AIP | Proceedings

HIGH-RESOLUTION PROJECTILE VELOCITY AND ACCELERATION MEASUREMENT USING PHOTONIC DOPPLER VELOCIMETRY

Scott Levinson and Sikhanda Satapathy

HIGH-RESOLUTION PROJECTILE VELOCITY AND ACCELERATION MEASUREMENT USING PHOTONIC DOPPLER VELOCIMETRY

Scott Levinson and Sikhanda Satapathy

Institute for Advanced Technology, The University of Texas at Austin, Austin TX 78759

Abstract. This paper describes the new photonic Doppler velocimetry (PDV) technique for measuring time-resolved projectile velocity and acceleration profiles for full flight of the launch package in a two-stage light-gas gun (LGG). This technique is shown to provide excellent temporal and spatial resolution in measurement. Two non-linear acceleration stages were observed for the first time on the LGG. When the gun bore was at atmospheric pressure, a strong opacity was observed during hypervelocity projectile motion >2200 km/s.

Keywords: Optical, IR, heterodyne, reflect, shock, VISAR, PDV
PACS: 42.79.Qx, 42.68.Ca.

INTRODUCTION

Photonic Doppler velocimetry (PDV) [1] was recently developed as an alternative velocimetry diagnostic to the VISAR and Fabry-Pérot [2] for short-range, high-velocity, shock experiments. The PDV uses a homodyne method that has many of the advantages of the VISAR [3] and other optical systems, while avoiding many of their disadvantages.

Previous applications of PDV involve measuring transient velocities (0–15 km/s) during shock events over relatively short times (< 500 ms) and short distances (< 0.2 m) [4]. We have extended this method to accurately measure the projectile velocity at high resolution over a longer period of time (> 10 ms) and distance (> 16 m) in the bore of a 10 m hypervelocity light-gas gun (LGG) and the 6 m flight-to-target. Except for a brief (~1 ms) interval just before muzzle exit—where the signal is likely attenuated due to shock formation in the air—the velocity profile has been resolved within 0.3 m/s in 1.3 ms time intervals for the entire travel from the gun beech to target. Highly accurate and resolved PDV velocity measurements have made practical the calculation of axial displacement and axial acceleration.

PHOTONIC DOPPLER VELOCIMETRY

The telecommunications industry has solved and/or greatly reduced the cost of many issues associated with transmitting information using near-infrared light. PDV exploits those benefits. Like continuous-wave radar at microwave frequencies, PDV is a Doppler-homodyne procedure that measures the beat frequency between an unshifted, near-infrared reference light wave propagating at wavelength λ_0 (or frequency $f_0 = c/\lambda_0$, c $\equiv$ speed of light) and the Doppler shifted light reflected off of a moving surface. Mixing the unshifted reference laser signal (frequency f_0) with the reflected, Doppler shifted signal (frequency f_1) using a square-law detector results in a homodyne signal having an instantaneous beat frequency within the bandwidth of the detector: $f(t) = |f_0 - f_1| = 2v(t)/\lambda_0$, where v(t) is the time-varying projectile speed.

IAT uses a four channel PDV system designed by David Holtkamp, et. al., of LANL [5, 6]. Here, we describe results of in-bore velocity measurements using channels 2 and 3 of IAT's PDV system shown schematically in Fig. 1. The PDV was used to measure projectile velocity profiles in IAT's 10-m LGG with probes located near muzzle and at the target, which was 6 m from the muzzle.

585

Misalignment issues during a launch were effectively eliminated in our experiments with the use of retro-reflective tape [7] on the illuminated face(s) of the projectile.

