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A Particle-Image Velocimeter for Measuring the Output of High-Energy Detonators

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Abstract. Results from feasibility experiments are presented to confirm that tracer-particle motion resulting from mass-velocity fields created by driving high-energy detonator output into dynamic witness plates can be successfully measured using particle image velocimetry (PIV). Experimental results, application challenges, and PIV system development are presented.

Introduction

In shock mechanics research, the ability to quantitatively measure the state of compression of shocked materials in two and three dimensions based on particle tracer methods is of extreme importance since such measurements provide precise temporal snapshots of two and three-dimensional shock-induced velocity fields. This is especially true in the science of detonation physics where such measurements provide enormous insight into fundamental questions for understanding shock-loading processes, effects of shock-front curvature, and mechanisms of energy conversion from stimulus to shock output. As an example, answering such questions is paramount to the understanding and development of newer, safer detonators.

To date, few attempts have been made to develop and implement standard particle tracer techniques to measure shock-induced flows resulting from explosive devices.[1] The experimental challenge lies in developing a methodology wherein a tracer particle's inertia does not hinder its ability to accurately move with the rapidly changing flow field.

We have recently developed the ability to characterize the output of unloaded explosive initiators (e.g. exploding bridge wires, exploding foils, laser-driven plasmas, etc.) using an optically-based diagnostic consisting of an ultra-high speed, time-resolved particle image velocimetry (PIV) system and inert, transparent polymers serving as dynamic witness plates.[2] Initiator output is directed into a witness plate, and measurements of shock and mass velocities are made in a two-dimensional plane aligned with the initiator centerline. The results allow initiator output to be quantified in any in-plane direction, typically along the centerline. The successful development and implementation of the new diagnostic to unloaded initiators provides the groundwork for characterizing full-up detonators employing high explosives (HE).

Within the context of PIV, flows induced by HE detonators are extreme in that they contain strong, curved shock waves moving at supersonic speeds. In order to accurately measure detonator-driven flows using PIV, one must contend with the time-dependent, light-refraction properties of the moving shocks that can introduce false motion of the particles into the PIV measurement by affecting the mapping property of the particle-imaging system.[3] We have developed and validated 1-D techniques for analyzing flows created by non-HE devices, e.g. exploding bridge wires, and are currently in the process of extending the techniques to the case of high explosives. As a result, the current paper primarily focuses on feasibility experiments that have been performed to confirm that one can successfully measure tracer-particle motion resulting from shock waves driven into polydimethylsiloxane (PDMS) samples by a detonating explosive. The experimental results are used to discuss the severity of the shock-refraction effects on the PIV measurements, and the current state of development of the new particle-image velocimeter in the Detonator Technology (W-6) group at Los Alamos National Laboratory is discussed.

Experimental

Laser Detonator

In this work a laser detonator is employed that operates by indirect laser irradiation via a metal foil.[4] The development and design of the device is summarized by Akinci *et* al.[5], where it is dubbed the "Laser EBW" based on its similar initiation mechanism to the exploding bridge wire (EBW). The explosive train consists of a low-density initial pressing (IP) followed by a high-density output pellet, where the employed explosive in both pressings is pentaerythritol tetranitrate (PETN). A qualitative illustration of the device is shown in Figure 1, where experimental firing details are included for reference. The alignment of the detonator to the PDMS witness plate, as well as the orientation of the laser-light sheet are also illustrated.

PIV Setup

The feasibility experiments were performed using existing equipment in the laboratory, while the final PIV system components were in the acquisition process. Regarding the employed particle-illumination lasers, image-field recording camera, PDMS witness-plates, and system timing, the preliminary PIV experiments were reproduced from the system presented by Murphy and Adrian[6]. Tracer particles were imaged using a 70-300 mm

