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MEASUREMENTS OF SPATIALLY RESOLVED VELOCITY VARIATIONS IN SHOCK COMPRESSED HETEROGENEOUS MATERIALS USING A LINE-IMAGING VELOCITY INTERFEROMETER*

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Abstract. Relatively straightforward changes in the optical design of a conventional optically recording velocity interferometer system (ORVIS) can be used to produce a line-imaging velocity interferometer wherein both temporal and spatial resolution can be adjusted over a wide range. As a result, line-imaging ORVIS can be tailored to a variety of specific applications involving dynamic deformation of heterogeneous materials as required by the characteristic length scale of these materials (ranging from a few µm for ferroelectric ceramics to a few mm for concrete). A line-imaging ORVIS has been successfully interfaced to the target chamber of a compressed gas gun driver and fielded on numerous tests in combination with simultaneous measurements using a dual delay-leg, "push-pull" VISAR system. These tests include shock loading of glass-reinforced polyester composites, foam reverberation experiments (measurements at the free surface of a thin aluminum plate impacted by foam), and measurements of dispersive velocity in a shock-loaded explosive simulant (sugar). Comparison of detailed spatially resolved material response to the spatially averaged VISAR measurements will be discussed.

INTRODUCTION

The detailed response of a heterogeneous material (e.g., a pressed, granular explosive) subjected to impact loading is driven by a number of microscopic properties including grain morphology, internal defects, tensile strength, shear behavior, heat conduction, etc. Effects at this scale should be correlated to the response of the material at mesoscopic scales, including detailed spatial variations in stress and thermal fields (dispersive behavior). Analysis of this detailed response is addressed by the current capabilities for three-dimensional numerical simulations (1). Much of the useful information required for validation and calibration of these simulations is lost, however, when observations are limited to spatially averaged "continuum" or "single spot" measurements. Hence, there is a critical need for diagnostic development that enables experimental validation of the mesoscopic scale processes that occur in impact loading of these materials. Characteristic length scales pertinent to the proposed diagnostics can range from a few µm (e.g., PZT materials) to a few mm (e.g., concrete).

Velocity interferometry is a well-established and frequently utilized technique for determining the velocity-time history of many types of samples. The wealth of information potentially available in spatially resolved measurements provides a

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compelling motivation to develop this diagnostic tool for mesoscopic scale studies of heterogeneous materials. Investigation of various methods to access spatial information in velocity interferometry has been an active area of research, including different concepts for line- and full-field imaging (2-5). An important recent enhancement of conventional "single point" VISAR methods is the development of a multi-point system, featuring simultaneous velocity-time measurements at up to seven different locations on the target sample (6).

In 1995, Baumung et al. (7) described a simplified design for a high-resolution, line-imaging interferometer with modest requirements for the continuous wave laser source (~1 W). Recently, we have utilized similar approaches in adapting the conventional optically recording velocity interferometer system (ORVIS) configuration (8) to fine-scale, spatially resolved measurements. A preliminary examination of applying techniques of this type to studies of laser-driven flyers has been reported previously (9). In this paper, we discuss additional interesting modifications to the ORVIS optical design and briefly describe methods for fringe data reduction and analysis. A line-imaging ORVIS has been designed and packaged for evaluation and use in well-controlled, well-characterized impact loading experiments at a gas gun facility. Results of initial experiments using this system to examine the mesoscopic scale dynamic response of a variety of heterogeneous materials will be discussed.

EXPERIMENTAL

Techniques for generating a line-imaging ORVIS assembly are illustrated in Fig. 1. As in the conventional configuration, coherent light from the source laser is directed through a small hole in a turning mirror and then focused onto the target of interest. Diffusely reflected light from the target is collected and roughly collimated by the focusing lens; the collimated beam reflects off the turning mirror and is reduced in diameter by the down-collimating telescope optics. The resulting beam is split into two equal-intensity components by the beamsplitter, one of which serves as a reference leg. The second leg passes through a variable-length fused silica cylinder. This optical component imparts a time delay (proportional to the cylinder length) in the second beam. Observed motion of the

