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Title: Simultaneous Photonic Doppler Velocimetry and Ultra-high Speed Imaging Techniques to Characterize Pressure Output of Detonators

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Simultaneous Photonic Doppler Velocimetry and Ultra-high Speed Imaging Techniques to Characterize Pressure Output of Detonators

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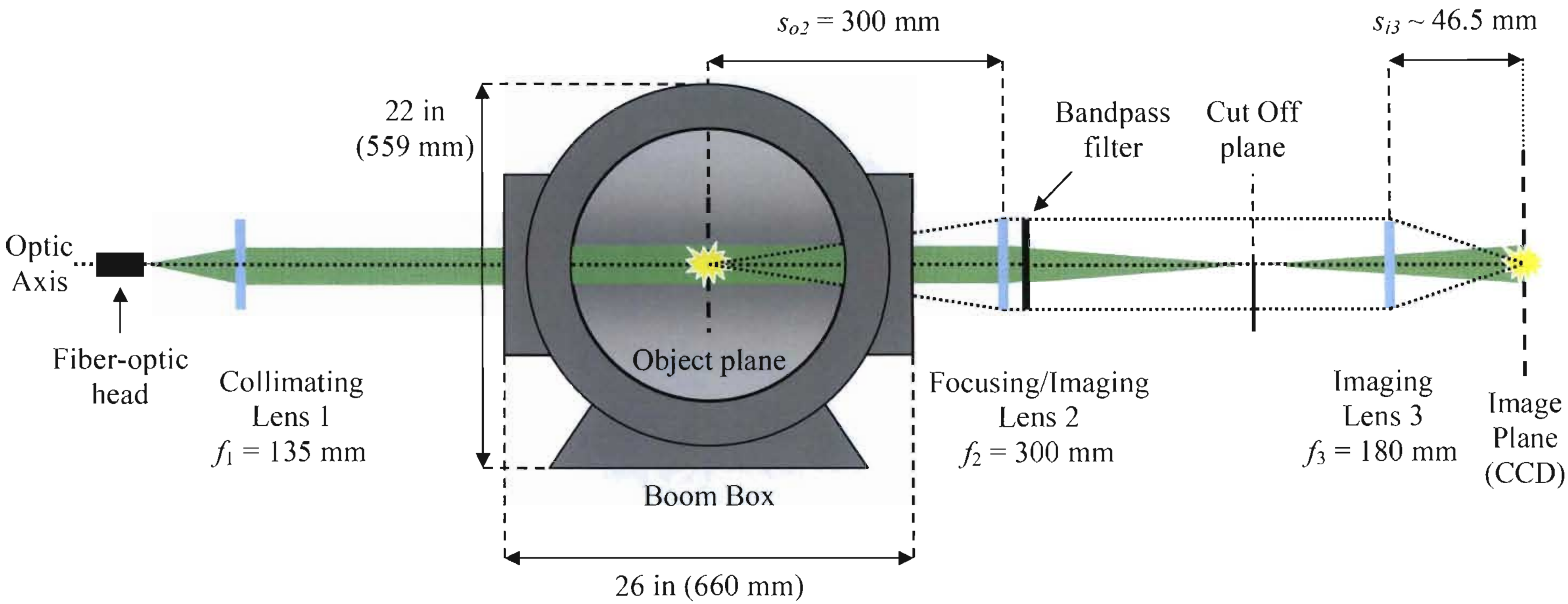
Abstract

Detonator output directed into both ambient air and polymethylmethacrylate (PMMA) samples is simultaneously investigated using ultra-high speed, time-resolved schlieren/shadowgraph imaging and photonic Doppler velocimetry (PDV) measurements. In air, one-dimensional measurements of explosive cup position are made from the time-resolved image sequences and are compared to time-integrated velocity curves obtained from the PDV data. The results demonstrate good agreement that validates using the two methods concurrently. In PMMA, both average and instantaneous shock velocities are calculated from 1-D measurements of shock position. Velocity-Hugoniot data for PMMA is utilized to map the shock velocity calculations to corresponding values of mass velocity and shock pressure. Simultaneous PDV data describing the motion of the explosive cup/PMMA interface are used to determine the mass velocity and pressure at the interface, and to compare to the mass and shock pressures calculated from the imaging data.

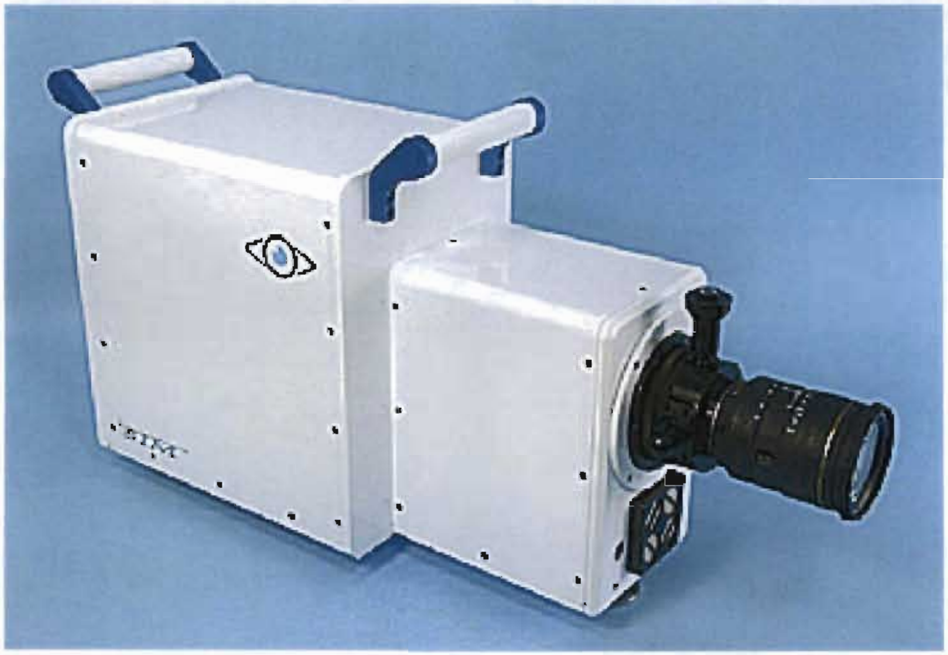
Defining Detonator Output …

- Useful to define detonator output quantitatively in terms of output pressure
- Detonator output typically defined by explosive performance, e.g. unique C-J state
- Most detonators employ a metal cup housing the explosive, e.g. Al, Ni, Steel, etc.
- The shock-impedance match between the explosive detonation products at the C-J state of the explosive and the metal cup material determine the output pressure of the detonator *in the metal.*
- **Output pressure of the detonator in the metal cup will be larger than the C-J state of the explosive.**