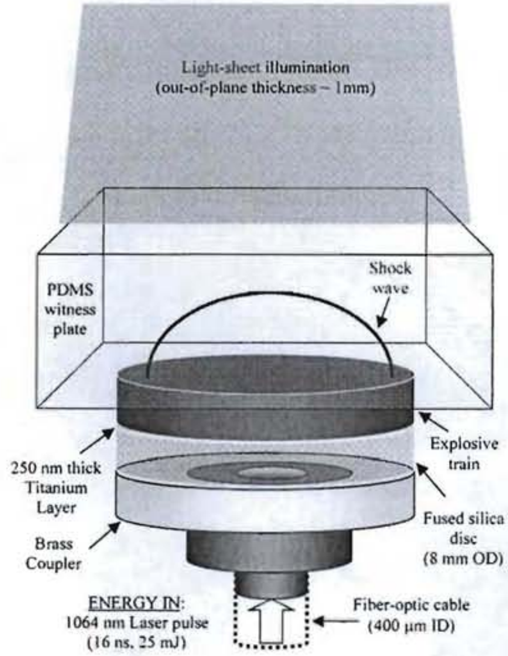

Fig. 1. Qualitative illustration of laser detonator.

Nikon lens (Zoom-Nikkor) providing an in-plane magnification of 1.15, and the image-exposure times were specified at 50 ns in order to minimize saturation of the CCD array due to the broadband explosive luminance generated by the detonating explosive.

Figure 2 contains a PIV image recorded prior to detonator initiation that provides the reference state of the particle-image field. Since cross-correlation techniques are utilized to extract the particle-image motion from the PIV images, standard PIV practice involves choosing the size of the interrogation window such that 5-10 particle images contribute to the calculated correlation peak. Accordingly, square interrogation windows having dimensions in the image plane of 128×128 pixels^2 are utilized at 50% overlap to yield strong correlations and a spatial resolution of 749 μm in the measurement volume. A representative interrogation window is included in Figure 2 for reference.

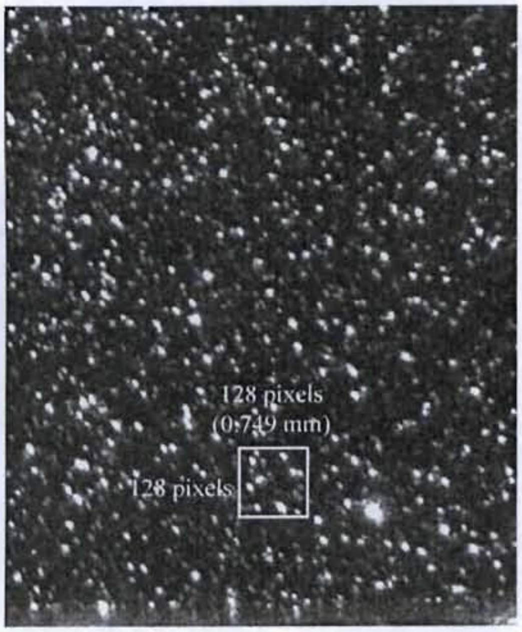

Fig. 2. Reference particle-image field including a representative interrogation window (white square).

Results and Analysis

Particle Displacement Fields

By switching the loading device on the PDMS witness plate from an unloaded EBW initiator to an HE detonator, the strength of the shock driven into the PDMS is expected to substantially increase, along with the accompanying light-refraction of the particle images inherent in viewing them through the curved shock. Additionally, time-resolved schlieren visualizations demonstrate the geometry of the shock front driven into PDMS by the laser detonator is not spherical at a nominal reproduction ratio of 1:1. Since we have yet to validate a correction procedure for removing the effects of shock-refracted light (particle-image position error) from recorded PIV images for the case of non-spherical shock fronts, the decision is made to investigate particle displacement fields rather than particle velocity fields. This allows us to narrow the source of any non-negligible, particle-image position error inherent in the ensuing PIV measurements to a single shock-compression state.[3]

With numerous resources in the literature available that provide detailed summaries of PIV theory and experimental implementation,[7,8] we choose not to elaborate on fundamental PIV practices and how the ensuing analysis deviates from those practices. Instead, we simply allude to the fact that by utilizing the known reference state of the particle-image field (which is typically not known in standard PIV experiments), a total displacement field of particle-image motion can be obtained by cross-correlating the reference image with a dynamic image taken after the shock has had some time to propagate through the PDMS sample.