The high-resolution PDV signals were digitally recorded during the railgun launch at constant digital sample rate $f_s = 1/\Delta t = 6.25$ GHz. The frequency and velocity spectral content of the signal were obtained by short-time Fourier transforms [8] of the digitized beat signals.
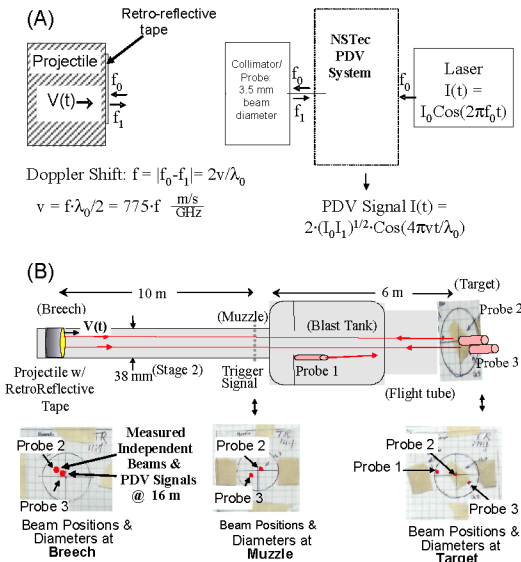

Figure 1. PDV system (A) and LGG experiment (B). Probes transmit and receive 1550 nm IR signals to/from the leading and trailing edges of the launch package. Retro-reflective surfaces are affixed to the leading and trailing sides of the cylindrical slug, which greatly reduced optical alignment issues. Prior to the launches, the diameters and azmuthal positions of the lasers striking the projectile were measured statically for projecile placement at the breech, at the muzzle or at the target.

A series of 50% overlapping, Hamming windowed, short-time Fourier transforms $x(v) = \mathfrak{F}(I(v(t))$ [5] of the digitized PDV signal records are used to calculate the spectral content of the instantaneous velocity v. The spectral content is calculated and displayed as a two-dimensional spectrogram $S(v_i, T_k) = 10\mathrm{Log}[|(v_i, T_k)|^2]$, where $x(v_i, T_k)$ is the discrete, fast Fourier transform of the

k^{th} sub-record of the beat signal intensity $I(f_i, T_k)$ specific to our high resolution laser: centered about time T_k and velocity $v_i = 774.6115 \cdot f_i$.

RESULTS AND DISCUSSION

We first discuss a launch where the bore was at full atmosphere using probe 2 located at the target. The overall features of PDV analyses are represented by the spectrogram shown in Fig. 2. It shows an intense narrow spectral peak increasing with time. The velocity may by identified from the beat frequency f_i corresponding to the spectral peak $S(v_i, T_k)$ of $n/2 = 8192$ components at each time T_k (separated by independent subinterval $\Delta T = n\Delta t = 2.6$ μs).
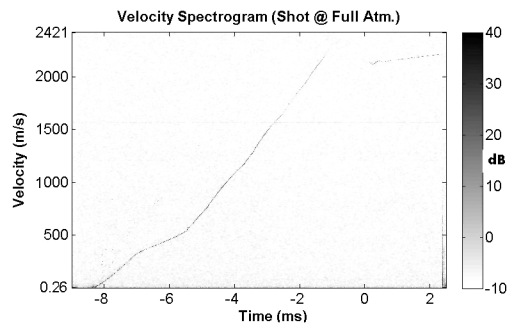
Figure 2. The velocity spectrogram is shown for PDV analyses of probe 2 of shot 1109 at full atmosphere. The spectral peak identifies the signal at each time and velocity. Undersampling resulted in ambiguous velocities when the projectile exceeded 2421 m/s.

Because the digitizer used for this experiment was limited to 10^8 samples/channel and the sample rate f_s to either 6.25 GHz or 12.5 GHz, $f_s = 6.25$ GHz was chosen to insure having ample continuous record length (20 ms). However, the lower 6.25 GHz rate resulted in ambiguous velocity detection whenever the actual projectile velocity exceeded the Nyquist velocity V_{Nyq} (2421 m/s) due to signal aliasing. Fortunately, the identifiable and generally monotonic increase in projectile velocity allowed us to identify a single time $(t_{Nyq}) = -0.91$ ms) in this experiment when the velocity reached V_{Nyq}. For each time $T_k < t_{Nyq}$, the instantaneous velocity v_i between manually selected bounds was taken to be equal to the detected velocity v_d corresponding to the maximum