Imaging Configuration for Visualizing Detonators

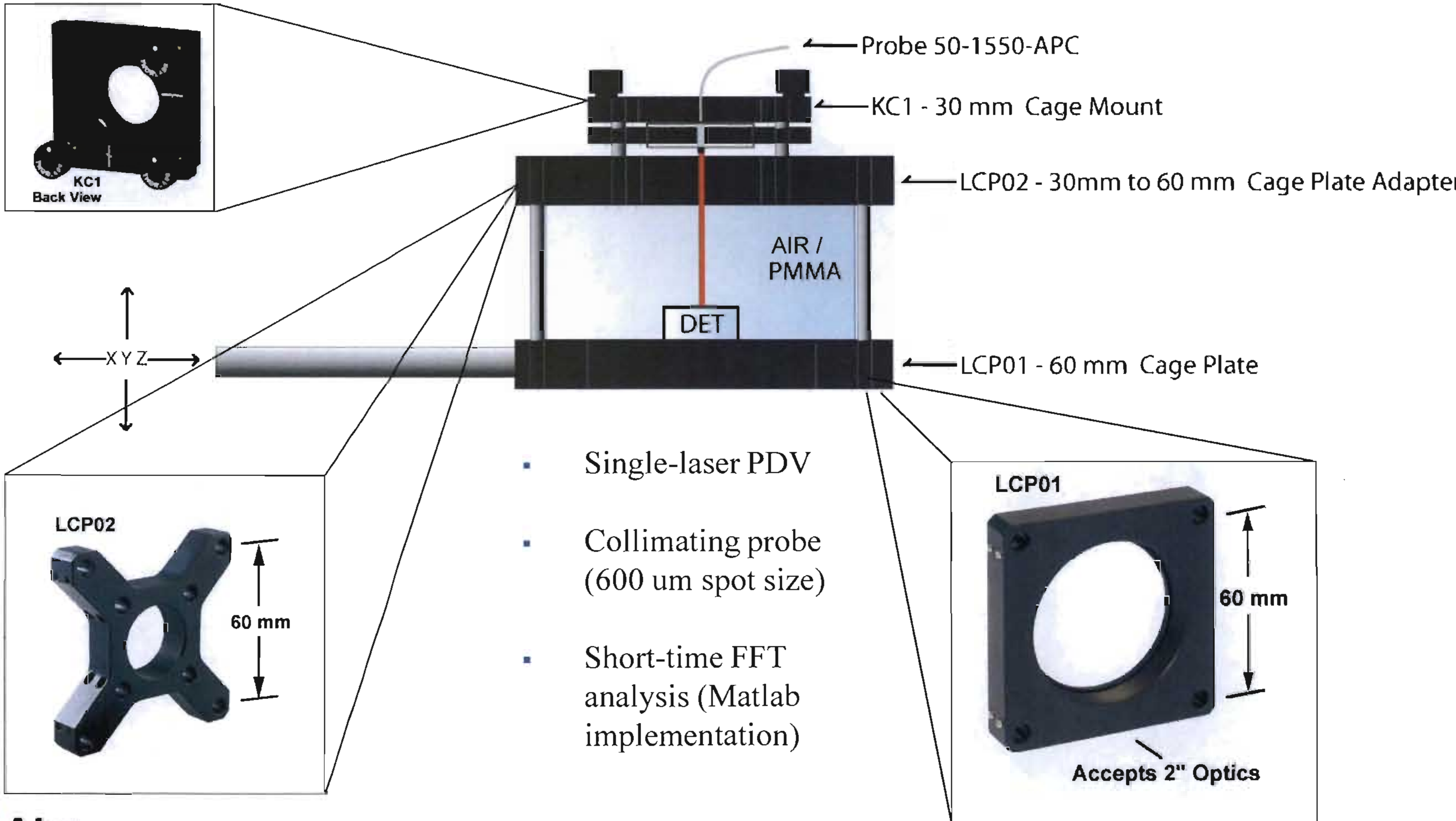


SIMD Ultra-high Speed Framing Camera



- 5 ns min exposure/interframe times
- 500 ns min frame-straddle delay on each camera module
- 8 intensified camera modules
- No parallax error from beam-splitting architecture
- No fiber-optic faceplate required for schlieren applications (greatly improves spatial resolution)
- 1360x1024 pixel arrays with 12-bit resolution
- Ghosting (phosphor lag) corrections can be made post-experiment

Photonic Doppler Velocimetry



- Single-laser PDV
- Collimating probe (600 um spot size)
- Short-time FFT analysis (Matlab implementation)

R&D Detonator Test Subject

- **Detonator**
  - PBX 9407 output pellet
  - Nickel cup (241 um thick)
- **PBX 9407**
  - D (1.60 g/cc) = 7.91 mm/us
  - P_{cj} = 26.5 GPa, u_{cj} = 2.09 mm/us
- ***P-u* Hugoniot of detonation products estimated using empirical curve from Cooper (1996)**