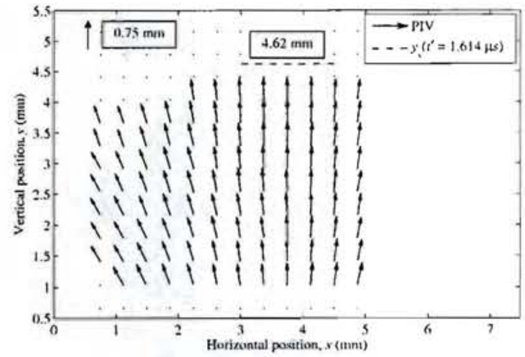

Fig. 3. Measured particle displacement field in response to a shock wave driven into a PDMS sample from a laser detonator placed in intimate contact with the sample (as illustrated in Figure 1).

Figure 3 displays a measured particle displacement field in response to a shock wave driven into a PDMS sample from a laser detonator placed in intimate contact with the sample, as illustrated in Figure 1. The displacement field corresponds to the measurement interval $(\tau,\ t_1) = (0.966, 2.580)\ \mu s$, where the $\tau = 966$ ns delay preceding the measurement is determined empirically for the laser detonator. This time corresponds to the delay measured with respect to the start-of-light of the detonator-driving laser pulse ($t = 0$) to the time it takes a shock wave to be generated in the PDMS witness plate. The latter instant is determined from time-resolved schlieren visualizations by measuring the temporal evolution of vertical shock-front position, $y_s(t)$, and extrapolating a power-law fit of the measured position data back to $y_s(t = \tau) = 0$. One can think of the τ delay as a modified function time for the laser detonator, where we are concerned with

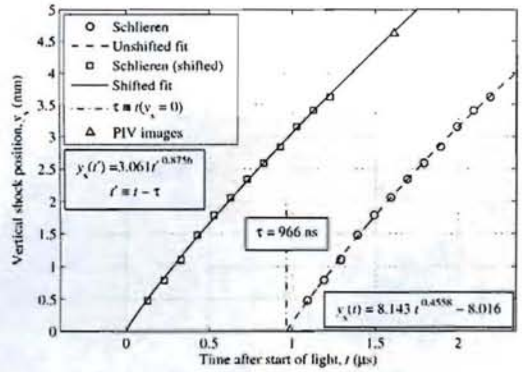

Fig. 4. Temporal evolution of vertical shock position in PDMS.

the formation of the PDMS shock rather than the first instant light breaks out of the detonator.

The schlieren data and empirical data fits used to determine τ are included in Figure 4. Notice by shifting the PIV exposure time by τ the measured vertical position of the shock front from the PIV data (open triangle in Figure 4) falls on the power-law curve that describes the time-shifted schlieren data (open squares in Figure 4). This observation supports the conclusion that the modified function time is accurate for the laser detonator.

Returning to Figure 3, the displacement data clearly demonstrates that motion of the tracer particles due to an HE detonator-driven shock wave can be measured using PIV methodology prior to destruction of the witness-plate sample. In particular, survival of a band of material containing the tracer particles behind the shock wave is essential to the successful application of the PIV technique, and this was observed clearly in the feasibility experiments. The issue of how accurately the measured tracer-particle motion in Figure 3 represents the true shock-induced motion remains of paramount importance to the successful implementation of a particle-image velocimeter that is capable of measuring the output of detonators employing HE. The displacement data in Figure 3 is used to assess the magnitude of the particle-image position error that lies in the measured data, and a discussion of this process is presented next.

