Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia Engineering 58 (2013) 384 – 391
Procedia Engineering
www.elsevier.com/locate/procedia

The 12th Hypervelocity Impact Symposium

Validation of an Impulse Measurement Technique with High Temporal and Spatial Resolutions

Denis Richard[a]*, Stan Ault[a], Ping Qian[a], Gary Rutledge[a], Lara Leininger[a], Dennis Baum[a], Michael Murphy[a]

[a]*Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA94551-0808, USA.*

Abstract

We present a new experimental technique to measure the force-time history of high-velocity impacts and high pressure blast waves. The technique is based on the classic Hopkinson-type strain bar, coupled with an interferometric velocimeter instead of strain gauges. The major benefits of this setup are its accuracy, temporal resolution, and its imperviousness to electromagnetic interferences. We explain the keys concepts behind the technique and describe the experimental setup. We present experimental and numerical data as proof-of-concept and discuss preliminary studies on the effect of plastic deformation of the bar and its consequences on the interpretation of the measured impulse-history.

Selection and peer-review under responsibility of the Hypervelocity Impact Society
Keywords: High-Velocity Impacts – Impulse – Strain Bar – Experimental Technique

1. Introduction

Understanding the force-time (or pressure-time) history of high velocity, high load impulses onto targets is of critical importance to evaluate the effectiveness of the impulse delivery mechanism, be it projectiles, fragments, shaped charge jets, blast or other. Having an accurate force-time history is also critical to evaluate the response of materials and fidelity of any predictive models.

In the present paper, we will discuss experimental results and analysis of a new higher fidelity technique for time-resolved impulse measurement using an old approach. We revisit the Hopkinson-bar momentum trap methodology using a new instrumentation method. Historical instrumentation of this approach using strain gages can suffer from sensitivity limits in high noise environments, and they cannot resolve the strain-wave features smaller than the scale of the strain-gage or frequency responses faster than 1/2 the strain-gage driver frequency. Moreover, strain gauges are sensitive to the electro-magnetic pulses (EMP) present in the plasma environment created during chemical detonation, and their use presents challenges for the study of explosively driven impacts.

Our approach consists of using a Hopkinson pressure bar to measure high resolution, time-resolved strain wave propagation using Photonic Doppler Velocimetry (PDV) methodology. The light-weight velocimeter is aimed at the free surface end of the bar opposite to the impact and effectively measures the material velocity induced by the propagating

* Corresponding author. Tel.: +1-925-423-5660; fax: +1-925-422-0779.
E-mail address: richard9@llnl.gov.

1877-7058 © 2013 The Authors. Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the Hypervelocity Impact Society
doi:10.1016/j.proeng.2013.05.044

stress waves due to that impact. This technique requires no mechanical contact with the measurement surface, is robust within context of high EMP explosive environments and is immune to electromagnetic interference suffered by other traditionally employed methods that utilize conductive wires to transmit the measured signal. A major benefit of this lack of sensitivity is that the direct transmission of the impulse can be measured, while in the case of strain gauges it is typical to have to wait for multiple reflections inside the bar before the EMP noise is down to reasonable levels. Such reflected signals are subject to damping and possibly alteration of their time history due to multiple transits along the bar.

First, we present the core concepts of the technique and describe the simple experimental setup. We show numerical and experimental results for the simple test case of an impulse hammer impacting the bar in order to verify and validate the concept. Then, we discuss experimental and numerical results obtained in the case of the impact of well-characterized shaped charge jet, which leads to a discussion on the effect of plastic deformation on the signal and the interpretation of the velocity history of the bar.