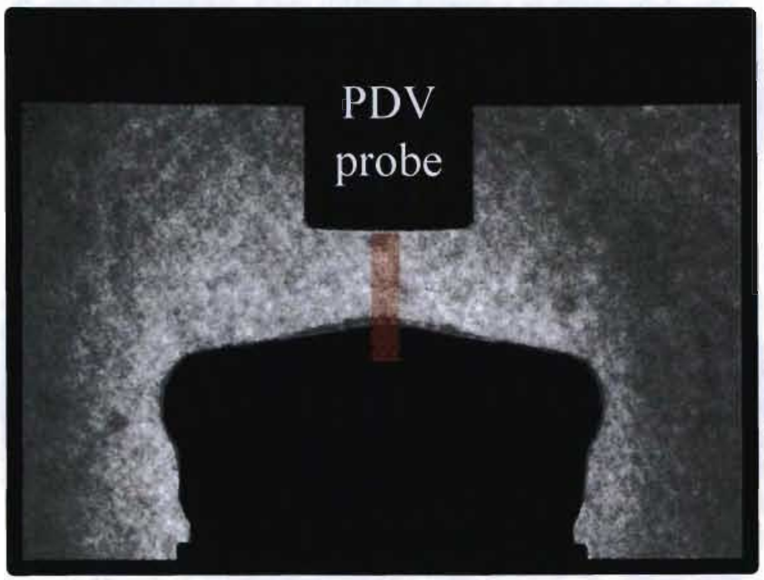
$$\frac{P}{P_{cj}} = 2.412 - 1.7315\left(\frac{u}{u_{cj}}\right) + 0.3195\left(\frac{u}{u_{cj}}\right)^2, \text{ for } \frac{P}{P_{cj}} > 0.08$$

- **Density and Hugoniot parameters for Nickel taken from Marsh (1980)**

$$U_s(u_p) = 4.60 + 1.44\,u_p\,, \text{ for } \bar{\rho}_0 = 8.875 \text{ g/cc}$$

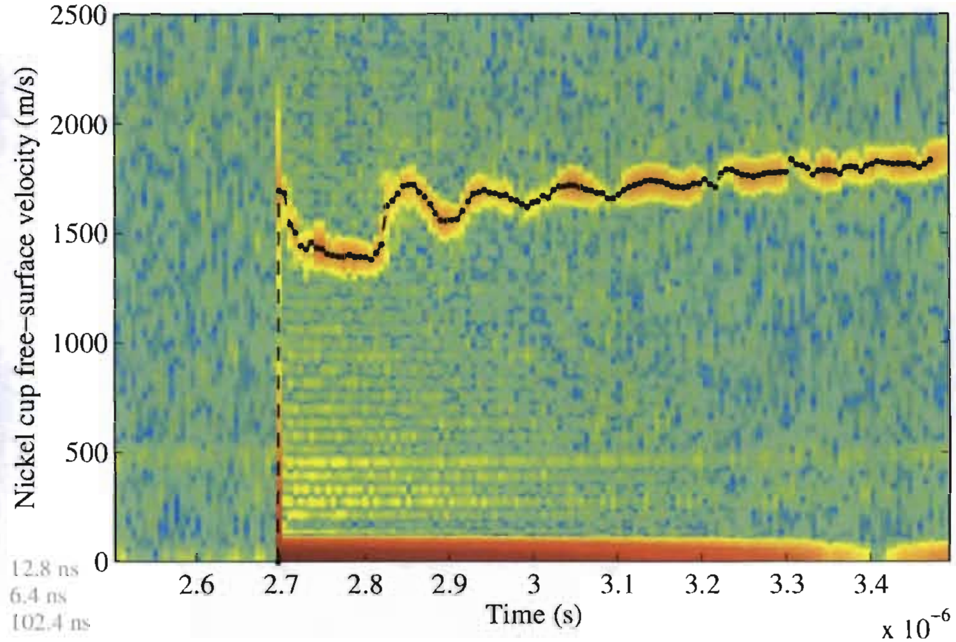
Detonator Output into Air

Ultra-high speed imaging



5 ns exposure, 50 ns inter-framing

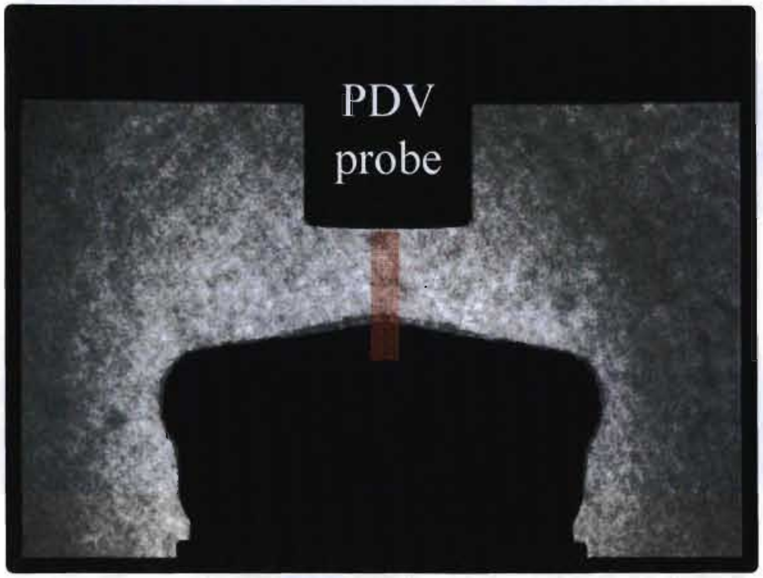
Centerline PDV



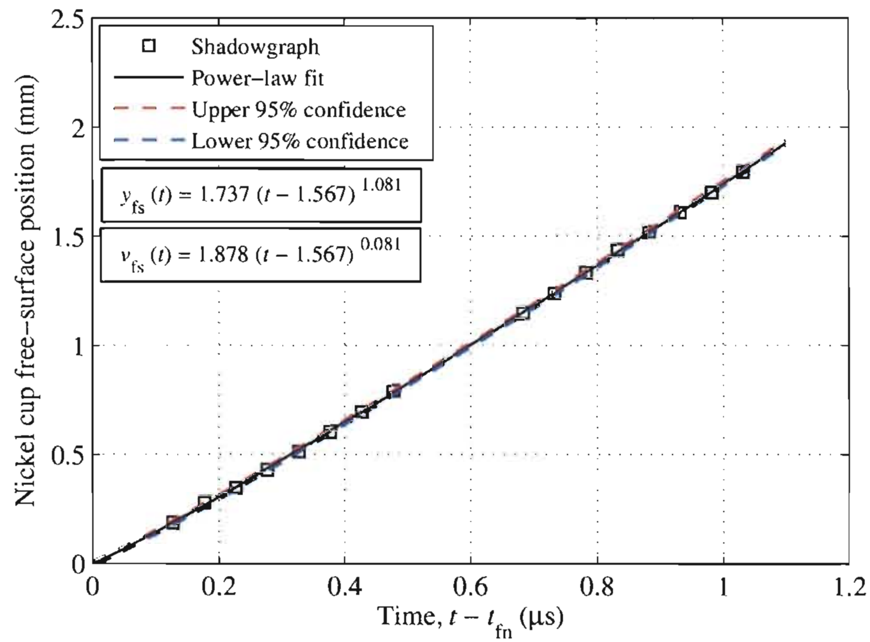
A Gaussian fitting method is employed to find the peaks of the measured velocity data for each FFT window