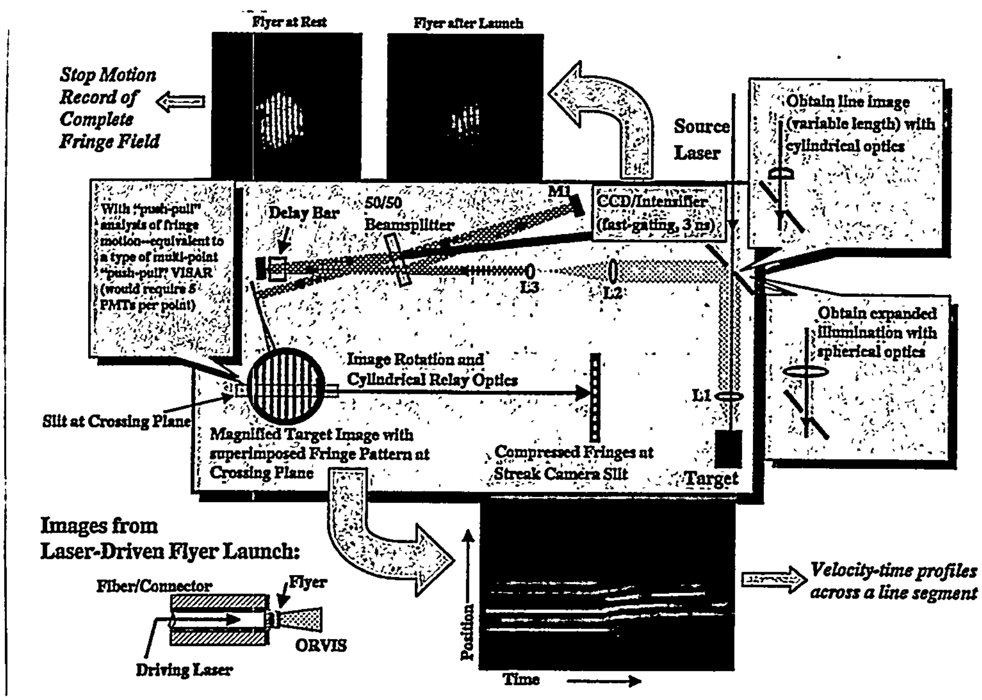

FIGURE 1. Schematic of experimental configuration for line-imaging ORVIS and stop-motion imaging of fringe field.

interference fringes generated by beam recombination (with mirrors tilted so as to produce a "straight-line" pattern) is directly proportional to target velocity. This motion can be recorded by a high-speed streak camera. The focusing lens and telescope optics can be adjusted to produce a magnified image of the target at the recombination plane (i.e., the location of best fringe contrast); in this mode, local variations in target surface velocity are reflected in corresponding local translations of the superimposed fringe field. Facile control of image size and spatial resolution can be achieved via suitable variations in the relative angles and spacing of the interferometer mirrors as well as the spacing and focal lengths of the imaging optics (9).

As demonstrated by Baumung et al. (7), the target illumination can be confined to a thin line segment by placing a cylindrical lens of suitable focal length in the source laser path ahead of the turning mirror aperture. Alternatively, one can place a spherical lens in this position and expand as desired the illumination area on target. A line image for recording by the streak camera can still be produced in this mode by placing a rectangular aperture of the desired width near the image/recombination plane. We have also explored a powerful new technique that utilizes a second, redundant set of fringes (cf. Fig. 1). A fast-gating (<3 ns) intensifier/CCD is used to capture a stop-motion image of the full fringe field at one point in time. In addition to producing data that can be used to generate a 2-D map of target surface velocity at one instant, this technique provides an informative diagnostic for the behavior of ORVIS fringe records.

Much of the initial evaluation of these techniques and the associated data reduction has utilized a test platform for laser-driven flyer generation. The rapid (ns timescale) accelerations and fine-scale (<10 μm) spatial features (e.g., nonplanarity, growth of perturbations due to drive instabilities) provide an excellent sampling testbed for assessing the capabilities of these diagnostic methods. The relevant details of the laser-driven flyer apparatus have been described previously (9, 10).

A compact version of the line-imaging ORVIS has been assembled and tested at the Explosive Components Facility (ECF) gas gun at Sandia National Laboratories. This system combines the interferometer optics, laser source and streak camera/intensifier/CCD detector on a single 2' x 6' optical breadboard. Coupling of this diagnostic to the test samples required design and assembly of a complex optical interface that could accommodate an 11-meter path to the gas gun target chamber. Targets that allow for simultaneous line-imaging ORVIS and standard dual-delay-leg, "push-pull" VISAR measurements on a variety of materials were designed and fabricated. Simultaneous use of both techniques permits direct comparison of spatially resolved vs. single spot ("continuum"-like) data.

