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Characterizing Detonator Output Using Dynamic Witness Plates

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Abstract. A sub-microsecond, time-resolved micro-particle-image velocimetry (PIV) system is developed to investigate the output of explosive detonators. Detonator output is directed into a transparent solid that serves as a dynamic witness plate and instantaneous shock and material velocities are measured in a two-dimensional plane cutting through the shock wave as it propagates through the solid. For the case of unloaded initiators (e.g. exploding bridge wires, exploding foil initiators, etc.) the witness plate serves as a surrogate for the explosive material that would normally be detonated. The velocity-field measurements quantify the velocity of the shocked material and visualize the geometry of the shocked region. Furthermore, the time-evolution of the velocity-field can be measured at intervals as small as 10 ns using the PIV system. Current experimental results of unloaded exploding bridge wire output in polydimethylsiloxane (PDMS) witness plates demonstrate 20 MHz velocity-field sampling just 300 ns after initiation of the wire.
Keywords: Detonator, Shock Wave, Dynamic Witness Plate, PIV
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INTRODUCTION

In the study of detonation physics there is a need for diagnostic tools that provide a means of characterizing the multi-dimensional output of explosive detonators. The approach taken in this work is to develop an optically-based system for measuring the flow properties behind shock waves created by such devices. In general, the magnitudes of the measured shock and mass velocities provide the basis for comparing detonator output.

With the intent of measuring flow velocities with a high level of accuracy, the new diagnostics are designed around the technique of particle image velocimetry (PIV). Fundamentally, the PIV technique involves seeding a flow with small tracer particles and imaging the particles at two instants t_1 and t_2 separated by a short time interval $\Delta t = t_2 - t_1$. As the particles move with the flow, their images provide a means of measuring their Lagrangian displacement $\Delta \mathbf{x}_p(\mathbf{x},t)$. Using a first-order, finite-difference approximation, the Lagrangian particle velocity $\mathbf{v}_p(\mathbf{x},t)$ is estimated from

$$\mathbf{v}_p(\mathbf{x},t) = \frac{\Delta \mathbf{x}_p(\mathbf{x},t)}{\Delta t} . \quad (1)$$

Under suitable conditions the Eulerian flow velocity $\mathbf{u}(\mathbf{x},t)$ is well-approximated by $\mathbf{v}_p(\mathbf{x},t)$. Detailed descriptions of PIV theory and experimental implementation are given in [1] and [2].

In the following sections, unloaded exploding bridge wire (EBW) output is investigated and its loading behavior on a polydimethylsiloxane (PDMS) witness plate is discussed. PIV results are compared to schlieren visualizations and preliminary photon Doppler velocimetry (PDV) data in order to address the physics governing the observed dynamic loading characteristics.

EXPERIMENTAL

The main advantage of extending the PIV technique to detonator output is the ability to measure a two-

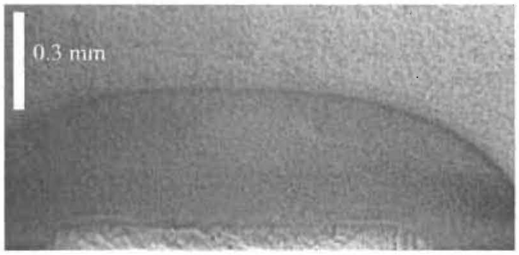

FIGURE 1. Visualized shock geometry in PDMS from an unloaded EBW viewed normal to the wire axis.

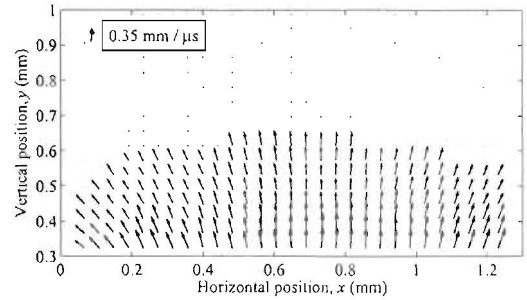

FIGURE 2. Particle velocity field in PDMS measured over the time interval (297,347) ns with respect to wire burst.