Detonator Output into Air

Ultra-high speed imaging

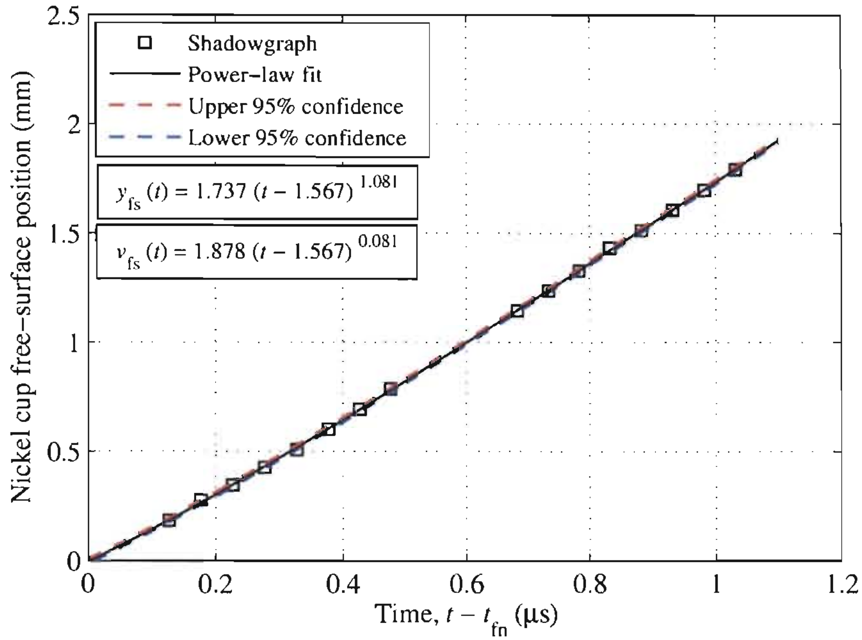


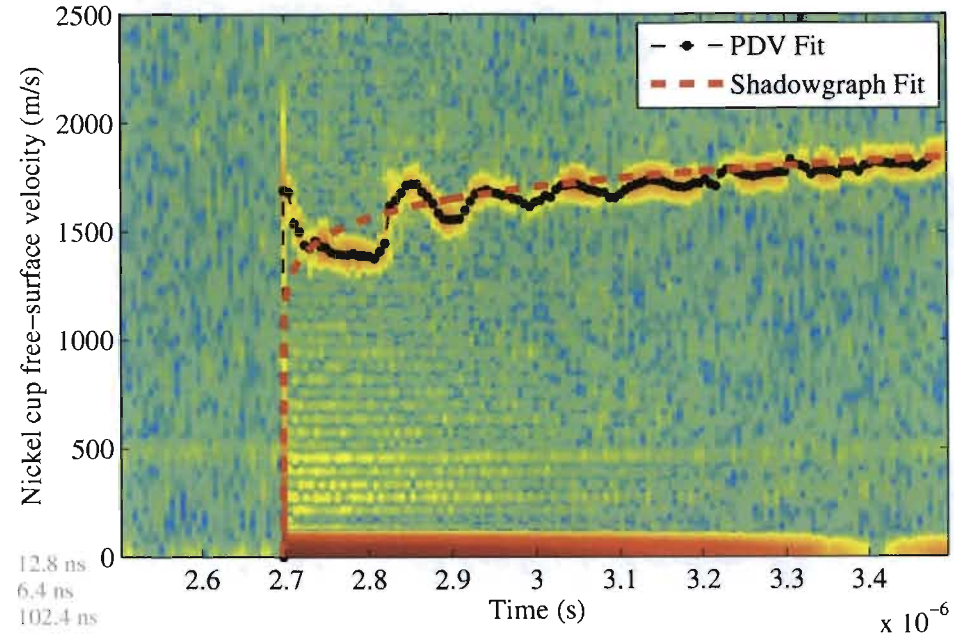
5 ns exposure, 50 ns inter-framing



Centerline cup motion of the detonator extracted from the image sequence

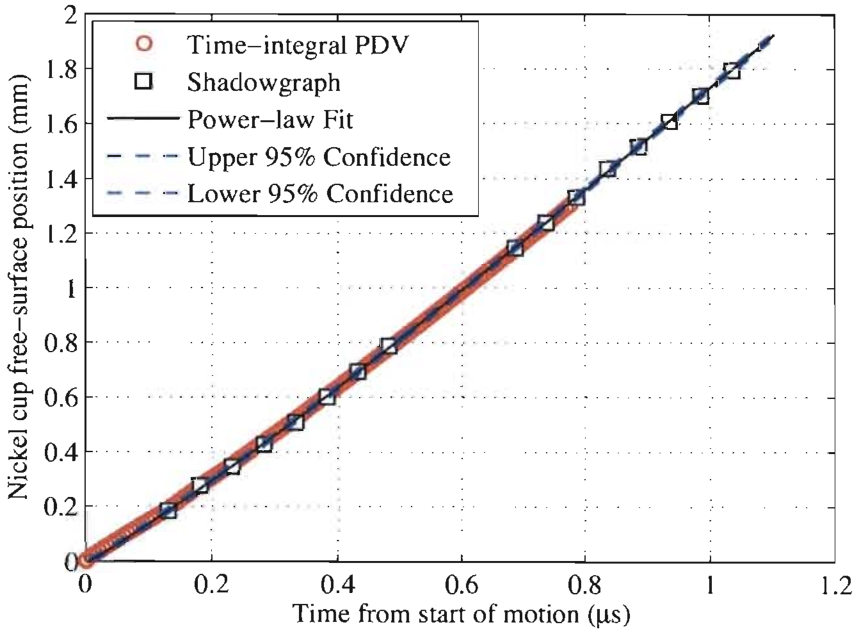
Detonator Output into Air – Centerline Results