2. The PDV-bar: core concepts and experimental setup

2.1. Stress wave transmission and material velocity in bars.

The core concept of the "PDV-Bar" technique, much like the classic Hopkinson bar [1], is to use a bar to collect the impulse resulting from an impact, rely on the induced strain-wave to propagate the information down to its opposite end and measure particle velocity time history. Hopkinson's original setup relied on a short piece of magnetic rod butted up against the one end of the bar; the momentum communicated to this fly-off rod was the measured quantity. In modern setups, strain gauges are positioned along the bar to measure the stress time history—and therefore impulse—due to the impact. In the PDV-bar setup, the stress is derived from the material velocity induced by the stress wave, and this velocity is being measured at the free surface of the bar end opposite the impact. The relation between the stress wave and material velocity can be found, assuming a few simplifying assumptions. (See Johnson, 1972 [2])

We assume that the impact induces a stress σ at one end of the bar. We make the hypothesis that the stress wave that subsequently propagates in the bar is a longitudinal plane elastic compression wave. A necessary requirement for this approximation to be valid is that the impact pulse duration must be several times that of the transit time (at sound speed) across the diameter of the bar [2]. This also means that surface, torsional and flexural waves, as well as Poisson effects are neglected. For a perfect elastic longitudinal wave, there is no dispersion of the signal. This is not true if plasticity occurs, as it introduces non-linearities in the wave equation. (Plasticity effects will be addressed later in this paper.) Under the assumptions mentioned above, the material velocity induced in the bar by the initial propagation of the compression wave can be related to the initial stress by

$$\sigma = \rho c_L v, \qquad (1)$$

where σ is the stress of the impact, ρ is the density, $c_L$is the longitudinal speed of sound, and v is the material speed—or particle velocity—in the bar. When the compression wave arrives at the end of the bar, it is reflected in the form of a tensile wave due the no-stress condition on the free surface. The tensile wave develops a negative stress, $-\sigma$, which propagates in the opposite direction and thus becomes an additional velocity component, of same amplitude and direction than the original wave. Therefore, at the free surface the material velocity doubles and the stress-velocity relationship becomes

$$2\sigma = \rho c_L v. \qquad (2)$$

Note that the additive contributions to the velocity of the compression and the tensile waves occur not only at the free surface but everywhere the compression and the reflected tensile wave co-exist, i.e. over a length of the bar equal to half the pulse length. The velocity exactly doubles compared to that due to the original compression wave at the free surface, but for the other material points in this region, the amplitude of their velocity is a function of the force history of the pulse, i.e. of the shape of $\sigma(t)$. Equation 2 therefore provides a straightforward way to derive the force-history of the impact when knowing the velocity, $v(t)$, of the free surface at the opposite end of the bar:

$$F(t) = \rho c_L v(t) A/2, \qquad (3)$$

where A is the bar cross sectional area.

2.2. Experimental setup

In order to measure this velocity, we use a Photonic Doppler Velocimeter, which is a fiber optic based LASER Doppler velocimeter, that can measure surface velocities ranging from cm/s to km/s. The PDV is simpler to setup and more portable that most other standard velocimeters and it can be quickly and cost-efficiently deployed in the field. In its basic incarnation, it consists of a LASER-generated optical courier that propagates through a multimode optic fiber and a probe lens to illuminate the target surface. The reflected light—which is Doppler-shifted because of the surface motion—is collected by the same probe lens and back through the fiber. It is then mixed with a fraction of the original frequency through a fiber coupler (see Fig. 1). The beat frequency between incident and shifted signal is proportional to the velocity of the surface. (see Strand et al. 2006 [3], Sargis et al. 1999 [4]) The accuracy of the PDV system is estimated to be 1% uncertainty in velocity and the time resolution, after processing, is 50 ns.