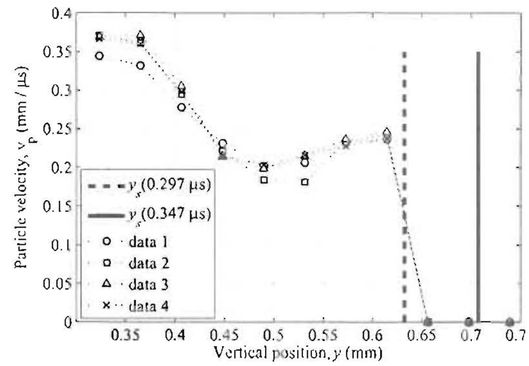

FIGURE 3. Spatial profile of particle velocity measured over the time interval (297,347) ns with respect to wire burst.

dimensional velocity field in any plane of interest defined within the three-dimensional flow field. Considering flows created by detonator-induced shock waves, the fidelity with which the particles can follow the enormous accelerations across shocks is critical to an accurate velocity measurement in a region behind the shock. The solution presented here is to combine an ultra-high speed, time-resolved PIV system [3] with the dynamic witness-plate methodology introduced by Murphy *et al.* [4] and analyzed by Murphy and Adrian [5].

All PIV measurements are made with the EBW (SE-1) axis aligned normal to the optic axis of the imaging system, and the velocity is measured in a plane directly above the wire. In this configuration, the geometry of an EBW-driven shock wave in a PDMS witness plate (Sylgard 184, Dow Corning) is visualized using schlieren imaging as depicted in Figure 1.

RESULTS AND DISCUSSION

A single velocity vector field corresponding to a measurement interval of (297,347) ns (measured with respect to EBW burst) is included in Figure 2, where the vector spacing is 41.6±0.2 μm. The geometry of the shocked region is consistent with the schlieren visualization in Figure 1. From the measured velocity field it is evident that vectors contained in a horizontal sub-region defined from 0.6 to 0.8 mm display nearly uni-directional motion. Measured particle velocities in this region are plotted as a function of vertical distance, and the resulting velocity profile is included in Figure 3. The observed trend in the measured profile suggests a complex shock-wave structure exists in the vertical direction, which means complex dynamic loading on the witness plate is occurring.

The recorded particle-image fields from the PIV experiment are displayed in a time-resolved sequence in Figure 4, where the pixel intensities have been inverted from the raw images. A physical boundary resembling a piston is observed propagating into the shock-compressed region of PDMS. With a piston continuously pushing on the witness-plate free surface, a velocity boundary condition is sustained at the surface, and the particle velocity induced by the EBW-driven shock is not expected to decay to zero velocity as long as the piston persists. We contend the observed piston results from the interaction of expanding wire plasma with the PDMS free surface.

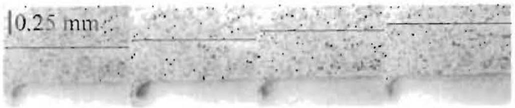

FIGURE 4. Time-resolved particle-image fields depicting the EBW piston propagating into PDMS during the interval (297,448) ns. Horizontal lines depict measured vertical shock positions.

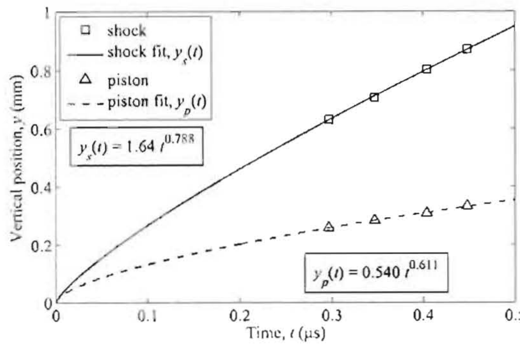

FIGURE 5. Measured shock and piston positions in a PDMS witness plate.

Measurements of vertical shock and piston position are made from the PIV images and plotted versus time in Figure 5. Power-law fits are included in the figure to analytically describe the temporal evolution of the shock and piston motion in the vertical direction. A time-derivative of each power-law fit provides expressions for propagation velocity in the vertical direction, allowing instantaneous shock and piston velocities to be obtained from the respective position measurements.

