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Use of a Multiplexed Photonic Doppler Velocimetry (MPDV) System to Study Plastic Deformation of Metallic Steel Plates in High Velocity Impact

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ABSTRACT

High-velocity impact experiments with a gas gun pose unique challenges, in terms of experimental setup and computational simulation, since the projectile-target interaction creates extreme pressure and temperature within few micro seconds. The objective of this study is to accurately measure the plastic deformation of plates under projectile impact that does not lead to full penetration. In this work, free surface velocities at the back side of target plates are measured using the newly developed Multiplexed Photonic Doppler Velocimetry (MPDV) system, which is an interferometric fiber-optic technique which can measure velocity from the Doppler shift of the light reflected from the moving back surface of the target. The MPDV system allows measurements of velocity from different locations on the target plate using multiple optical fiber probes oriented in specific directions and patterns. Data are reduced using a Fast Fourier transformation (FFT) technique to obtain the free surface velocity profiles. These velocity profiles can present insights into the dynamic behavior of impacted materials under shock loading conditions.

Keywords: MPDV, multiplexing, high-velocity impact, velocimetry, data reduction

INTRODUCTION

Early experimental work in impact dynamics and shock physics included relatively simple diagnostic. Significant effort has taken place in the past few decades to develop new and accurate diagnostic systems to acquire data from this type of experiment. High-velocity impact experiments in modern days depend upon velocimetry data to represent the dynamic behavior of materials. A few of these diagnostic tools are already available to use in such dynamic impact experiments, for example, the velocity interferometer system for any reflector (VISAR) [1] and the photonic Doppler velocimeter (PDV) system [2]. PDV is an interferometric fiber optic technique to create Doppler induced beats where beat frequencies are related to surface displacement along a probe's beam axis. Ever since the design of modern PDV architecture, PDV systems have gained popularity for their relatively low system cost, ease of implementation, and robustness in both high-velocity and low-velocity dynamic impact experiments [3]. Many high-velocity impact studies have listed PDV as their primary diagnostic tool [4, 5]. Most of them focused on using single-probe PDV fiber to collect velocimetry data from a single point. Recent developments to PDV systems include frequency- and time-domain multiplexing with PDV (i.e. the MPDV system), which can record velocimetry data from several points onto a single digitizer channel. The concept of frequency upshift PDV or, heterodyne PDV (i.e. frequency-domain multiplexing) was first introduced by Daykin and Perez [6]. As described by Daykin [7], frequency-domain multiplexing used four channels into a single optical fiber, and then multiplexed this previous configuration twice in the time domain to get 8-velocity histories (i.e. velocimetry) in a single digitizer.

Multiplexed PDV (MPDV) is one of the most powerful tools invented in recent years and hence, researchers are currently focused on exploring the applications and abilities of such MPDV systems, including accuracy, and extraction analysis of MPDV data [8–11]. The main objective of this article is to discuss the capability of MPDV systems in simple plate perforation experiment with high-velocity projectile impact i.e. a fundamental shock physics problem. The experiment was designed with different thickness steel plates to prevent complete penetration of the high-velocity projectile and to measure the resulting plastic deformation of the target plate. The use of an MPDV system in this kind of dynamic impact experiments provide a significant insight in the dynamic behavior of the target plate as a result of the penetration process.

EXPERIMENTAL SETUP

Two-stage Light Gas Gun

All high-velocity impact experiments were conducted with a two-stage light gas gun (Figure 1a). A brief working principle of this gas gun is summarized here. The propellant gas in the powder breech drove a cylindrical piston into the pump tube. The moving piston then pressurized the light gas (hydrogen, helium, or nitrogen) in pump tube, which eventually burst a petal valve between the pump tube and the launch tube and accelerated the projectile down the launch tube and the drift tube. The projectile then impacted the target, which was bolted to a mounting frame inside the target chamber (Figure 1b). A time interval system measured the projectile velocity by measuring the time between triggering two lasers at a specific location in the drift tube.