1-D Particle Displacement Analysis

A simple differential equation governing 1-D motion of the p^{th} tracer particle in response to a moving shock wave is expressed as[3]

$$\frac{\mathrm{d}y_p(y_{p0},t')}{\mathrm{d}t'} = [H(y_p - y_s(t') + C_s) - H(y_p - y_s(t'))]\, \mathrm{v}_0(t')\,, \qquad (1)$$

where $t' = t - \tau$, $y_p(y_{p0}, t')$ is the Lagrangian position of the p^{th} tracer particle, $y_{p0} = y_p(0)$, H denotes the Heaviside function, and $\mathrm{v}_0(t')$ describes the time-varying magnitude of the particle velocity immediately trailing the shock front. Basically, the initial position of a tracer particle determines when it interacts with the detonator-driven shock wave, and hence, the amount of time it has to displace before having its new position recorded at some general PIV exposure time t'_1. In Equation 1, C_s denotes the *distance* over which the velocity remains at the value $\mathrm{v}_0(t')$. The assumption is made that the magnitude of the jump in particle velocity decays in time, but the spatial profile of particle velocity decays so slowly that it can be treated as constant. Future photon Doppler velocimetry (PDV) experiments are planned to investigate the validity of this assumption further.

With the shock wave propagating through PDMS in the current experiments, $\mathrm{v}_0(t')$ can be expressed in terms of velocity-Hugoniot parameters[9] and the vertical shock velocity $\mathrm{V}_s(t')$ as

$$\mathrm{v}_0(t') = \frac{\mathrm{V}(t') - C_0}{s}\,, \qquad (2)$$

where C_0 and s are experimentally determined[2] as 1.184 and 2.319, respectively, and $\mathrm{V}_s(t')$ is obtained from the first derivative of the time-shifted fit for $y_s(t')$ included in Figure 4. Note $t' = 0$ and $y = 0$ have been defined as the time at which a detonator-driven shock wave is generated in PDMS and the origin of the shock in Eulerian coordinates, respectively.

Equation 1 is numerically solved in Matlab for a line of particles spanning a vertical distance of 5 mm and spaced 10 μm apart. The assumed forcing function given by Equations 1 and 2 is plotted at multiple instants in Figure 5 to visualize the temporal evolution of the specified mass velocity.

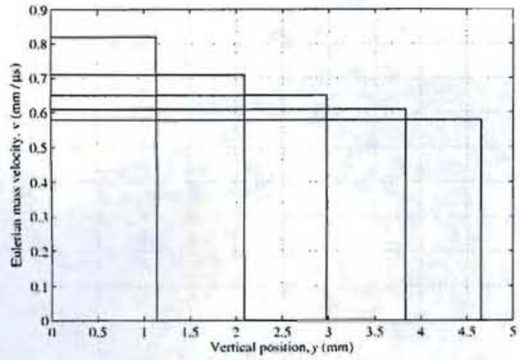

Fig. 5. Temporal evolution of assumed mass-velocity profile specified in Equations 1 and 2

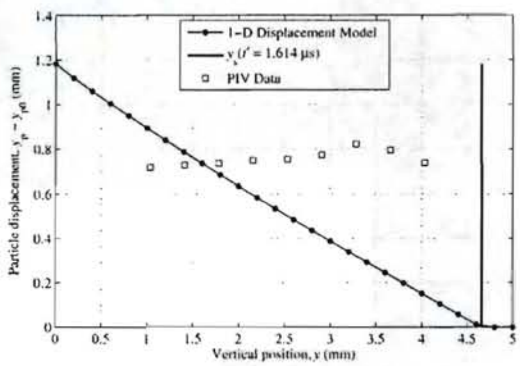

Fig. 6. Spatial profiles of vertical particle displacement measured and calculated from (0, 1.614) μs measured with respect to formation of the shock in PDMS.

All of the solutions to Equation 1 are evaluated at $t_1' = 1.614$ μs, and the total particle displacements $(y_p(t_1') - y_{p0})$ are plotted in Figure 6 (data markers shown at 200 μm spacing for clarity). From the measured particle-displacement field shown in Figure 3, the column of vectors corresponding to a horizontal position of 3.74 mm are plotted in Figure 6 for comparison to the calculated data. The noticeable overestimation of the measured displacement data to the corresponding calculations suggests there is a large amount of position error introduced into the PIV measurements by viewing the tracer particles through the curved shock.

