the object are simple, this can be accomplished by calibrating against known mass variations.

The precision that can be obtained by these techniques is of course dependent on many things. These include the source size, type of film pack, x-ray spectrum and filtering, blast protection, and geometry. The precisions described should therefore be considered indicative of what is possible, and not as absolutes. The radiographic geometry for the various examples to be discussed is shown in Figure 2. The typical distance from source to object ranged from 1.22 m to 1.83 m, and the typical distance from object to film ranged from 0.30 m to 1.22 m. The films used were either AA or M direct recording films sandwiched between front and back 1-mm lead intensifying screens. The blast protection (not shown) was typically 25 mm of aluminum near the source and a like amount in front of the film. The ray R_1 represents a tangent ray to an edge while R_2 represents the next full ray in sequence that has passed through the entire length t of the object. If the edge is parallel to the beam axis the difference between the location of R_1 and R_2 on the film depends on h , the

distance off axis. If the difference becomes too large the edge no longer approximates a step discontinuity in the object mass. For the experiments to be described here, that was not a serious problem. Except where so noted, reading of positions on the films was accomplished by locating a crosshair on an enlarged projection of the radiograph. Reading of angles was accomplished by locating a crosshair parallel to a feature on the actual film.

Foils

Typical past uses of embedded foils included gold foils embedded in explosive¹ or aluminum.⁴ The location of a foil is chosen from the peak or valley in the film density. For 0.025-mm gold or tantalum foils the precision in choosing the position from the radiograph is usually ± 0.025 mm. As the foil gets off axis and h increases, the recorded image of the foil broadens and the uncertainty in location can increase. This effect can be reduced by tilting the foil to keep it parallel to rays coming from the source. The main problem is that when the foil tilts it loses contrast. The position of a 1-mm steel foil, for example, has been determined to ± 0.05 mm. Thus, if the film contrast is appropriate for an observer, even thick foils can be centered and located quite precisely.

If a shock wave crosses an embedded foil at an angle, the sudden reduction in the specific volume of the material leads to the foil being abruptly bent. This technique is depicted in Figure 3. The initial angle θ_1 can often be set when constructing the experiment. The angle θ_2 then remains to be measured. A difficult application is shown in Figure 4. In this case a low-density beryllium foil was embedded in a radiographically thick object--96 g/cm² of uranium. The uranium was shock-compressed by 51 mm of the explosive PBX-9404 detonated by a P-40 planewave lens. The results of the measurement are shown. The precision for θ_2 would have been about four times smaller if the example had been a uranium foil in a beryllium sample. The actual volume ratio was obtained by electrical measurement of the shock wave velocity and comparison with the measured Hugoniot relationship that relates this velocity to compression. Although the bent foil determination by an observer does not achieve the precision of electrical or optical techniques in these simple equation-of-state measurements, it is still a useful quantitative tool and can be applied in some complicated circumstances where the more conventional techniques cannot.

Position of mass discontinuities

The image of a step is blurred by a number of things. One source of blur can be the source size. With PHERMEX's submillimeter spot this is not a serious problem. Another is the scatter that can come from collimators or blast protection near the source, the object itself, blast protection for the film, or the film pack itself. The tilt of the step can also cause geometrical extensions. Finally, in dynamic radiography there is the simple problem that an edge travelling at 2 km/s moves 0.2 mm during the 100-ns radiographic pulse. These problems are compounded by the fact that a position must be picked from the blurred image and that choice, even for the most experienced observer, can be influenced by overall film blackness and contrast. Results for an observer's choice of static edge location are presented in Figure 5. The distance from the beam axis is the variable h in Figure 2. The solid line is the least squares fit to the data. The increased correction with increasing h is a result of R_1 and R_2 separating. If the observer always picks the same ray to represent the edge, then the correction is directly proportional to the distance h . This is strictly a geometrical correction. The failure of the fit to pass through the origin, however, indicates a bias in the choice of location. Thus, if an absolute edge position is needed in a dynamic radiograph, the safest thing to do is to hold the source strength constant and obtain a calibration such as this with a number of static radiographs.