In order to validate the 1-D particle-velocity measurements in Figure 3, PDV methodology is employed. A metal coupler is designed to axially align an SE-1 EBW header, a PDMS disc having sub-millimeter thickness, and a PDV collimating probe. EBW output is driven into one end of the PDMS, and the optical probe collects scattered light from the opposite end (free surface in air) that is sputter-coated with a gold layer of 200±20 nm thickness. A preliminary PDV measurement is included in Figure 6, where the thickness of the PDMS sample is measured as 760±10 μm. The PDV data and the velocity spatial profiles in Figure 3 are in good agreement, as both depict an initial particle-velocity jump of nominally 250 m/s followed by a rise to 350 m/s. Additional structure is observed in Figure 6 that is consistently present in additional PDV experiments. The data alludes to the duration over which the expanding plasma interacts with the witness plate.

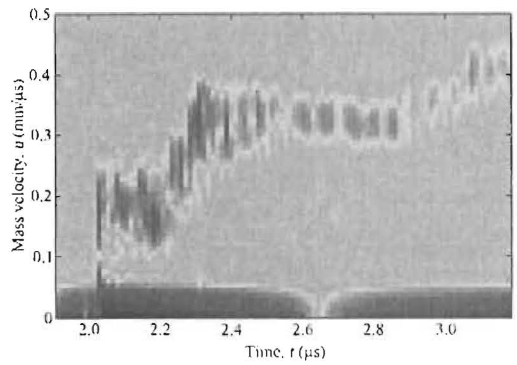

FIGURE 6. PDV data obtained for an EBW-driven shock wave propagating through a PDMS sample with 0.76 mm thickness.

With agreement between PIV and PDV measurements and a proposed physical mechanism for the observed shock structure, particle-velocity values are extracted from the PIV data in the region immediately behind the measured shock positions. The extracted data are paired with corresponding shock velocities (U_s) obtained by taking the time-derivative of the analytical expression for vertical shock position and evaluating the resulting expression at the PIV measurement times. The measured particle velocities are assumed to correspond to the PDMS mass velocity (u), and the $u - U_s$ pairs are plotted on the velocity-Hugoniot plane for Sylgard 184 (x-labels in Figure 7). Experimental data of Marsh [6] and Fritz (unpublished) are included for comparison to the PIV results, where a linear fit has been applied to the data yielding Hugoniot parameters [7] of $C_0 = 1.184$ and $s = 2.319$.

We have recently extended PIV analysis to the case of curved moving shocks and shown that shock-refraction effects can constitute an error of up to 13% on the PIV velocity measurements [8]. As a result, the PIV measurements are corrected for velocity error due to shock refraction and plotted in Figure 7 (open circles). Both the corrected and uncorrected

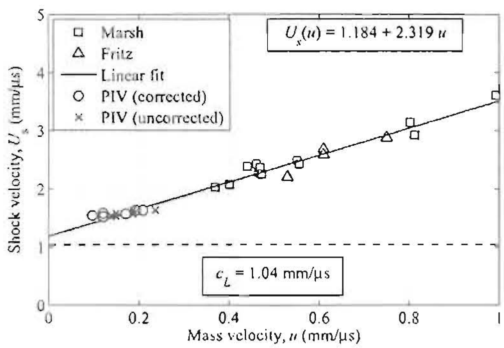

FIGURE 7. Experimental velocity Hugoniot data for Sylgard 184.

data sets are in close agreement with existing velocity measurements. For reference, the longitudinal sound speed of unshocked PDMS is included in Figure 7 with a measured value of 1.04 ± 0.002 mm/μs obtained using standard pulse-echo techniques.

CONCLUSIONS

Instantaneous velocity-field measurements are made on mass flow behind EBW-driven shocks in PDMS witness plates. A single PIV measurement quantifies the velocity of the shocked material and visualizes the geometry of the shocked region within the measurement plane. The result provides spatial velocity data corresponding to a single instant in time. Time-resolved PIV measurements describe the temporal evolution of the compressed region.

Good agreement is observed in comparing measured PIV data to experimental PDV results. Since the PDV measurements characterize the time-history of mass velocity in a small region of interest, both PIV and PDV techniques provide velocity profiles that are needed to characterize the structure of a detonator-driven shock load. A choice between utilizing the presented PIV methodology over existing PDV techniques is fundamentally a choice between wanting to resolve the spatial or temporal evolution of the flow. Instantaneous particle and shock velocity measurements plotted on the velocity-Hugoniot plane for the witness-plate material demonstrate close agreement with existing Hugoniot data. The results lend support to the applicability of the new sub-microsecond, time-resolved PIV system to characterizing detonator output based on measurements of shock and induced-mass velocities.

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