In order to understand the reason for such a significant error in the PIV measurements, we return

Fig. 7. Schlieren visualization of laser detonator output directed into a PDMS witness plate. Shock front visualized 2.388 μs following detonator initiation.

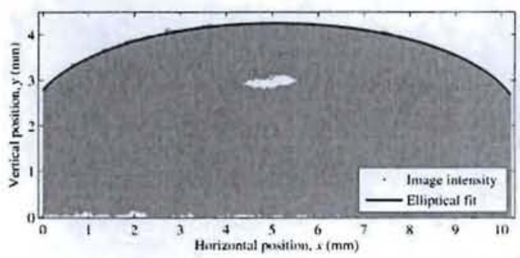

Fig. 8. Extracted pixel-intensity map used to compute an elliptical fit for the shock-front geometry visualized in Figure 7.

to existing, time-resolved schlieren data of laser detonator output into PDMS. Figure 7 contains a schlieren visualization recorded 2.388 μs after initiation of the detonator and is within 200 ns of the instant the dynamic PIV image is recorded (2.580 μs). Notice the shock-front boundary is highly elliptical. One expects the strong density jump across the shock combined with the highly elliptical curvature to severly refract scattered light from the tracer particles, in support of the position error demonstrated in Figure 6.

As previously mentioned, we are currently in the process of validating correction procedures for removing position error due to light refracted at the shock front from measured PIV data for general shock geometries. The correction is fundamentally a ray-tracing scheme,[3] which means an analytical description of the shock geometry is required for the light-refraction calculations. In order to satisfy this requirement, current plans are to implement a simultaneous PIV and schlieren experiment so the shock fronts can be clearly visualized at the same intants the PIV exposures are recorded. As an example of how the schlieren visualizations will be utilized, a pixel-intensity map has been extracted from the schlieren image in Figure 7 and used to obtain an elliptical fit for the shock front. The results are presented in Figure 8.

New Particle-Image Velocimeter

The new particle-image velocimeter currently being developed is based on both a new image-capture and particle-illumination device. Regarding capturing the PIV images, we have recently acquired an ultra-high speed camera system manufactured by Photosonics as the SIMD multi-channel framing camera. The unit employs eight intensified camera modules, each capable of recording two exposures with a minimum frame-straddle delay of 500 ns. The image sensors are standard 1.4 Mpixel arrays with 12-bit grayscale resolution. The current model is capable of 5 ns minimum exposure and interframe times, and there is no noticeable parallax error from the employed beam-splitting architecture. We have yet to notice any significant perspective error from module to module, but have not performed experiments to quantify such an error if it exists. Overall, the performance of the camera thus far has been exceptional, and we are currently designing the PIV experiments with the SIMD as the focal point.

Regarding particle illumination, we are implementing a custom eight-pulse PIV laser system manufactured by Quantel USA. Design specifics for the system have been presented previously.[10] In brief, the system is composed of four, dual-cavity PIV laser heads (CFR PIV-200) and external beam-combination optics to spatially align all eight beams to within at least 95% overlap in both the near- and far-fields. Each laser outputs 100 mJ in nominally 8 ns pulses, making the system useful for experimental measurement volumes spanning a few mm to a few feet. By coupling the eight-pulse laser system with the SIMD camera system, flow fields can be sample 8 times at up to 100 MHz or 16 times at up to 14 MHz.

Outlook

Once a standard postion-error correction procedure is in place, the new particle-image velocimeter will be able to capture time-resolved velocity fields from a single detonation event in order to examine both temporal and spatial variations in explosive output. With accurate, multi-dimensional, time-resolved measurements of detonator-induced flow fields in hand, i.e. data describing the spatial and temporal evolution of shock and mass velocity, the temporal and spatial evolution of pressure, temperature, and internal energy of the shocked media can be directly obtained using well-known shock physics and an accurate equation of state for the shocked material. As a result, the PIV data can be used as verification and validation sets for our multi-dimensional physics models in support of developing reliable simulation codes. Moreover, using PIV data to develop reliable computations allows complex experiments to be performed in simulation space without the difficulty, or even impossibility, of implementing them in the laboratory or field.

Acknowledgments

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