(a) (b)

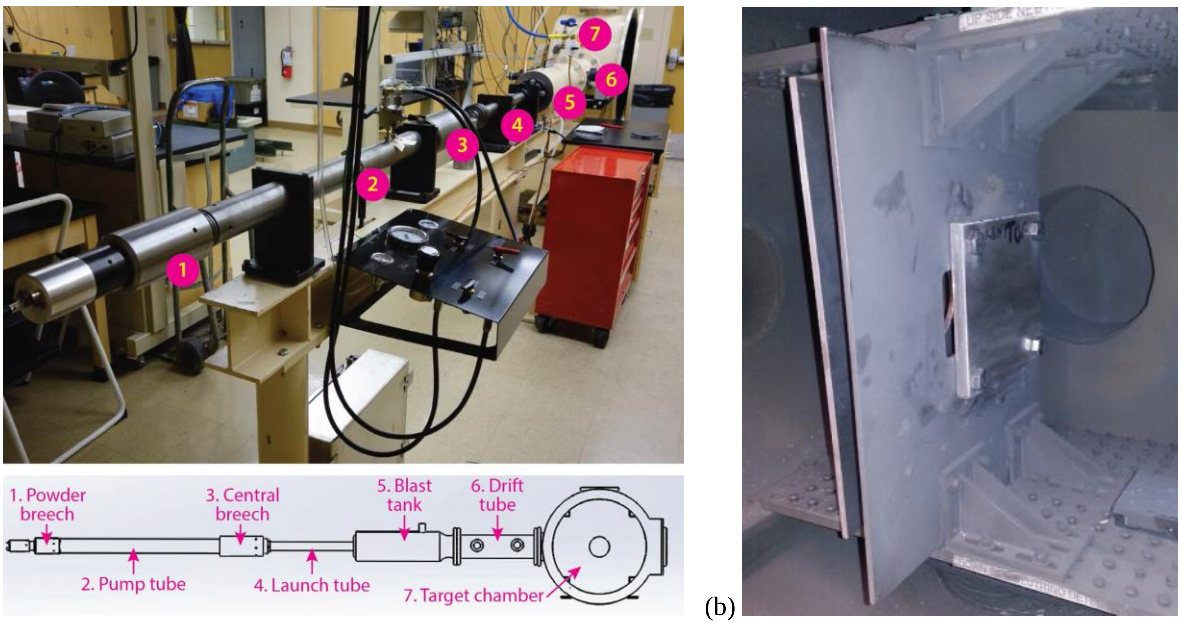


Figure 1: (a) Schematic of two stage light gas gun, (b) bolted target plate

Materials

All gas gun experiments performed in this work used cylindrical Lexan projectiles with 5.58 mm diameter and 8.61 mm length. Three different types of steel plates were used as target materials: ASTM A36, HY100 and 304L. All target plates had a dimension of 152.4 x 152.4 x 12.7 mm. The thickness of target plates was chosen such that full penetration does not occur during the experiment but for which a significant bulge happens. This allowed the MPDV system to collect velocimetry data in a regime where significant plastic deformation was occurring. Depending upon the type of gas used and the fill pressure, the projectile impact velocity varied from about 4.5 to 6.8 km/s.

Projectile Velocity Determination

In all gas gun experiments, the projectile velocity was monitored by using a laser intervalometer system. The unit had two laser sources separated by a fixed distance. Each laser beam was passed through one port to a receiving station which had a narrow band pass filter to ensure that 32 photodiodes in the arrays were free from any external light. The flight of the projectile interrupted both laser beams within a time interval which was recorded by the digitizer.

MPDV System

As mentioned earlier, this work was focused on exploring the capability of MPDV system in dynamic impact experiments. The modern architecture of MPDV system was already explained E. Daykin [6] and hence, shown in Figure 2 here. The architecture shown in figure 2 consists of eight lasers with two different wavelengths (defined by corresponding ITU bands). First, all four measurement lasers were multiplexed onto a single mode optical fiber, and then their signals were separated to their respective optical probes using a circulator and demultiplexer. Then measurement signals were multiplexed again (time-domain multiplexing) and sent to attenuators and combined with their respective local oscillators [3].

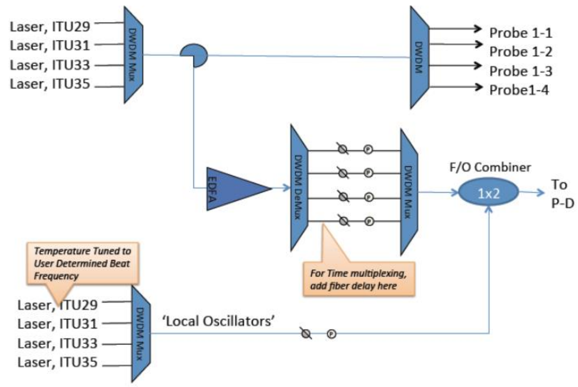


Figure 2: The architecture of conceptual MPDV with 4x frequency multiplexing as described by E. Daykin [6]

All gas gun experiments performed to study the plastic deformation of steel plates in this work used four different types of MPDV probe array systems: 9-probe, 11-probe, 12-probe, 25-probe (Figure 3). MPDV probes were focused on the back side of the target plate to capture velocimetry data at specific points around the expected center of impact. Probes were spread 10 mm to 15 mm approximately in both horizontal and vertical directions on the target plates. The MPDV system was triggered by the second laser in the intervalometer laser system assembly. A delay time was set in the MPDV system based on the projectile velocity to collect data from the back surface of the plate at the correct time. A schematic of the data acquisition by MPDV system is shown in Figure 4.