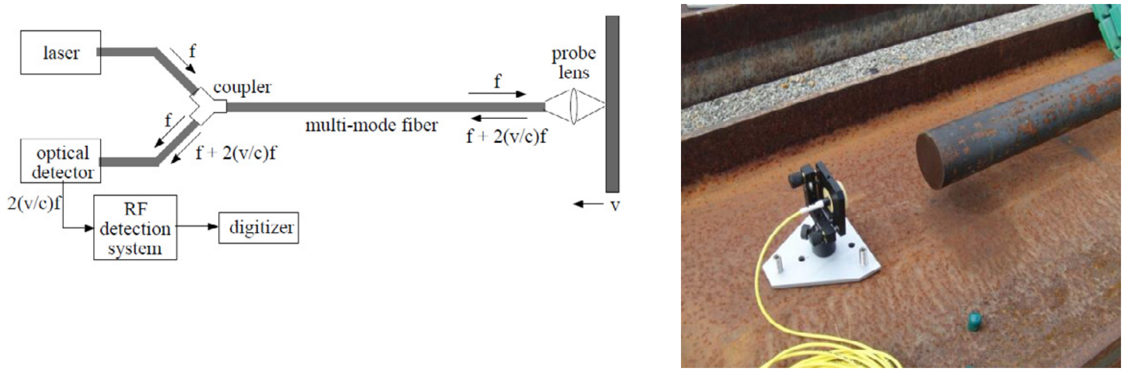

Fig. 1. Left: Concept of Photon Doppler Velocimetry; the moving surface is on the right, in front of the probe (from Sargis et al., 1999 [4]). Right: Photograph of PDV probe and optical fiber positioned to measure the velocity of the end surface of a Hopkinson-type pressure bar.

Fourty-foot (12.19 m) long hot-rolled steel bars (with diameters varying from 2 ½'' to 4'') have been used for verification tests of this new diagnostic and validation has been performed using high velocity shaped charge jet impact. The length has been chosen to allow the study of impulses of long durations—up to about 2 ms, which translate to pulse lengths of over 33 feet (10 m) in steel. Figure 1 shows the simple experimental setup, with the PDV probe lens in an optical mount aligned with the axis of the bar, facing the end surface; the visible yellow optic fiber leads to the rest of the PDV system. Fig. 2 shows a schematic of the complete experiment. The same setup was used In order to verify the basic PDV-bar concept, simple experiments and numerical simulations were performed. The simple test problem utilized an instrumented hammer impact on one end of the bar. Numerical simulations were carried out to verify the basic propagation (without dissipation) of the stress in the bar and how this translated to material velocity at the free surface. Experiments were performed to verify the PDV signal collected after impact on the bar of a calibrated impulse hammer.

2.3. Numerical calculations of wave propagation and material velocity

We have investigated the validity of the PDV-bar concept using a two-dimensional, axisymmetric, numerical model of the 40-foot pressure bar. We used the arbitrary lagrangian-eulerian code ALE3D developed at LLNL [5-6]. The material model for steel features constant shear modulus and yield strength and a polynomial equation of state. An impulse analogous to that of a calibrated impulse hammer was applied as a force boundary condition at one end, and the material velocity at various points along the bar axis was tracked in order to follow the wave propagation and verify that there was no significant loss or dispersion of the signal in this geometry. The yield strength of the bar material was chosen so that a small plastic deformation could actually occur at the impacted end (with a resulting permanent depression where the loading was applied of 154 microns).