586

level $S_{Max}(v_i, T_k)$. For aliased signals [9] occurring after t_{Nyq}, the detected velocity was calculated using an alias correction which assumes that velocity $v_d(T_k)=2\cdot V_{Nyq}- v_i(T_k)$ and acceleration are both continuous at t_{Nyq}.
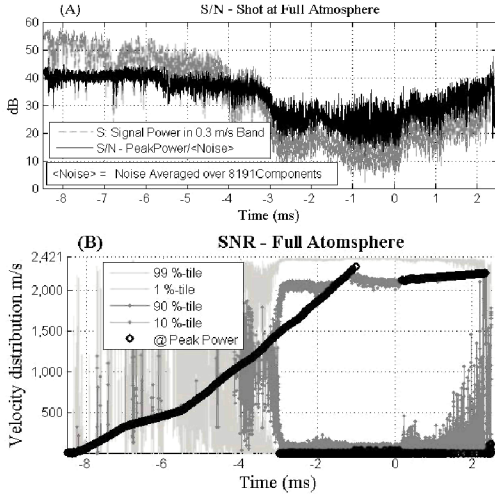

Figure 3. Figures-of-Merit. The signal peak power and S/N correponding to Fig. 2 are shown in (A). Percentiles 1 %, 99 %, 10%, 90 % and peaks are given in (B).

The signal/noise ratio and percentiles are two figures of merit for $v_d(T_k)$ and are shown in Fig. 3. The velocity signal at time T_k was usually taken as the highest spectra level $S(v_d, T_k)$. The average noise N was computed as the average of all other (8191) components at each time T_k.

The spectrogram in Fig. 2 shows that the signal tracks the projectile for most of the launch—as the signal to noise ratio S/N in Fig. 3 exceeds 20 dB during times t< - 1 ms. The signal peaks shown in the percentile plot of Fig. 3 reveal that manually selected bounds were unnecessary until t = ~-3 ms, after which the signal peaks were frequently associated with very low velocity.

The Fig. 4 shows the aliased-corrected detected velocity time series and corresponding calculations of the displacement, acceleration and 50 % normal error bars for acceleration. The velocity was successfully detected until ~1 ms (~3 m) before muzzle exit, when the signal was strongly
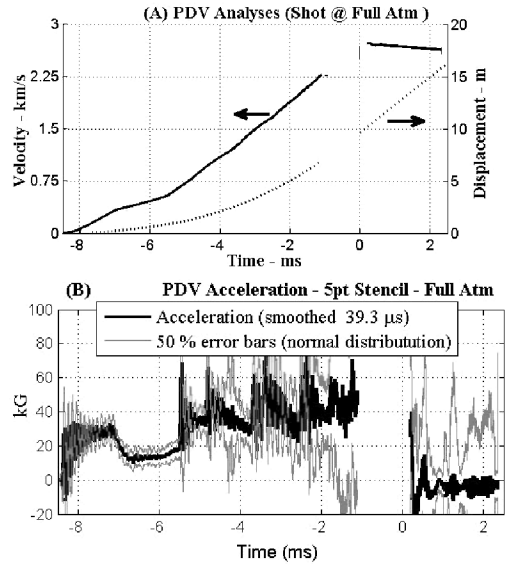
Figure 4. The detected velocity and its integral (displacement) are shown versus time (A). Numerically differentiated velocity (smoothed over 39.3 µs) provide acceleration estimates (B) with 50 % error bars.

attenuated, but then recovered after exit—where its nearly constant negative slope is indicative of 39 km/s^2 drag. Integration of the velocity profile resulted in a displacement curve that reliably indicates position of the muzzle (10 m at t =0) and 16 m target at impact. The acceleration estimates show a non-uniform acceleration while the projectile was in-bore, and a deceleration outside of the bore is consistent with the decreasing velocity due to air drag.

In our second experiment, we analyzed the velocity and balloting of a slug launched in a vacuum. The Fig. 5 shows the projectile velocity displacement and acceleration vs. time in 10-Torr vacuum, under similar conditions as the (full-atmosphere) shot in Fig. 4. Here, the velocity was detected for a longer period than that at full atmosphere, losing signal for only about 400 µs near exit. After exit, the velocity reached a 2782 m/s maximum, and no drag was observed. Comparing the acceleration profiles between the atmospheric and vacuum shots (Figure 6) indicates that air drag (after 0 ms) was entirely responsible for velocity reduction after exit. Both also indicate that the in-bore acceleration is non-linear, showing