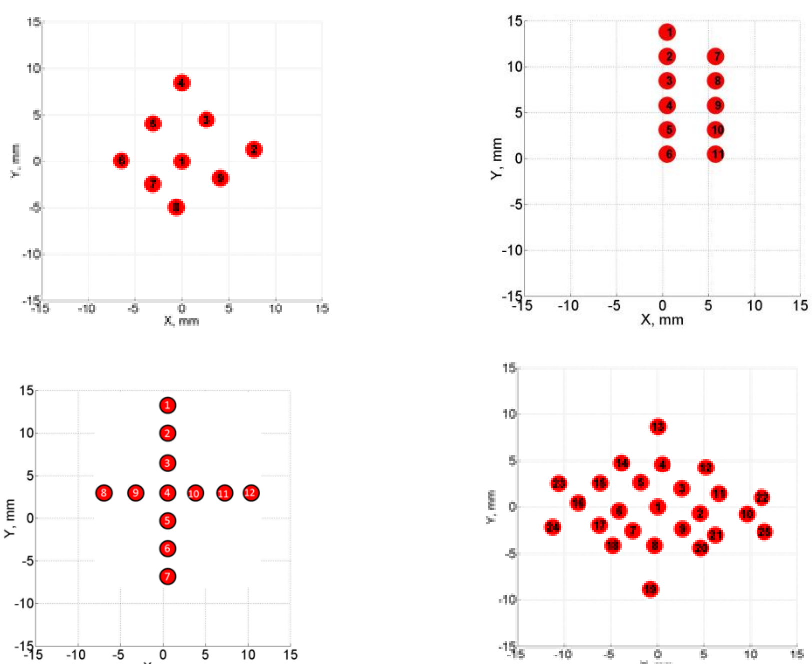


Figure 3: Schematic of MPDV probe array arrangement: (a) 9-probe (b) 11-probe (c) 12-probe (d) 25-probe

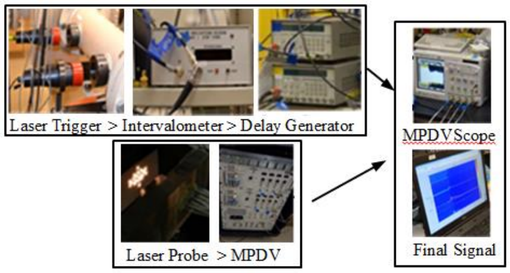


Figure 4: Schematic of MPDV data acquisition system

Data Reduction Technique

As part of growing interest in MPDV systems, researchers have started to develop new tools to analyze the large amount of data collected from MPDV systems. A few of them have already been described [6, 12]. In the present work, the MPDV system collected data at a sampling rate of 10 GSa/s. All the raw data collected by the MPDV system were analyzed by software tools developed by National Security Technologies (NSTec), which uses a sliding Fast Fourier transformation (FFT) to get the free surface velocity profiles.

RESULTS

Physical Observation of the Target Plates

In all gas gun experiments, impact of high-velocity Lexan projectiles created a crater on the front side and a bulge on the back side of target plates (Figure 5). Lexan projectiles disintegrated due to the enormous pressure and heat generated upon impact. After each experiment, crater and bulge details for each target plate were measured. The distance between the flat rear surface of the plate and peak point of the bulge was taken to be the height of the bulge. An average value for multiple measurements of crater diameter, depth of penetration and bulge were taken as the final measurement. All the crater details and bulge dimensions are listed in Table 1. Sectioned plates showed spall due to release wave interactions. The results show that the size of spall cracks is proportional to impact velocity. Details of spall cracks from some of these experiments are also listed in Table 1.