An application of the examples given thus far can be found in the problem of a shocked sample spalling a thin layer from the front. A characteristic film density is shown in Figure 6. Both the spall layer and remainder of the original sample would be moving to the left at the time of the radiograph. The hydrodynamic objective here is to measure the thickness of the spall layer. The left (front) surface of the spall is for the most part the same surface that could have been seen before in a static radiograph. The right (back) surface of the spall, however, is a new surface created when the original sample ripped apart. Past experiments have attempted to measure the thickness S by locating the front and back spall surfaces.^{1,4} A circumspect, but more precise technique is available. The spall layer is in fact a thick foil whose center can be determined. The front spall surface is amenable to locating through calibration. The quantity $S/2$ can then be directly determined. The gap opening can likewise be obtained from a determination of $(S + G)/2$. An experimental test of this approach is depicted in Figure 7. A lead sample was shocked by 51 mm of the explosive Baratol detonated by a P-40 planewave lens. The lead sample had a precut 0.91-mm layer pressed onto the sample. This layer was made thinner than the natural spall layer for this system to ensure a known thickness would take flight. The dynamic measurement compares exceedingly well with the prepared value. An actual set of spall experiments with lead is shown in Figure 8. The first spall thickness measurement was made with the uncalibrated

surface-to-surface technique.⁵ The next three were new measurements of old tests with the calibrated surface-to-center techniques. Each of the spall layers had flown a different distance at the time of the radiograph. The last value represents a repetition of one of the older tests. The increase in precision there is a result of better alignment and calibration. Both the hydrodynamics and measuring technique appear to be reproducible.

Orientation of mass discontinuities

The relative angle of shocks or edges is also an important analysis problem. The observer here need not locate the actual position--only the direction. When the discontinuities are curving, the problem may be that of finding the slope at a particular point. An example of a typical problem is shown in Figure 9. The detonation wave in the explosive runs at constant velocity, so after a reasonable distance of run the flow in the area shown becomes independent of time. A determination of θ_1 , the angle the first shock in the lead makes with the plane of symmetry, allows the conditions of the first shock to be determined.⁶ Likewise, the determination of θ_2 , the angle for the reflected shock near the collision point, permits properties of the second shock to be determined.⁷ The results of four experiments in lead are shown in Figure 10. The precision of the angle determination is typically about $\pm 0.2^\circ$. The lead, which begins with a density ρ of 11.34 Mg/m³, has been compressed as much as 51%. The Gruneisen parameter γ can be determined from a comparison of the final double-shocked state with the well-measured Hugoniot relation for single shocks.^{8,9} In this experiment the result for γ reduces to a function of the measured angles. Although the precision with respect to angle measurements remains relatively constant, the relatively cooler double-shocked state gets farther from the single-shock Hugoniot as the final density rises, and this leads to increased precision in γ . For lead the product $\rho\gamma$ should be almost constant. Although the sensitivity of $\rho\gamma$ to the measured angles has not been explicitly described, the fact that the results indicate it slowly increasing with increasing ρ is indicative of consistency among the experimental measurements.

Orientation of mass gradients

An experiment that produced a continuously varying mass density, and hence film density, is shown in Figure 11. The rarefaction fan represents a continuous gradation in density from the compressed density behind the shock to the released density near the surface that is expanding into the void. The hydrodynamic point of interest is the head of that rarefaction wave that moves at the sound velocity in the shocked material. The angle θ_1 can be determined by experimental design; angle θ_2 must be measured. The observer must, in essence, use the density variation in the rarefaction region to project a boundary with the almost constant area behind the shock. The results of such a measurement on the explosive PBX-9404 are given in Figure 12. To permit a determination of the detonation pressure, the results of this experiment are presented in the context of the Chapman-Jouget model. This relates that pressure P to the initial density ρ , the constant detonation velocity D , and another parameter γ that depends on the sound speed behind the detonation wave, and hence on the angles shown. The standard deviation for θ_2 is unusually small. For this type of measurement it is normally two to three times larger. The final result in detonation pressure is commensurate with other exhaustive determinations and lends credence to the possibility of this type of measurement.