587

two stages of acceleration which transition early during the launch (~2 m from the breech).
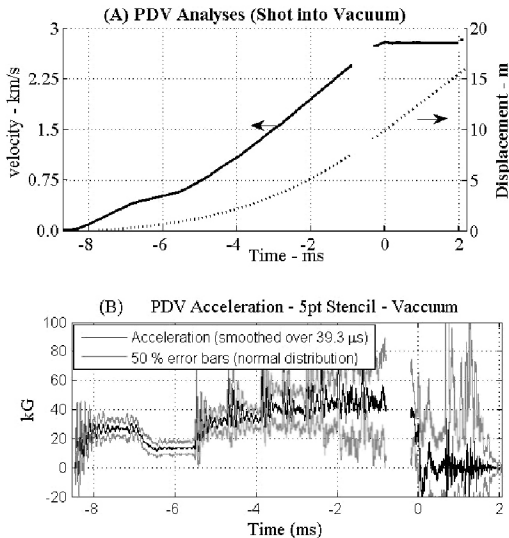

(A) PDV Analyses (Shot into Vacuum)

(B) PDV Acceleration - 5pt Stencil - Vaccuum

Acceleration (smoothed over 39.3 µs)
50 % error bars (normal distribution)

Figure 5 Shown in Figure 5 are the corresponding LGG shot dynamics of Figure 4 for a LGG shot in a vacuum.

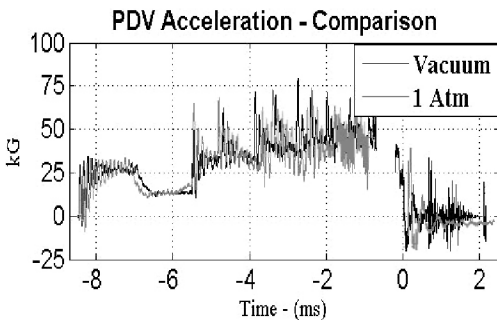**PDV Acceleration - Comparison**

Vacuum
1 Atm

Figure 6 The accelerations of shots at full pressure and in vacuum are re-plotted on same axis.

CONCLUSIONS

The homodyne PDV technique was successfully used to measure highly resolved axial motion of a launch package in the bore of the IAT LGG. A strong opacity was observed for projectile velocity > 2200 km/s at the muzzle end of the gun when it was operated at atmospheric pressure —since the PDV velocity signal was strongly attenuated near the muzzle. Signal transmission was significantly improved when the same tests were conducted in vacuum, suggesting that the development of a shock front is likely to be responsible for the opacity. Since PDV provides such an accurate and spatially resolved measurement of the axial velocity for nearly the entire flight of the launch package, we were able to observe two non-linear acceleration stages on this launcher [10].

REFERENCES

1. O. Strand, D. Goosman, C. Martinez, and C. Whitworth, "Compact system for high-speed velocimetry using heterodyne techniques," Rev. Sci. Inst. 77, 83108, 2006.
2. C. F. McMillan, D. R. Goosman, N. L. Parker, L. L. Steinmetz, H. H. Chau, T. Huen, R. K. Whipkey, and S. J. Perry, Rev. Sci. Instrum. 59, 1, 1988.
3. L.M. Barker and R.E. Hollenbach. J of Appl Phy, 43(11):4669, 1972.
4. O. Strand, private communications, August 2007.
5. B. A. Jensen, D. B. Holtkamp, P. A. Rigg, and D. H. Dolan, 'Accuracy limits and window corrections for photon Doppler velocimetry,' J. Appl. Phys. 101, 013523 (2007).
6. National Security Technologies, Adam Iverson, David Esquibel, LLC., March 2007.
7. http://en.wikipedia.org/wiki/Retroreflector.
8. P. D. Welch, *IEEE Trans. Audio Electroacoust.* Vol. AU-15 (June 1967) pp. 70–73.
9. C. E. Shannon, PROC. IRE, vol. 37, no. 1, pp. 10–21, Jan. 1949.
10. S. J. Levinson, D. B. Berry, B. Pededersen, Stephan Bless, 'Comparison of Theory and Measurements of a Two-Stage Light-Gas Gun' 16th APS Top. Conf on Shock Compression of Condensed Matter, N1.2.