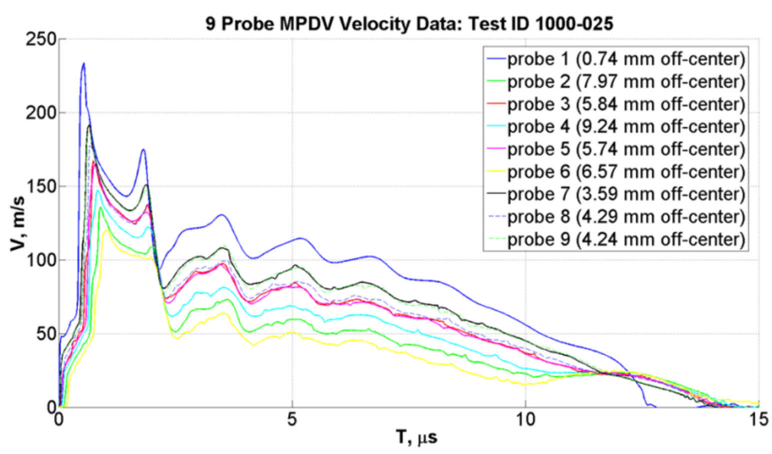
Table 1: Physical measurement of target plates after impact

Test ID	MPDV system details	Target Plates	Impact velocity, km/s	Crater diameter, mm	Penetration depth, mm	Bulge, mm	Spall crack details	
							Diameter, mm	Width, mm
1000-024	9 probe	A36	5.708	17.2 ± 0.3	7.7 ± 0.3	3.1 ± 0.3	21.4 ± 0.2	1.9 ± 0.1
1000-025			4.763	15.4 ± 0.3	6.5 ± 0.3	1.4 ± 0.1	14.5 ± 0.2	0.2 ± 0.1
1000-088	11 probe	304L	6.583	17.3 ± 0.2	6.4 ± 0.3	2.4 ± 0.1	n/a	n/a
1000-089		HY100	6.698	16.5 ± 0.3	6.4 ± 0.2	3.0 ± 0.3	n/a	n/a
1000-090	12 probe	HY100	6.743	15.5 ± 0.1	4.5 ± 0.3	3.3 ± 0.1	n/a	n/a
1000-091		304L	6.758	15.5 ± 0.2	3.9 ± 0.1	3.2 ± 0.2	n/a	n/a
1000-026	25 probe	A36	4.823	15.1 ± 0.2	6.5 ± 0.5	1.5 ± 0.1	n/a	n/a
1000-027			5.088	16.9 ± 0.8	7.0 ± 0.4	2.3 ± 0.2	n/a	n/a
1000-028			5.157	15.9 ± 0.4	6.5 ± 0.5	1.7 ± 0.2	18.5 ± 0.1	0.7 ± 0.1

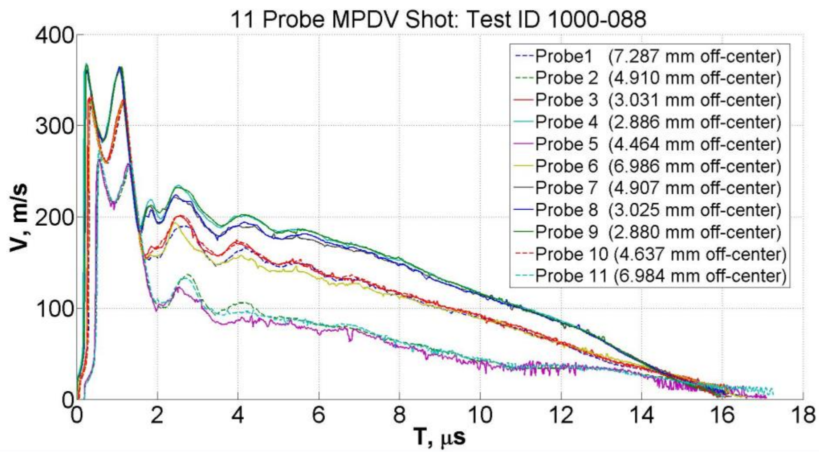
Figure 5: Typical target plate after impact (Test ID 1000-024)

