Photon Doppler Velocimetry (PDV) Characterization of Shaped Charge Jet Formation

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Abstract

Photon Doppler Velocimetry was used to characterize the early time formation of the jet from a 65-mm diameter shaped charge with a copper liner. This tool provided a high fidelity, high temporal resolution technique to characterize the axial velocity evolution of the shaped charge jet’s first motion to exit from the base of the conical liner. The measurements were then compared with continuum mechanics shock physics simulations, using both CTH and ALEGRA, to understand the jet formation process and evolution.

Keywords: Shaped Charge Jet, Photon Doppler Velocimetry, PDV

1. Introduction

Unlined shaped charges are high explosive devices engineered to focus reaction products, resulting in regions of intensified local pressures [1]. When a shaped charge is lined with a material, usually a metal, one can create a jet traveling at very high velocity. This jet is formed as a result of extreme pressure and strain rates that occur when a material is driven by high explosive to collapse on its axis of symmetry. These devices have many useful applications ranging from oil drilling and metal cutting to use as warheads. A common geometry used to create a jet is that of a high explosive cylinder with a metallic lined hollow conical cavity at one end. The cylinder is then detonated from the solid end. Upon detonation a spherical wave front propagates through the high explosive and engulfs the conical liner, causing liner collapse, followed by...
jetting of the liner material along the cylinder’s symmetry axis. This type of device has proven to produce a jet of material traveling at relatively high velocity, some exceeding 10 mm/μs.

Significant efforts have been put into understanding and modeling the formation of shaped charge jets and the physics governing the jetting process. In the late 1940s, Birkhoff et al. [2] developed a steady state hydrodynamic jetting theory based on an incompressible fluid, which was considered to be the first adequate representation of the jetting process. This method was improved on by Pugh et al. [3] who implemented a variable rate liner collapse velocity. This modification collected light, which was used to measure the jet tip of a shaped charge warhead. Godunov et al. [4] added compensation for material strain rate effects by adding a viscous correction. Practicality of creating metallic lined shape charges typically necessitates what may be a non-ideal geometry near the cone’s apex. This non-ideal geometry typically takes the form of a spherical cap at the apex of the conical liner. The first addition of an apex model and its pending implications on formation arose in the late 1970s and early 1980s. Two separate approaches were used. The first approach was to apply hydrocodes to predict early jet formation [1, 5]. The second method incorporated segmenting the liner into multiple sections, to which one could apply the different analytical models [6, 7]. The application of differing models was based on the dominance of the model to the material motion. Near the apex, radial material flow is less of a factor, and therefore momentum/energy transfer models such as that outlined by Gurney et al. [8, 9] were found to be useful. Because the treatment of the apex differs from that of the conical liner collapse, and the liner collapse velocity decreases from the liner apex to the liner base, the velocity of the tip is analytically handled as a summed momentum divided by the summed mass [7]. Present day state-of-the-art methods use finite element shock physics codes to predict jet formation from initiation of the high explosive forward [10]. This method theoretically has the capability of handling the entire event as a unified problem through solving the differential equations of motion.

The current work focuses on early time experimental characterization of the jet formation and comparison to CTH [11] and ALEGRA [12] continuum mechanics based methods of prediction. Experimentally, Photon Doppler Velocimetry (PDV) [13] was used to measure the jet tip of a 65-mm diameter copper shaped charge from the liner’s first motion to near its maximum velocity. Prior assessments of jet formation were done using radiographic and optical photography studies [14-16]. Because of experimental complication, these studies typically began after the tip exits the shaped charge cone. For this particular warhead, the jet tip exits the conical liner ~10 μs after the first motion. The PDV measurements therefore provide experimental insight into a region that was previously uncharacterized. Because the jet formation is time dependent, high fidelity measurements of the formation are necessary to validate the process. PDV is well suited to make such measurements as it provides velocity measurements at a high temporal resolution (on the order of 1 - 10 s of nanoseconds [17]). It also has advantages over techniques such as VISAR [18] in that it can measure multiple surface velocities simultaneously. This is important for jet measurements as the machining of the liner creates a surface that is not pristine, and therefore ejects a cloud of particles near the tip that have individual velocities of different magnitudes.

2. Experimental

To characterize the early time formation of a jet, the material velocity of a 65-mm shaped charge warhead with a 44° copper liner was measured along its symmetry axis using PDV. The jet’s tip velocity was recorded from the shape charge liner’s first motion to a time concurrent with that when the jet material is traveling near the jet’s asymptotic tip velocity (the asymptotic tip velocity was measured by Summers [19] previously). A schematic representation of the experiment is shown in figure 1. Generally, a collimated probe of a PDV system directs laser light onto the apex of a stationary conical liner. Upon detonation of the high explosive, acceleration of the conical liner caused a Doppler shift in the reflected light, which was captured and recombined with a portion of unaltered light. The beat frequency, along with compensations for changes in the index of refraction of the propagating medium (air), can be directly correlated to the surface velocity of the reflecting medium [13].