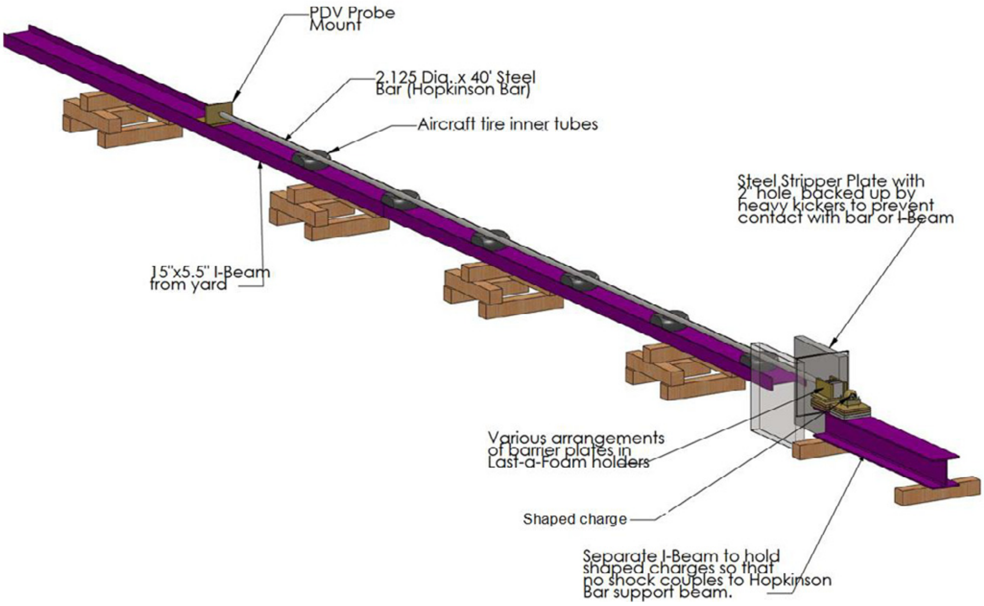

Fig. 2. Schematic of the PDV-bar experimental set-up

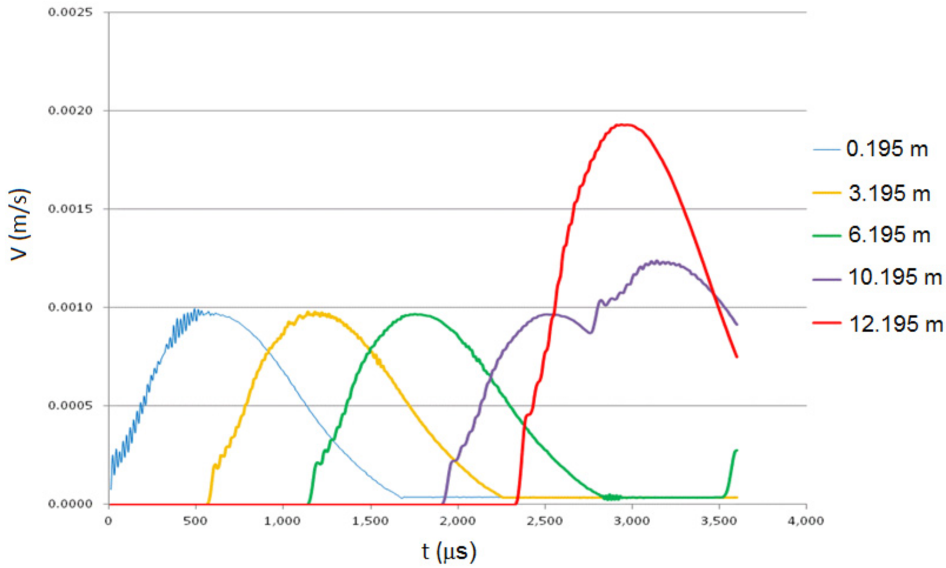

Fig. 3. 2D axisymmetric calculations of material axial velocity inside the pressure bar at several distances from impact as a function of time. The last point (12.195 m from impact) is the free surface at the end of the bar. The wave propagates without significant attenuation or dispersion. The histories of the last two points (12.195 m and 10.195 m) demonstrate the effect of the overlapping of incident compression and reflected tensile wave.

Figure 3 shows the computed material velocity as a function of time at five locations on the bar axis. The first three locations (at 0.195 m, 3.195 m and 6.195 m from the impact) show the material velocity induced by the incident compression wave created by the impact. No significant loss or dispersion is observed. The last point—i.e. the free surface where PDV measurements are to be performed—shows the doubling in velocity expected from Eq. 2, with still no significant distortion of the signal. The point at 10.195 m is an interesting illustration of the velocity history at a location where the incident compression and reflected tensile waves partially overlap in time. Up to about t = 2,800 µs this point experiences the stress of only the compression wave; after that time, it experiences a superposition of the compression and tensile waves. The induced material velocities add up linearly assuming the waves can be regarded as purely elastic. These results validate the basic PDV-bar concept, even when small plastic deformations are present at impact.

2.4. Experimental validation with calibrated impulse hammer

We performed experimental characterization experiments in which we used a load-cell instrumented impulse hammer (model Dytran 5802A) to apply a measured impulse into one end of the bar. The PDV measures surface velocity which is converted to force through Eq. 3. Figure 4 shows the comparison of the force histories as given by the instrumented hammer (green curve) and by the PDV measurement. Both sources are in excellent agreement in terms of both amplitude and timing, the only noticeable difference being the high frequencies present in the hammer data. Whether this difference is due to dispersion and high frequency damping in the bar, to noise in the hammer instrumentation or to smoothing due to the PDV post-processing of the data has not been investigated yet. For all practical purpose, this result clearly demonstrates the sound basis of the PDV-bar setup.