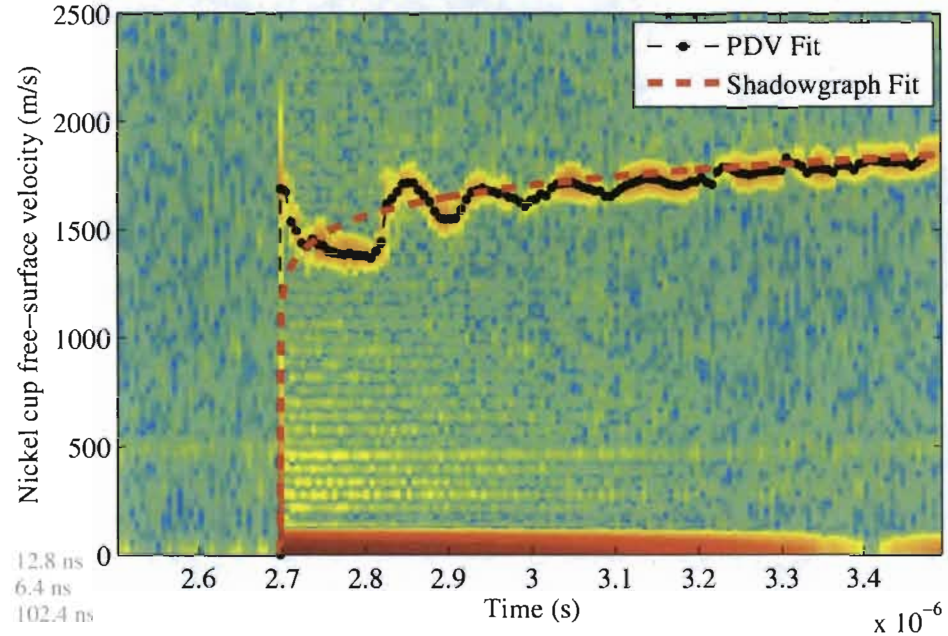




The reduced imaging data yields a free-surface velocity history that increases in time, like that of an explosively-driven flyer. Comparison of the free-surface velocity calculated from the imaging data (red dashed line on spectrogram) to the centerline PDV measurement shows good agreement from the viewpoint of accurately measuring the bulk motion of the metal cup.

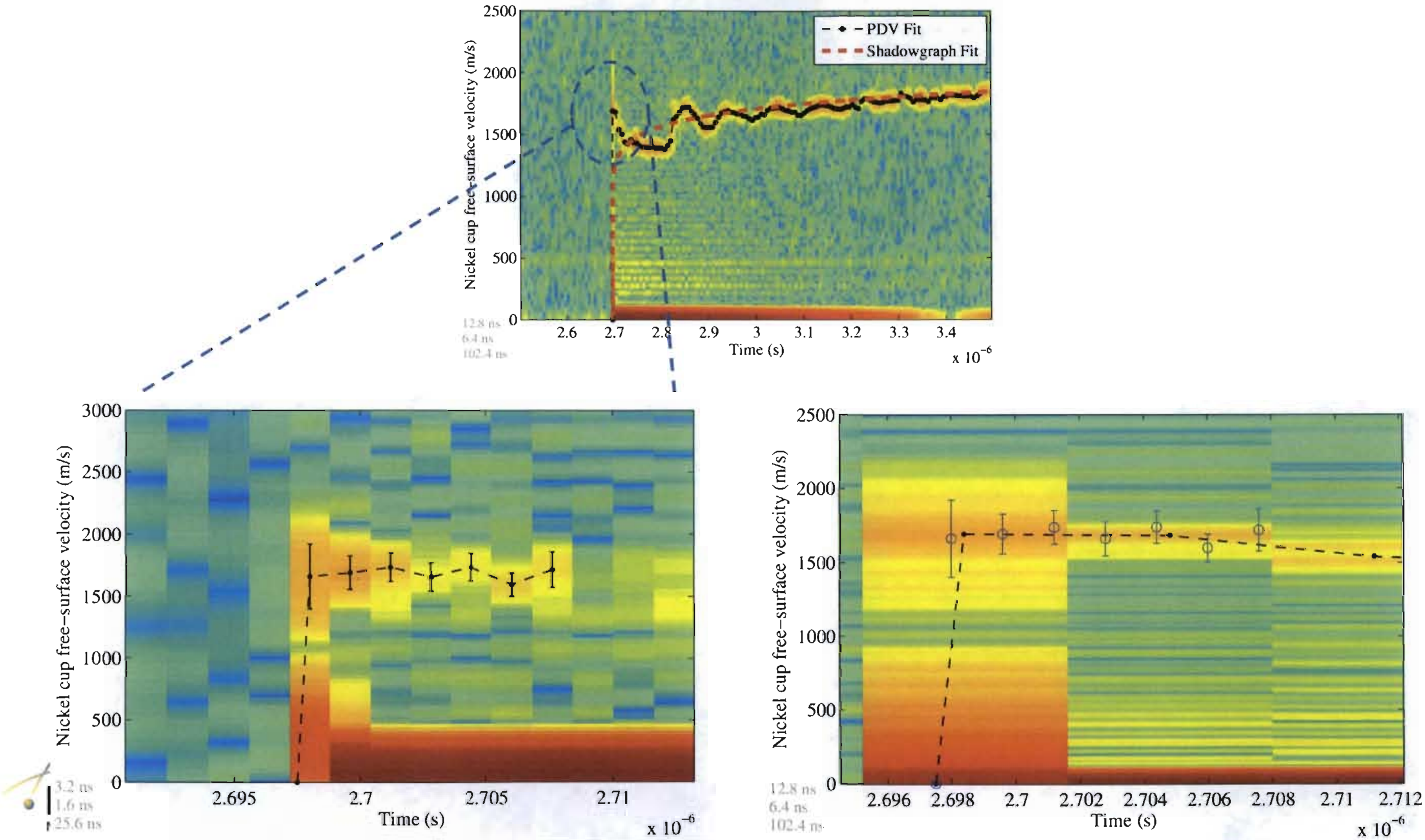
Detonator Output into Air – Centerline Results