![Fig. 1. Schematic representation of the experimental setup used to measure the velocity evolution of shaped charge jet formation.](image-url)
The PDV system used was purchased from Third Millennium Engineering of Plano, TX, (2G177PDV1A 4-Channel PDV receiver). The system incorporated a 1% tap coupler to extract unaltered light prior to the circulator of the PDV system. This light, along with the Doppler shifted light is recombined, and directed onto an AC coupled (~35 KHz cutoff), 10-GHz class PIN photodiode. The system was driven using a 2-W, single mode, linear polarized Erbium fiber laser, centered at $\lambda = 1550.5$ nm, which was purchased from IPG Photonics (ELR-2-1550-LP-SF). The probes purchased from AC Photonics (ICL15A070LSD01), consisted of a GRIN lens attached to a fiber pigtail. The lens collimated the light over a working distance of 300 mm and had ~0.8-mm spot size. FC-APC optical connectors were used to reduce reflection at fiber optic junctions. The output of the PDV’s photodiode was recorded on a LeCroy 820 ZI oscilloscope connected using SMA patch cords. The experiment was recorded using an effective bandwidth to 16 GHz with a sampling rate of 40 Gigasamples/sec.

Simulations of the jet formation were calculated using two finite element analysis shock physics codes, CTH [11] and ALEGRA [12]. All simulations were computed using only the solid dynamics platforms and Eulerian mechanics. The problem input was defined to include a thickness $\tau = 12.7$ mm, diameter $\phi = 19.05$-mm cylindrical Pentolite booster, the LX-14 main charge, and the OFHC copper liner. The problem was initiated using point detonation, and all simulations included air as the background material. Simulations were performed in two-dimensional (2-D) cylindrical geometry, three-dimensional (3-D) rectangular geometries, and radial trisection geometries. The 2-D simulations used 0.1-mm square cells, and the 3-D rectangular used 0.2-mm square cells. The 3-D radial trisection simulation used two cores, with the inner core having approximately three thousand elements per azimuthal slice and the outer core about two thousand elements per slice. The cell size ranged from 0.20 to 0.30 mm from the inner core to the outer core. The trisected parts were stitched together, converging radial elements with roughly square elements. The mesh is constructed such that finer cell sizes are focused toward the center, which encompasses the jet liner having approximately five to six elements across the liner thickness.

For consistency, we chose a set of “standard” material models that were used throughout. The models were chosen from the standard databases that are distributed with the codes and were checked for consistency. We chose a Mie-Gruneisen equation of state (EOS) for the copper liner, paired with a Steinburg-Guinan constitutive model and a Johnson-Cook material fracture model. These selections were based on the accuracy of predictions with conductivity/temperature measurements made when firing a similar shaped charge jet through vacuum [10]. Excursions from the standard model were performed to probe EOS, constitutive, and fracture models. The specifics of these excursions will be specified throughout.

3. Results and Discussion

Figure 2 shows a spectrogram from the PDV measurement of the jet along its axis of symmetry. The spectrogram plots spectral density of material at a particular velocity as a function of time, using a rainbow color scheme with red color indicating high spectral density and blue color indicating low spectral density. The measurements were adjusted in time so first movement of the AC-14 liner apex occurred at $t = 0$.

Fig. 2. Photon Doppler Velocimetry spectrogram acquired along the symmetry axis of a 65-mm diameter copper shaped charge jet.
Fig. 3. Geometrical setup and material position of a 65-mm diameter copper shaped charge as calculated by CTH using a 2-D cylindrical geometry mesh.

To further comprehend the early time “jet” formation process, we compare the experimentally measured results with 2-D CTH simulations. Figure 3 plots calculated material position and figure 4 plots calculated material pressure. In the simulations, the liner material was separated into seven segments to enhance visualization of the process. A velocity extraction from the 2-D CTH simulation is overlaid on the PDV spectrogram in figure 5. For ease of interpretation, alphabetic characters are used to indicate equivalent time snapshots of the images in figures 3 and 4 and the velocity profile in figure 5.