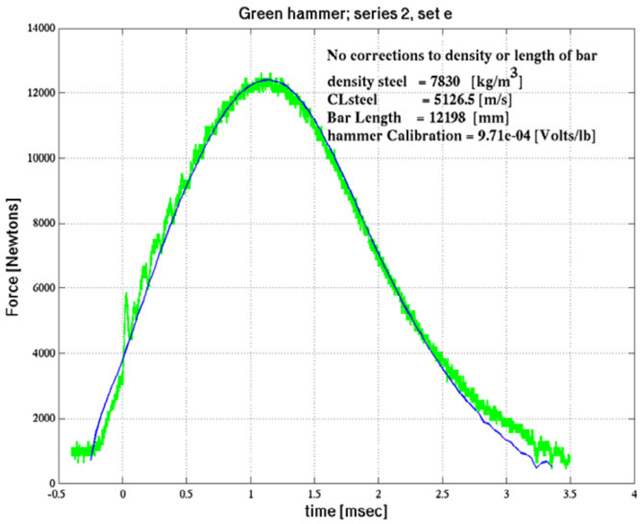

Fig. 4. Comparisons with the reference impulse hammer and PDV measurements show good correlation. The green curve shows the force history as given by the instrumented impulse hammer; the blue curve is the same quantity derived from PDV measurements.

3. High velocity impacts: Effects of plastic deformations

The results shown until this point have been either purely elastic or weakly plastic—in the sense that plastic deformation was small, if present at all in the bar. In the case of a high velocity impact with a large impulse delivered to a small area of the pressure bar, the bar is likely to experience significant damage over some its length.

We have performed high velocity impact experiments by shooting a porous granular shaped charged jet into a PDV-bar. Figure 5 shows the force history measured from one of these shots along with a photograph of the damage at the end of the bar. In this case, the deformation extends about 1/2 inch deep into the bar. Even though the stress propagation is elastic beyond that short depth, there are two concerns with this plastic deformation. First, while the equations for the propagation of an elastic wave are linear, it is not the case for the plastic wave propagation case; strong non-linearities could introduce significant distortions of the original signal. Secondly, we assumed that the impulse was applied to a flat surface and propagated as a plane wave; the deformation of the surface as it is impacted will distort the wave front and here again, possibly the transmitted signal.

To measure the effects of plasticity on the signal, we performed numerical simulations with a simple model of a porous granular jet impacting a steel bar. The jet geometry is cylindrical, and of constant cross-section. Its velocity varies linearly (classic stretching shaped charge jet), and its density is calculated so that the force history of the impact matches the experimental data showed in Fig. 5. As in the case of the hammer test, if the impact remains perfectly elastic and if there is no dispersion or loss in the bar, the velocity at the end of the bar will obey Eq.3. We ran two different calculations of the model, one with the yield stress value of the actual steel bar used in the experiment and one with a very large yield stress—one hundred times the actual value.

The time history in Fig.5 shows three transits of the stress-wave. The first pulse (between 0 to 1 ms) is due to the directly transmitted wave, the following two pulses being reflections bouncing inside the bar between the two free end surfaces. The losses and alterations in theses subsequent reflected pulses are evident. The PDV-bar approach allows us to acquire the first pulse, while the classic strain gauge setup would not, due to EMP noise obscuring the signal.