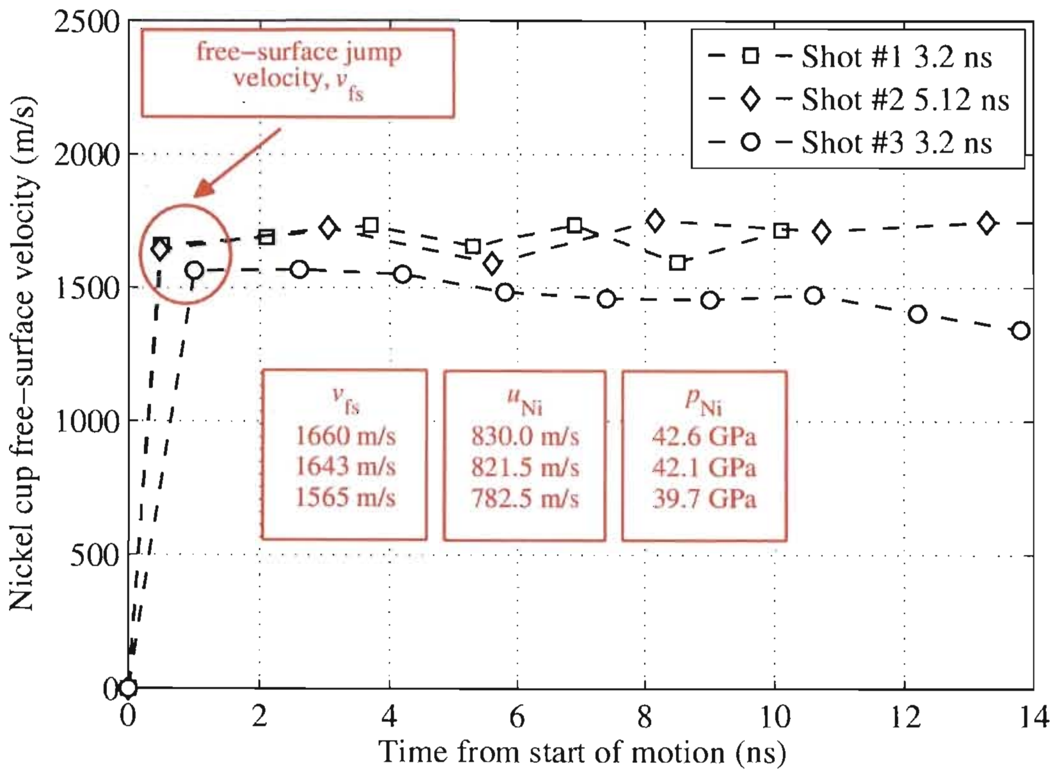


By integrating the fit to the PDV data, a direct comparison is made to the position measurements of the nickel cup obtained from the time-resolved image sequence. Excellent agreement is observed that supports the use of simultaneous time-resolved imaging and PDV techniques to validate the reduced data resulting from each method.

Detonator Output into Air – "Jump-velocity" Determination



Detonator Output into Air – "Jump-velocity" Determination

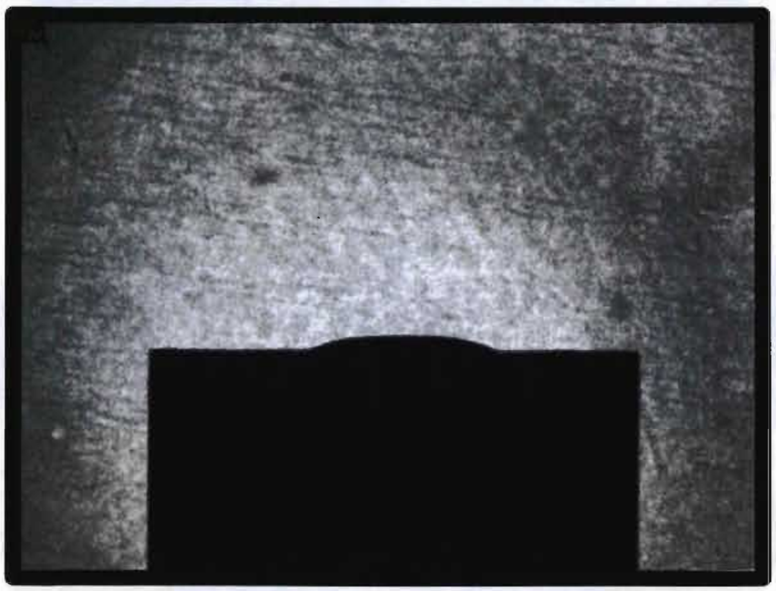


Interface variables	*Detonation interaction (calculation)	Numerical Simulation (CTH)	Experiment (PDV)
u_{int} (mm/us)	0.825	-----	0.830 0.822 0.783
P_{int} (GPA)	42.4	42.9	42.6 42.1 39.7
*CTH results suggest the shock strength in Ni decays by 8% over the 241 um cup thickness			

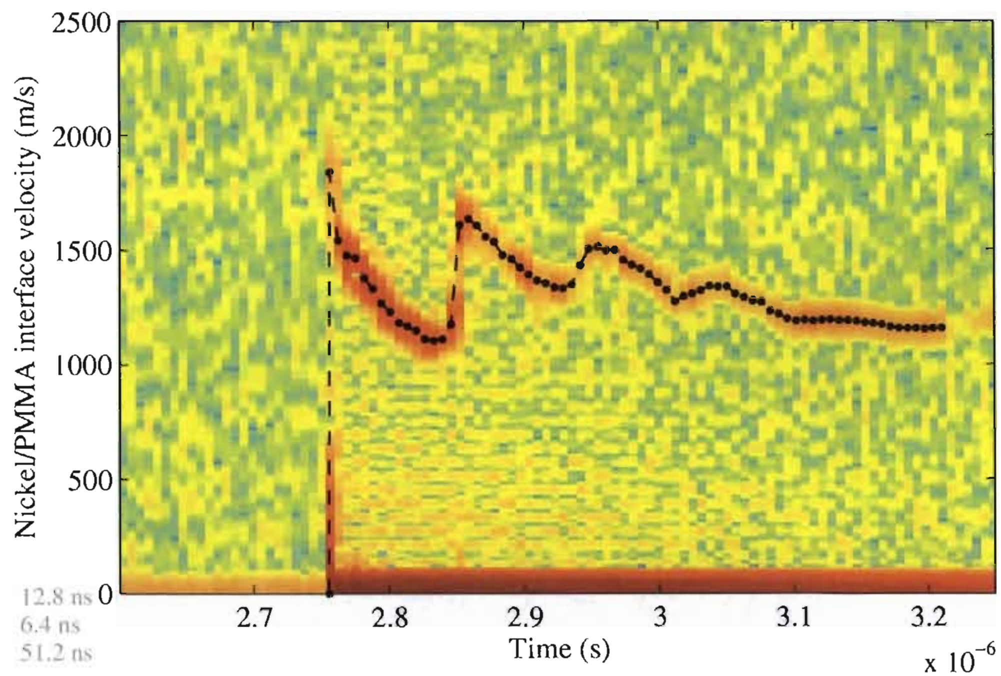
Very good agreement between PDV experiments, empirical predictions, and numerical simulations.