At $t = 0$, shock breakout from the high explosive detonation causes the liner material to begin moving with an axial particle velocity $U_p \approx 2000$ m/s. Experimental measurements indicate a slight velocity increase with time, but the rise is near the noise threshold and therefore cannot be deemed conclusive. This is in contrast to the simulations, which show material velocity decrease or “pull-back.” The simulated velocity decrease is an effect generated from interaction of a rearward propagating rarefaction and the forward propagating Taylor wave characteristic of a high explosive drive. The wave interaction generates tension ($-0.1$ GPa), which is indicated by a lack of color in figure 4 ($t = 0.32$ $\mu$s). By $t = 1.82$ $\mu$s the compression wave has reflected off of the liner’s back surface twice, which is experimentally evidenced as two increases in velocity spectrogram (see figure 2). In a uniaxial compression experiment, a similar phenomenon commonly termed “ringing” would appear as a discontinuous increases to new, constant velocities. In the shape charge problem, the increases occur as temporally broadened accelerations.

The simulated velocity profile is highly correlated with the experimental measurements during $t = 0 - 2$ $\mu$s. Because of the high correlation, we assume the simulation can be used to explore the physics that contribute to the acceleration’s non-discontinuous nature. Focusing on the figure 4, $t = 0.82 - 1.82$ $\mu$s images, and corresponding velocity vector plots (not shown), one arises to the conclusion that radial flow and subsequent jetting of copper liner material significantly contributes to the total axial particle velocity. The radial flow arises from the shock front sweeping along the liner’s hemispherical apex, and increases in magnitude with distance swept due to the continual angular reduction between the liner wall and the symmetry axis. The contributions manifest in two forms: they add directly to the material particle velocity, and they elongate the propagation path along which the reflected waves must traverse. Effects of the radial compressive flow and subsequent jetting become most obvious during the time spanning $t = 1.82 - 2.32$ $\mu$s, where the collapse occurs from a portion of the hemisphere liner that has a relatively acute angle. This is evidenced by the sharp pressure increases within the material. During this time the contribution to axial particle velocity from the radial compressive flow dominates that of subsequent shock reflections.
At $t \approx 2 \mu s$, the spectrogram indicates transition to a region of relatively constant material velocity of $\text{Up} \approx 6500 \text{ m/s}$ for a duration of $2 \rightarrow 3 \mu s$. In the simulation, a similar region existed but only lasted for a duration of $\approx 1 \mu s$ (denoted by point A). The simulation shows a rarefaction wave propagating from the tip into the jet’s bulk that causes this response. The experiment indicates a small amount of high velocity material is ejected during the transition, with the overall process appearing ballistic in nature. The simulation reports velocity from a “tracer,” i.e., velocity from a predefined point attached to the material within the simulation. The reported tracer undergoes a velocity decrease, not a ballistic response. The simulations also show material was not ejected from the main jet (concluded by examining the material volume fraction in relation with the simulation grid). Combination of these simulated phenomena infers that the main jet undergoes a velocity decrease at this time. The large velocity spikes that appear in the simulated results arise from the tracer subsiding in a mixed material cell containing both air and copper. This results in brief periods of tracer separation from the main jet followed by recollection. Of greater concern is the duration discrepancy between the experiment and simulation. Because the rarefaction
is geometrically dependent, one can hypothesize that the simulations may not accurately represent the early time material deformation and flow. Here we also note that we are comparing with a single experiment, and have not commented on its reproducibility. We have also not addressed the error associated with probe alignment relative to the free surface velocity vector. From the simulations it is clear that other than the ideal origin of the apex, the velocity vector is not along the axis. The analysis method, however, only considered measured velocity to be along the direction of the probe, therefore adding error to the measurements.

Near \( t \sim 2.5 \mu s \), the jet formation transitions from mechanics that were dependent on hemispherical liner collapse to those dependent on conical liner collapse. During this phase the pressure increases sharply, and can be more accurately modeled by the Pugh-Eichelberger-Rostoker theory \([3]\). This collapse accelerates material to an axial velocity higher than the mass that was previously accelerated from the shaped charge’s apex (commonly referred to as “reverse velocity gradient”). Figure 6 shows the computed axial material velocity from \( t = 3.32 – 5.32 \mu s \), indicating this phenomenon.

At \( t \sim 3.5 \mu s \) outward radial flow of material (similar to that occurring during erosion) becomes a significant factor in defining the pressure state near the jet tip. This flow, combined with the forward propagating pressure from the conical liner collapse, returns the tip to a state of positive pressure near \( t \sim 4 \mu s \). The PDV measurement supports this, showing what appears as acceleration in the spectrogram, but is actually a combination of material acceleration and acceleration continues through time, with the jet approaching an asymptotic velocity. In our experiment, the asymptotic velocity was not measured because the jet interacted with the PDV probe.

Here we note that the simulations show a second tension band occurring from a release wave that initiates just behind the large mass of the jet tip. This tension contributes to thinning of the jet diameter and reduces the local particle axial velocities, but would not be realized in our measurements as the tension never propagates to the tip. In an attempt to understand some of the differences between the experimental measurement and the simulated results, we have explored variations of the material models and problem setup using simulations. The first excursion probed variation of the liner material’s constitutive model.