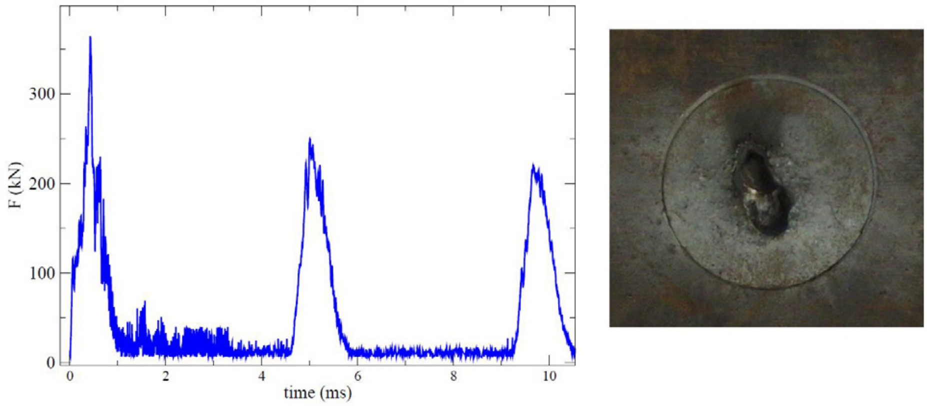

Fig. 5. Left: measured force history of a high velocity shaped charge jet. Right: Damage to the input end of the bar due to the jet penetration. Such plastic deformations complicate the interpretation of the measured PDV-bar signal in terms of time history. (Zero time corresponds to first detected velocity.)

The initial condition at the interface between the jet and the bar is shown on Fig. 6, as well as the resulting damages at the end of the simulations. In the figure, the high yield steel has remained mainly elastic and little plastic damage is seen. The low yield steel shows damage comparable to that of the actual experiment. We therefore have one case which should mostly obey Eq. 3 and one case that should show the deviation of that relationship for plastic deformations such as observed experimentally.

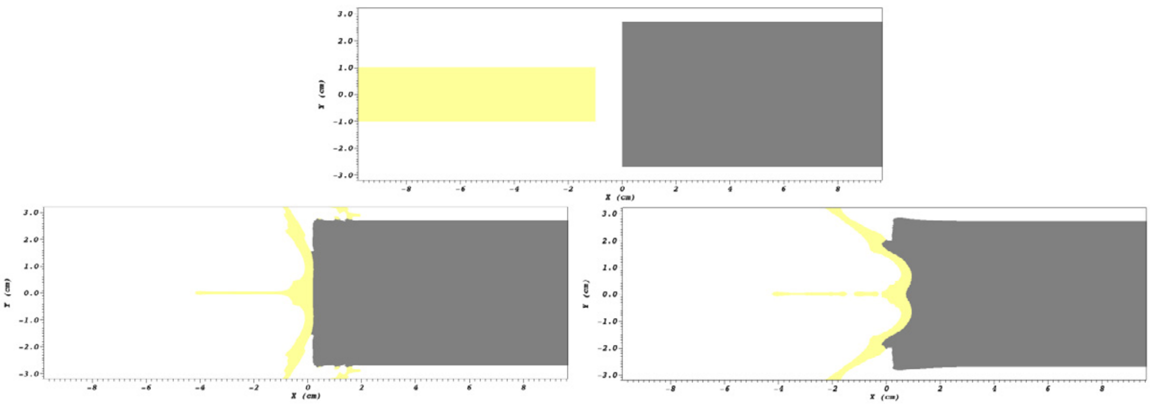

Fig. 6. High velocity impact simulations. Upper: Initial condition showing a close up of the steel bar (grey) and granular jet (yellow). Bottom (left) end time for high yield steel case (small deformation) and (right) low yield steel (large plastic deformation).

The computed time history of the material velocity transmitted to the end of the bar is shown on Fig. 7. The blue curve is the velocity expected from Eq. 3. The red curve is the case with little plastic deformation. The most notable characteristic of this curve is that it reproduces the impact force history well but with a clear damping of the higher frequency features. Another notable difference is the trend of the transmitted impulse to be slightly larger than the loading, a feature that could be due to some outflow of the impacting material—due to momentum conservation.