Free Surface Velocity

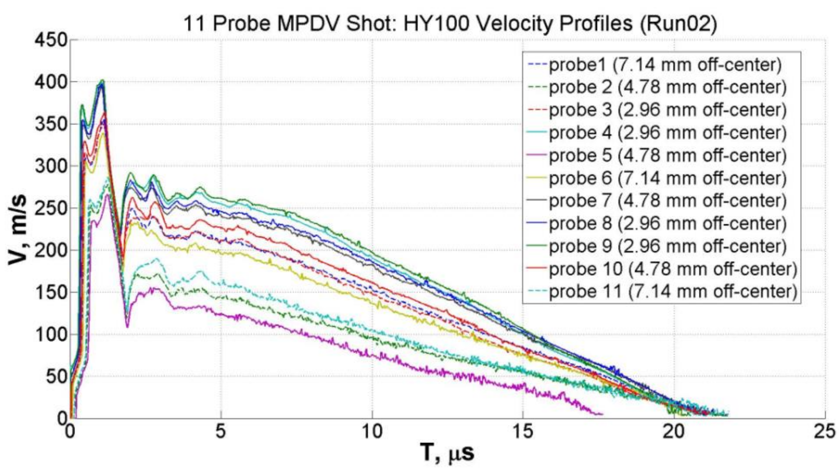
Typically, all MPDV experiments captured free surface velocities from target plate for 30-40μs whereas, the first 5μs contains the most important features related to the dynamic properties of the materials used. Free surface velocity profiles at times up to 15-20μs from typical 9-probe, 11-probe and 25-probe MPDV experiments are presented in Figure 6. It should be noted that due to the similar type of velocity profiles for 304L and HY100 steels in 11-probe and 12-probe MPDV experiments, only 11-probe velocity profiles are presented in Figure 6. In general, all A36 and 304L steel showed a two-wave structure velocity profile in compression: an elastic wave followed by a relatively sharp plastic wave. Because of known material properties differences between steel and stainless steel, subtle differences do exist in the measured wave profiles. The velocity peak for the plastic wave was proportional to the impact velocity. Velocity profiles also showed a second velocity peak and a spall signature in the form of a 'pullback velocity' signal within the first 5μs. Supposedly, all low carbon alloy steels should show another wave rise after the plastic wave due to the α↔ε phase transition [13] similar to what was observed in shocked iron [14, 15]. However, in the case of HY100 steel, the signature of α↔ε phase transition is not prominent in our gas gun experiments at the rear surface. We suspect this could be due to the complex, asymmetric nature of the stress wave at that location in the target plate, and the relatively low stress amplitude of the wave at the rear surface of the target plate. Fundamental shock compression experiments that do observe the phase transition wave have all been done with a condition of uniaxial strain, which is not the case for the stress wave we observe. In all MPDV experiments, the impact center is within ± 3.0 mm from the nearest PDV probe. Therefore, probes located closest to the impact center showed the earliest arrival of the free surface velocity signal and showed the highest peak velocities in general; but there were certain exceptions. While the exact reason of these anomalies is not yet understood completely, possible reasons may include the complex asymmetric nature of the stress wave.



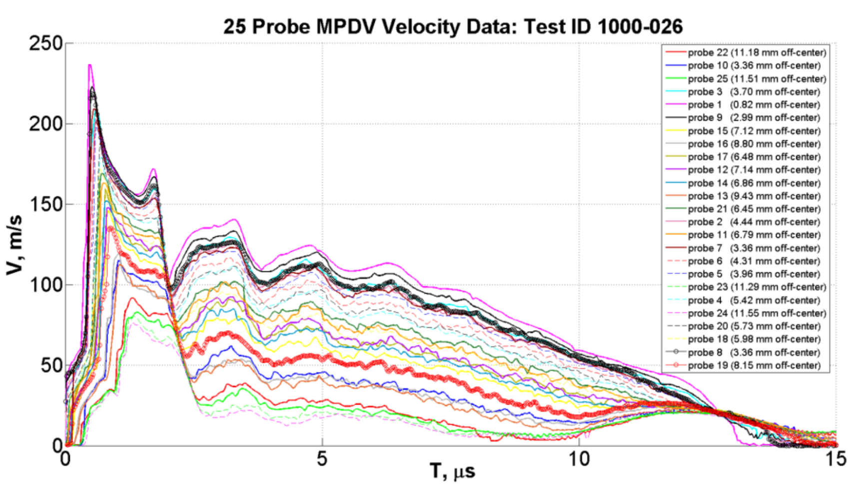
(a) Typical 9-probe MPDV Velocity Profiles for A36 steel



(b) Typical 11-probe MPDV Velocity Profiles for 304L steel



(c) Typical 11-probe MPDV Velocity Profiles for A36 steel



(d) Typical 25-probe MPDV Velocity Profiles for A36 steel

Figure 6: Velocity profiles collected from gas gun experiments by MPDV system

CONCLUSION

Gas gun experiments were performed to measure the plastic deformation of steel plates during high-velocity impact and an MPDV system was used to measure free surface velocity during these experiments on the back of the target plate. Plastic deformation as represented by bulge of the target plates and crater damage were proportional to impact velocity. Velocimetry data captured by MPDV systems provide information on the comparative dynamic behavior of target plates made of different materials. Although, significant efforts are still needed to analyze these MPDV data accurately, implementation of MPDV system in high-velocity impact experiments certainly provides a new horizon for the researchers to explore. Work is ongoing to interpret the results of these experiments.

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