Detonator Output into PMMA

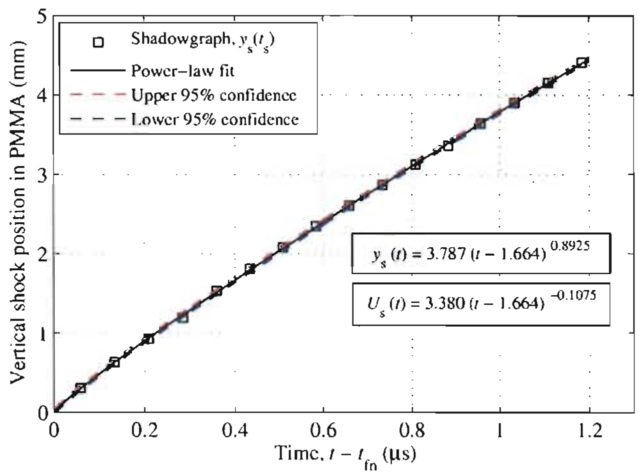
A PDV probe (collimating) is axially aligned with the detonator center, and is viewing the nickel cup through a PMMA window placed in intimate contact with the cup. The velocity of the nickel/PMMA interface is obtained at the detonator center, which allows the interface pressure to be determined.

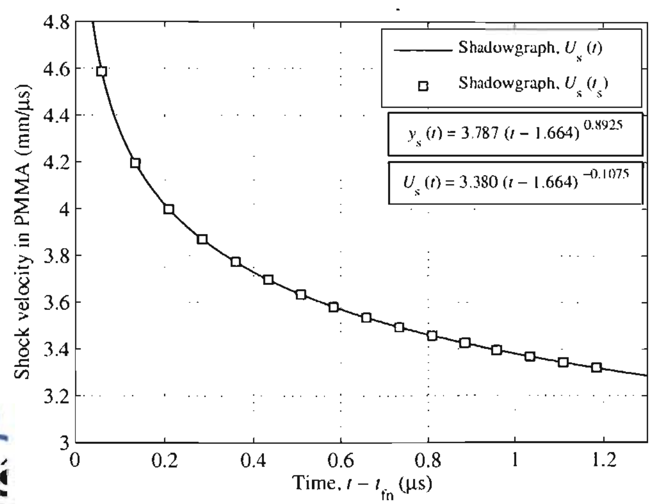