APPROACHES TO DATA REDUCTION

To exploit the information associated with each recorded fringe in line-imaging ORVIS data, it is necessary to develop a suitable method for image analysis. Baumung et al. (7) described an approach (analogous to reduction of VISAR interferograms) that extracts the intensity modulation along a line parallel to the time axis of the streak camera record (cf. Fig. 1). The simplest implementation of this reduction method generates components that are, in effect, quadrature coded using intensity "lineouts" along the center of a fringe and at ¼ the distance to the center of a neighboring fringe. Velocity-time data can be obtained by importing these records into standard VISAR data reduction software. One clear drawback of this approach, however, is the requirement for an additional record that accurately tracks the reflected beam intensity. In experiments involving fine-scale perturbations, significant intensity fluctuations within the field of image data are typically encountered.

A more robust approach applies "push-pull" VISAR analysis concepts (11) to reduce the ORVIS fringe records. In this technique, "lineouts" are recorded at positions corresponding to the fringe center as well as at 1/4, 1/2, and 3/4 the distance to the center of a neighboring fringe. These data can be treated in the same manner as that recorded by four PMT channels in a "push-pull" VISAR. This approach is shown schematically in Fig. 2. In examination of fringe records from flyer data, the results are uniformly consistent with averaged results from a global reduction program (12) and we have encountered very few difficulties (e.g., spurious fringe jumps, etc.) in data reduction. This treatment is much less sensitive to small-scale intensity fluctuations. Also, it is not a requirement

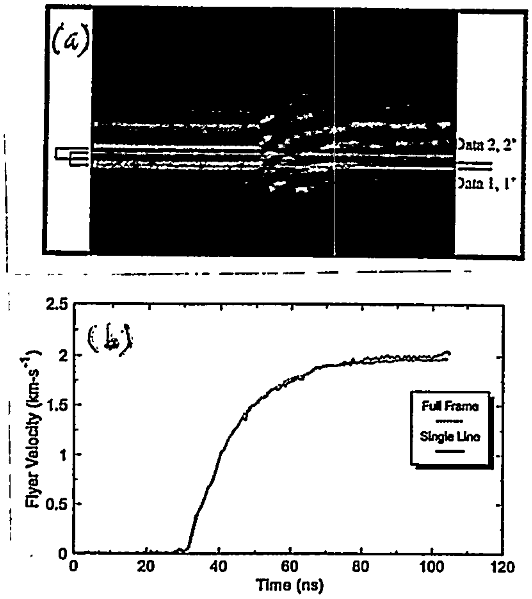

FIGURE 2. Illustration of "Push-Pull" Analysis Approach: (a) ORVIS image data from laser-driven flyer launch; (b) Comparison of single-line analysis with global method.

to register each single-line analysis with a fringe center. Considerably finer resolution of small-scale perturbations in velocity can be achieved by extending the analysis to positions between fringes as well. This "rolling push-pull" approach has been used in reduction of the experiments described below. An analogous routine can be used to generate an areal target surface velocity map (at one point in time) from the stop-motion images of the fringe field.

RESULTS AND DISCUSSION

Fused Silica Symmetric Impact Experiments

For initial evaluation of the line-imaging ORVIS in gas gun studies, we used a well-characterized symmetric impact configuration in which a 3.25-mm-thick disc of fused silica (backed by carbon foam on an aluminum projectile) impacted a second 5-mm-thick sample of fused silica. Line-imaging ORVIS and VISAR measurements of the "free surface velocity" at the distal face of the target were obtained. For a given impact velocity, the wave profile arriving at this surface can be predicted to high accuracy. The known velocity-time response includes a ramp wave that peaks (after a predictable rise time) to a value matching that of the impact velocity, followed by a rapid unloading that occurs at a time dictated by the sample geometry. Results for one test at an impact velocity of 0.25 km-s^{-1} are shown in Fig. 3. Spatial variations in the velocity-time profile are expected to be negligible in this configuration; however, significant variations in velocity (~0.03-0.05 km-s^{-1}) were observed upon processing of the "raw" ORVIS data. Much of this effect was traced to systematic oscillations in the detector response (also clearly observed in baseline traces). The reduced ORVIS data in Fig. 3 reflect a correction for this effect as incorporated into the analysis routines. Allowing for residual noise in the image records, the velocity-time profiles measured by both line-imaging ORVIS and VISAR were then found to be consistent with expectations.