Mass gradients

An experiment with a different continuously varying mass density is shown in Figure 13. The shocked surface emits low-density ejecta that can obscure optical diagnostics. The mass of the ejecta is so low that the high-energy beam from PHERMEX passes through with virtually no attenuation. Thus a 480-kV flash x-ray source was used to look across a 203-mm-long lead plate. The plate itself was opaque to this energy. The hydrodynamic objective was to quantify the mass of the ejecta. The principal mechanism for ejecta was thought to be surface roughness. Thus a calibration was included by giving one-half the lead sample an rms surface finish of about 0.1 μ m and the other a finish of 4 μ m. The resulting edge profiles are shown in Figure 14. These were obtained by using a microdensitometer to simulate a long (~10-mm) 100- μ m slit parallel to the edge. The data was then smoothed. Step wedges were included in the experiment to calibrate mass variations against actual film density. The experiment also had two types of gauges to independently monitor ejecta. The first was thin collector foils suspended over the surface and monitored for motion with laser velocity interferometers. The second consisted of thicker buffer materials that would support elastic waves. These were monitored with quartz gauges. The ejecta was recorded as it impacted and transferred momentum to either the collecting foils or buffers. The results of this experiment are shown in Figure 15. Here velocity ratio refers to the velocity of the ejecta divided by the velocity of the hard surface. Accumulated mass is the total amount of mass moving faster than the given velocity. The measuring systems did not all have the same sensitivity. The radiographic result is terminated where it runs out of the

calibrated range. The general agreement among methods is reasonable for this type of experiment and helps confirm the hypothesis that the ejecta sticks to the collectors.

Conclusion

A great deal of quantitative data can be gleaned by a skilled observer from flash radiographs of dynamic events. The experiments, however, must be kept relatively simple and easy to interpret, and the need for proper calibration is mandatory in many cases.

Acknowledgments

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Figure 1. Characteristic film-density profiles

Figure 2. Radiographic geometry

$$\text{Volume Ratio} = \frac{\tan \theta_1}{\tan \theta_2}$$

Figure 3. Bent foil technique for determining shock compression

Figure 5. Comparison of edge location correction with distance from beam axis

SPALL THICKNESS = 0.53 ± 0.11 mm

Figure 7. An experiment to test a technique for measuring spall thickness

$$\theta_1 = 45^\circ \quad \theta_2 = 38.67 \pm 0.79^\circ$$

$$\text{Volume Ratio} = 0.800 \pm 0.023$$

$$\text{Actual Ratio} = 0.815 \pm 0.001$$

Figure 4. Foil in a thick object

Figure 6. Characteristic film-density profile of a spalled layer

Figure 8. Reproducibility of spall measuring technique

Figure 9. Regular reflection caused by explosive shocking from each side

$\theta_1(\text{deg})$	21.06 ± 1.16	18.18 ± 2.22	20.54 ± 2.22	19.32 ± 1.18
$\theta_2(\text{deg})$	23.20 ± 1.19	19.78 ± 1.13	22.72 ± 2.28	21.16 ± 1.16
$\rho \text{ (Mg/m}^3\text{)}$	14.48	15.17	16.36	17.16
v	2.17 ± 0.41	2.14 ± 0.48	2.04 ± 0.17	1.96 ± 0.08
$\rho v \text{ (Mg/m}^2\text{)}$	31.4	32.5	33.4	33.6

Figure 10. Results of regular reflection in lead

Figure 11. A rarefaction wave behind a shocked region

$$P = \frac{\rho D^2}{v+1}$$

$$v = \frac{\sin \theta_2 + \sin \theta_1 \cos(\theta_1 + \theta_2)}{\sin \theta_1 - \sin \theta_2}$$

$$\theta_1 = 60^\circ \quad D = 8.80 \text{ km/s} \quad \rho = 1.844 \text{ Mg/m}^3$$

$$\theta_2 = 44.23 \pm 0.15^\circ$$

$$P = 36.8 \pm 0.3 \text{ GPa}$$

Figure 12. A rarefaction wave measurement in explosive PBX-9404 presented in the context of the Chapman-Jouquet model

Figure 13. Low-density material ejected from a shocked surface

Figure 14. Comparison of profiles for surfaces with different amounts of ejecta

Figure 15. Fluff from a shocked lead surface with 4- μ m rms finish