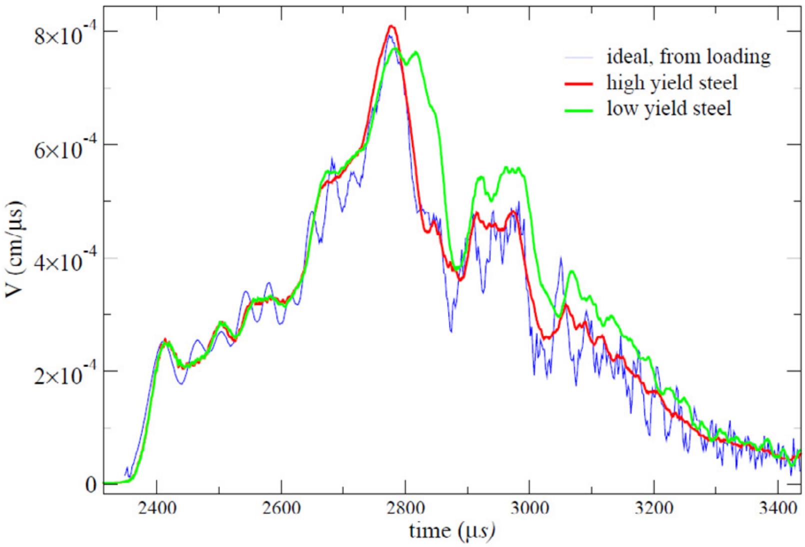

Fig. 7. Material velocity history at the free surface of the bar from impacts in high and low yield steel bars for a high velocity impact calculation. The blue curve is the expected velocity if the loading propagates ideally, the red curve is the computed material velocity for a high yield stress steel bar (resulting in little deformation from impact) and the green one for a low yield bar (large damage). (Zero time corresponds to begin of impact on the bar.)

The green curve shows the velocity time history in the case with plastic deformation consistent with what is seen in the experiments. The effect of plasticity on the coupling between the impactor impulse history and the stress propagating down the bar is evident. The early part of the impulse history is properly represented by the material velocity, but once the impulse reaches higher values—e.g. when plastic deformation is occurring—the transmitted velocity history is distorted. This phenomena limits the expected accuracy of the characterization for a given impactor with this diagnostic as it also would with the strain gage approach. One recommendation is to select a high yield stress material for the bar in order to avoid damage and deformation.

The integrated impulse at the end of the bar of the high yield (elastic) case is 4% higher than the loading. This difference includes numerical and physical effects—possibly some outflow of impacting material, which alters the load due to conversation of momentum. That same total impulse for the low yield case (plastic) is 10% higher than in the elastic case. The obvious conclusion from these calculations is that in such a case the original impactor could be reasonably well characterized in terms of total impulse and impulse history even though not all its features could be resolved.

4. Conclusions

We have demonstrated a new technique to measure the time history of forces, based on the coupling of a Hopkinson-type pressure bar and a lightweight and highly accurate velocimeter. The major benefits of this technique compared to strain gauges are the lack of sensitivity to EMP—and therefore lack of noise—and its ability to measure the directly transmitted impulse—first transit—as opposed to having to wait for a clean signal after multiple reflections.

When the problem is mostly elastic, the measured material velocity on the free surface at the end of the bar shows excellent agreement with the impact force history. For high velocity impacts, in the absence of plastic deformation, there is good agreement but for the smoothing of time history—i.e. the damping of higher frequencies—and a slight overestimation—i.e. the transmitted impulse if larger than the loading—in numerical simulations that is possibly due to material outflow. When plastic deformations are significant, there is a definite alteration of the time history. This issue can likely be corrected by using bar of high yield strength material. These limitations due to plastic deformations are not due to the PDV measurements, but to the fundamental properties of propagation and plastic deformation of the bar itself. Strain gauges or other instrumentation based on pressure bars would face the same problems.

Acknowledgements

This work was funded by DOE/NNSA and the Joint DoD/DOE Munitions Technology Development Program. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] B. Hopkinson, 1914, "A Method of Measuring the Pressure Produced in the Detonation of High Explosives or by the Impact of Bullets," Philos. Trans. R. Soc. (London) A, 213, pp. 437-456.
[2] Johnson, W., 1972, "Impact Strength of Materials," Edward Arnold Publishers, London.
[3] Strand, O., Goosman, D., Martinez, C., Whitworth, T., Kuhlow, W., 2006, "Compact system for high-speed Velocimetry using heterodyne techniques," Review of Scientific Instruments 77, 083108.
[4] Sargis, P., Molau, N., Sweider, D., Lowry, M., Strand, O., 1999, "Photonic Doppler Velocimetry," LLNL report, UCRL-ID-133075.
[5] https://wci.llnl.gov/codes/ale3d/
[6] Nichols, A., 2007, "Users Manual for ALE3D: An Arbitrary Lagrange/Eulerian 3D Code System", LLNL Technical Report, UCRL-MA-152204 Rev 6