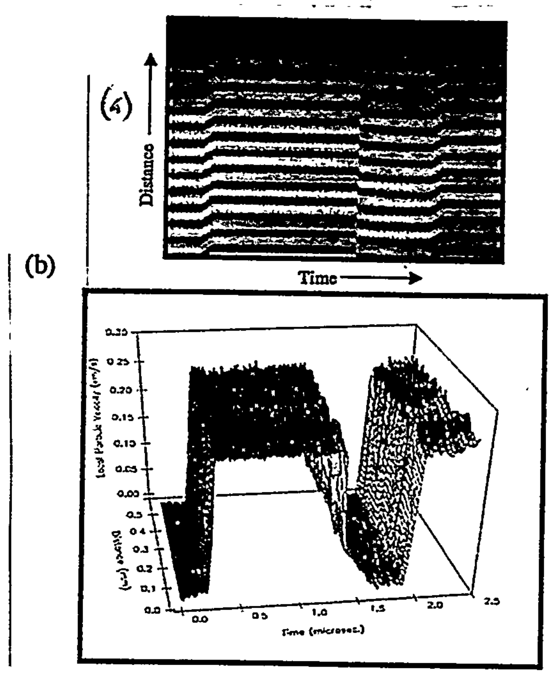

FIGURE 3. Line-imaging ORVIS results from fused silica symmetric impact experiment: (a) image data; (b) reduced velocity-time data.

Foam Reverberation Experiments

In one application of line-imaging ORVIS to the investigation of the mesoscopic response of heterogeneous materials, we tested a configuration in which low-density foam (6.3-mm-thick) impacts a thin (1-mm-thick) aluminum witness plate. Measurements at the free surface of the aluminum typically show a steady "ring up" of velocity with superimposed features arising from the detailed microstructure of the high-porosity foam. Due to the compact geometry of the ORVIS assembly employed in the gas gun tests, we were unable to use optical delay cylinders longer than about 10 cm, resulting in a practical lower limit of ~0.5 km-s^{-1} for the velocity-per-fringe constant (VPF). The limited recording time of the streak camera/CCD detector proved to be an additional constraint, limiting data collection to a period <2.5 μs. Nevertheless, we were able to observe detailed structure in the low-amplitude spatially resolved image data, as shown in Fig. 4. The averaged response determined by the line-imaging ORVIS was entirely consistent with the record obtained by standard VISAR (at a different measurement location). With a properly configured instrument (low VPF, longer recording times), detailed studies of the mesoscopic scale structure in this experimental system should be readily achievable.

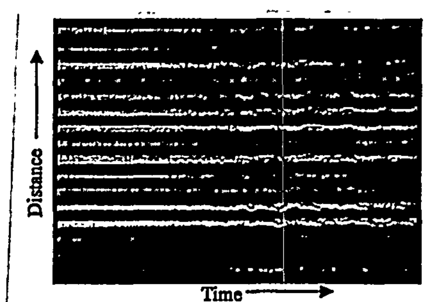

FIGURE 4. Line ORVIS record from foam reverberation experiment.

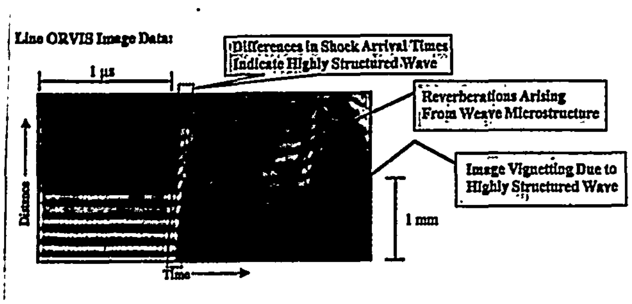

FIGURE 5. Line ORVIS record of shocked GRP

Glass-Reinforced Polyester Experiments

Another heterogeneous material examined under impact loading was a glass-reinforced polyester (GRP) composite. A thick (25-mm) fused silica impactor was used in these tests. The wave transmitted by 3.2-mm-thick samples of the composite was passed through a thin (~1-mm) PMMA buffer and examined at the interface of this buffer with a PMMA interferometer window. An illustrative case of the spatially resolved response of the GRP is shown in Fig. 5. Several effects are evident including a systematic difference in the shock arrival time with position (~60 ns over a transverse distance of 2 mm), high-amplitude reverberations in the wave profile, and the occurrence of severe vignetting over certain regions of the sample. These effects arise from the complex periodic geometry of the composite weave that leads to a highly structured wave with resonance-like effects. Effects of this type (including widely varying particle velocities depending upon measuring position) are clearly indicated by detailed numerical simulations using a realistic approximation to the weave geometry and component material properties (13).