Figure 7 overlays the calculated velocities on the spectrogram when replacing the constitutive model with a Johnson-Cook formulation, and a hydrodynamic formulation. Although small deviations were noticeable, neither change resulted in an appreciable material velocity change throughout the time span of interest. This is expected with the high pressure and strain associated at the early stages of this problem. To quantify the error, the maximum velocity discrepancies occurred at \( t \sim 6.8 \mu s \) where the hydrodynamic solution predicted a velocity 3.3% less than the Steinburg-Guinan solution. The effects of strength are consistent with previous studies and is further supported by the late time applicability of Brikoff et al. \([2]\).
hydrodynamic theory, which predicts a tip velocity of $U_{\text{jet}} = 9.2$ m/s compared to the experimentally measured 9.1 m/s (which is still undergoing acceleration according to the PDV measurements).

Fig. 6. Material Y-velocity profile near the apex of a 65-mm diameter copper shaped charge as calculated by CTH using a 2-D cylindrical geometry mesh.

Fig. 7. Comparison of Steinburg-Guinan, Johnson-Cook, and hydrodynamic constitutive models on the velocity profile calculated using CTH paired with a 2-D cylindrical geometry mesh. The results are overlaid on the spectrogram measured experimentally using PDV.
Similar excursions were made that probed the liner’s fracture model and EOS. The fracture model was probed by setting the fracture threshold to unphysical high and low values. The EOS was tested by replacing the “standard” Mie-Gruneisen EOS with a multi-phase SESAME table. The maximum velocity deviations calculated during either test varied less than 0.1% from the “standard” setup.

Larger simulation velocity deviations were found as a function of the initial problem geometry and mesh alignment. Figure 8 overlays jet tip velocity predictions as calculated by CTH and ALEGRA codes using 2-D and 3-D meshes. Generally, all models do well at predicting the gross features: shock breakout and velocity increase from shock ringing; the velocity plateau associated with the rarefaction initiated at the jet tip; and acceleration toward an asymptotic velocity. However, quantitative comparisons show maximum velocity deviations of ±10% from that calculated by the “standard” model. Comparison also revealed that the temporal onset and duration of particular features show errors of up to 40%. These errors when integrated over the formation time can result in significant errors, on the order of 10 of mm or 1 μs after the tip passes the base of the conical liner.

The final computational excursion probed the detonation geometry used to initiation the shaped charge. Here, a “disk” detonation of area similar to that of an RP-80 explosive bridge wire was used. Figure 9 overlays the jet tip velocity predictions as calculated by CTH. The change in initiation geometry causes a flattening of the shock front that sweeps across the shaped charge liner. This is graphically depicted when plotting the pressure profile as in figure 10. The changes modify both the magnitude of the material velocity that jets from the hemispherical portion of the liner, and shortens the duration of the rarefaction that occurs at the tip. These results support the claim that this portion of the formation process is strongly geometrically dependent, and that the simulations may not be accurately capturing the material flow and interface tracking.

Fig. 8. Comparison of mesh geometry and continuum mechanics method (CTH vs. ALEGRA) on the computed velocity spectrum of a 65-mm diameter copper shaped charge jet. The results are overlaid on the spectrogram of measured experimentally using PDV.
Fig. 9. Comparison of detonation geometry on the velocity spectrum of a 65 mm diameter copper shaped charge jet as calculated using CTH paired with a 2-D cylindrical geometry mesh. The results are overlaid on the spectrogram measured experimentally using PDV.

Fig. 10. Material pressure accumulated near the apex of a 65 mm diameter copper shaped charge when initiated with point and disk geometries. The results were calculated using CTH paired with a 2-D cylindrical geometry mesh.

4. Conclusions

This work demonstrates how Photon Doppler Velocimetry was used to characterize the early time formation of a jet formed from a 65-mm diameter shaped charge lined with copper. The measurements were compared with shock physics simulations, using both CTH and ALEGRA, to understand the jet formation process and evolution. The comparison revealed multiple phenomena contribute to the early time formation of a shaped charge jet. These include a high explosively driven shock and its subsequent ringing, jetting and acceleration from a hemispherical portion of the liner’s apex, complex geometry based rarefactions, and jetting and acceleration from the conical portion of the liner. The comparison also revealed the strengths and weaknesses of Eulerian based shock physics simulations during each stage of the jet’s velocity profile.
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References

[12] ALEGRA is a Family of Arbitrary Lagrangian-Eulerian Shock Physics Codes Developed by Sandia National Laboratory.