Explosive Simulant (Sugar) Experiments

The preponderance of our efforts has focused on the investigation of pressed, granular sugar as a simulant material for the important explosive HMX. The utility of this candidate simulant has been previously described (14). Chemically inert to shock loading to fairly high pressures, granulated sugar is similar in particle size distribution to typical batches of "coarse" HMX (mean particle size ~120 μm) used in various applications. Tests on this material can address mesoscopic scale thermomechanical effects in the absence of complications due to rapid reactions. Our tests are intended to provide experimental data for direct comparison and validation of 3-D numerical simulations focusing on the thermomechanical response (1). In addition, the line-imaging ORVIS results can be directly compared to the substantial data base developed from magnetic gauge ("continuum") experiments by Sheffield et al. (14).

Accordingly, simultaneous ORVIS and standard VISAR measurements have been made on the wave transmitted by 4-mm-thick pressed sugar samples in a gas gun target design very similar to that used in the previous magnetic gauge studies; i.e., Kel-F impacting sugar pressed to 65% theoretical maximum density in a Kel-F target cup. Impact velocities ranging from 0.32-0.68 $km\text{-}s^{-1}$ have been used. Initial results from both optical diagnostics are consistent with the systematically varying dispersive behavior of the wave profiles seen by Sheffield et al. This includes comparable measured shock and particle velocities as well as very similar rise times in the transmitted wave. The VISAR data in Fig. 6 demonstrate that the rise times decrease from 700 ns to approximately 200 ns over the above range of impact velocities. Mesoscopic scale velocity variations are clearly evident in the spatially resolved ORVIS data, as shown in Fig. 7. Variations in the observed amplitude of oscillations in the wave profile vs. position provide insight at the mesoscale that should be helpful in defining appropriate material descriptions and interface conditions for detailed computational modeling (1). With continued development of these experimental techniques, the opportunity exists to explore systematic variations in material properties (e.g., tailored particle size distributions) in order to validate current models and influence the development of advanced modeling approaches.

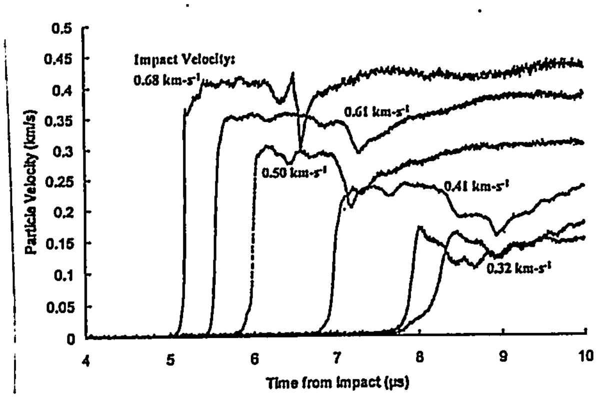

FIGURE 6. Particle velocity waveforms from standard VISAR measurements for shocked samples of granulated sugar.

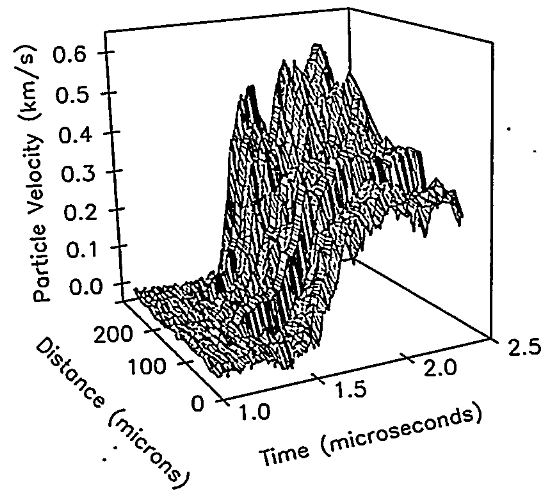

FIGURE 7. Spatially resolved velocity-time record of transmitted wave from shocked sample of granulated sugar (0.5 $km\text{-}s^{-1}$ impact velocity)

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