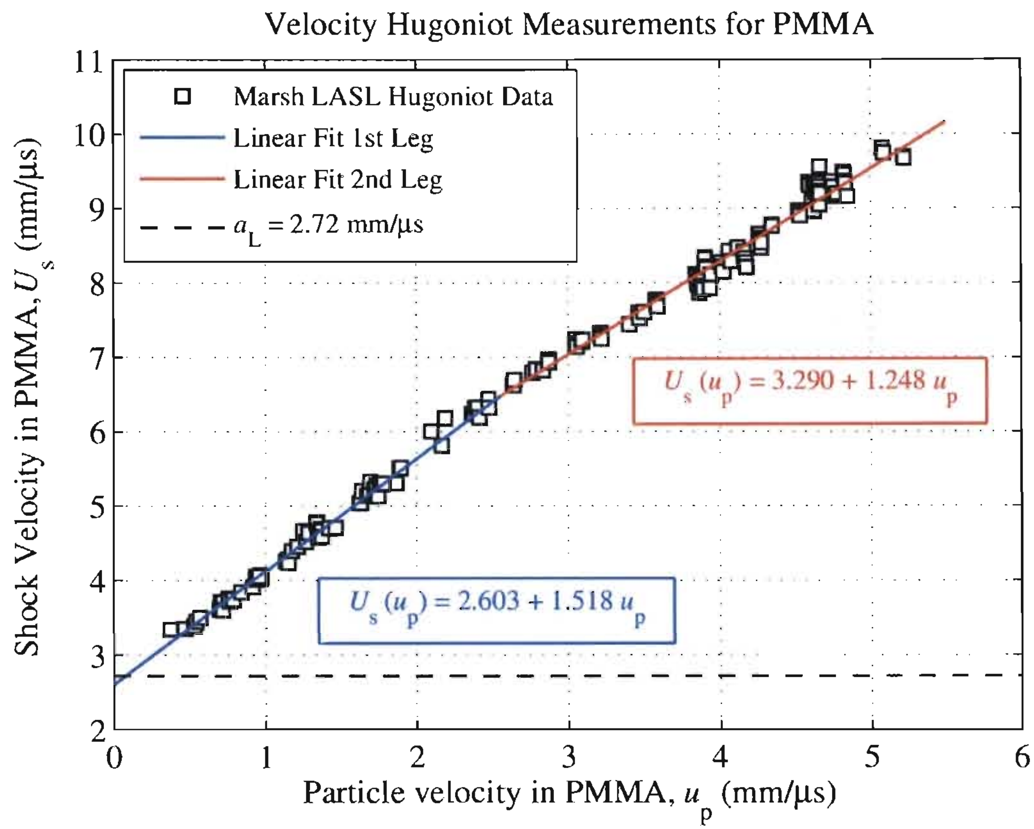
5 ns exposure, 75 ns inter-framing



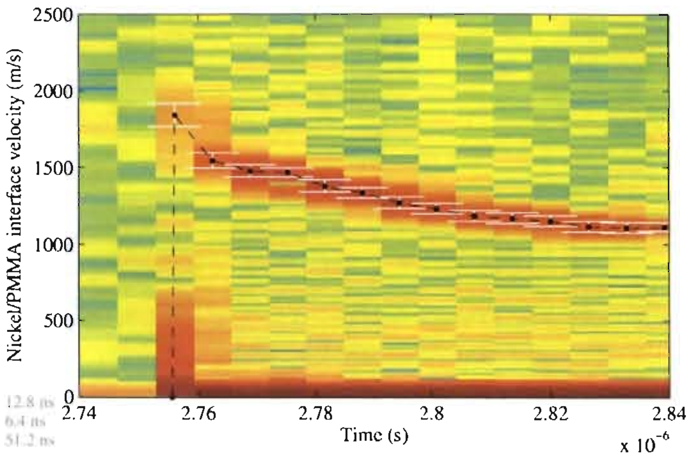
Detonator Output into PMMA – Centerline Imaging Results

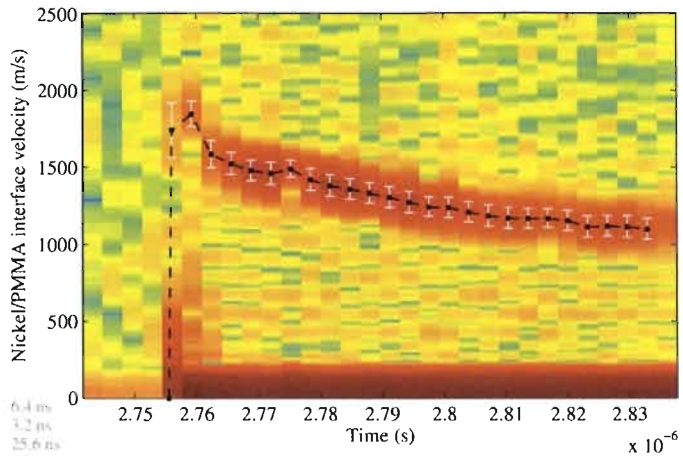


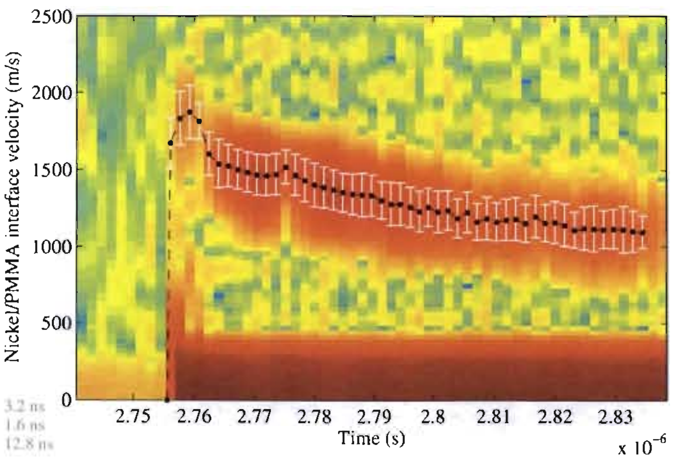


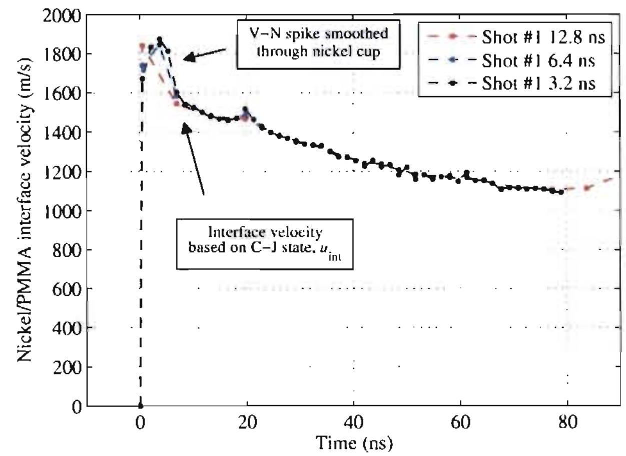


Detonator Output into PMMA – Centerline PDV Results

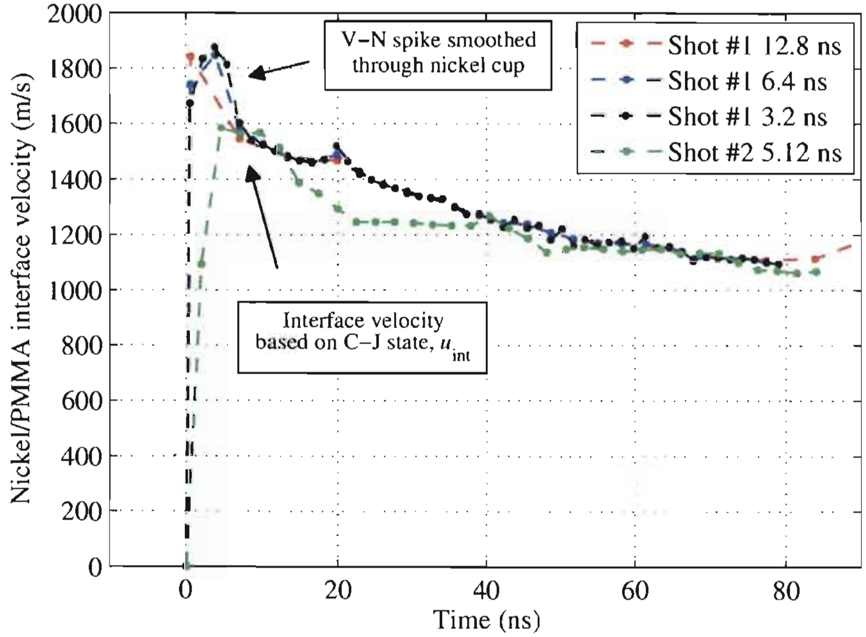




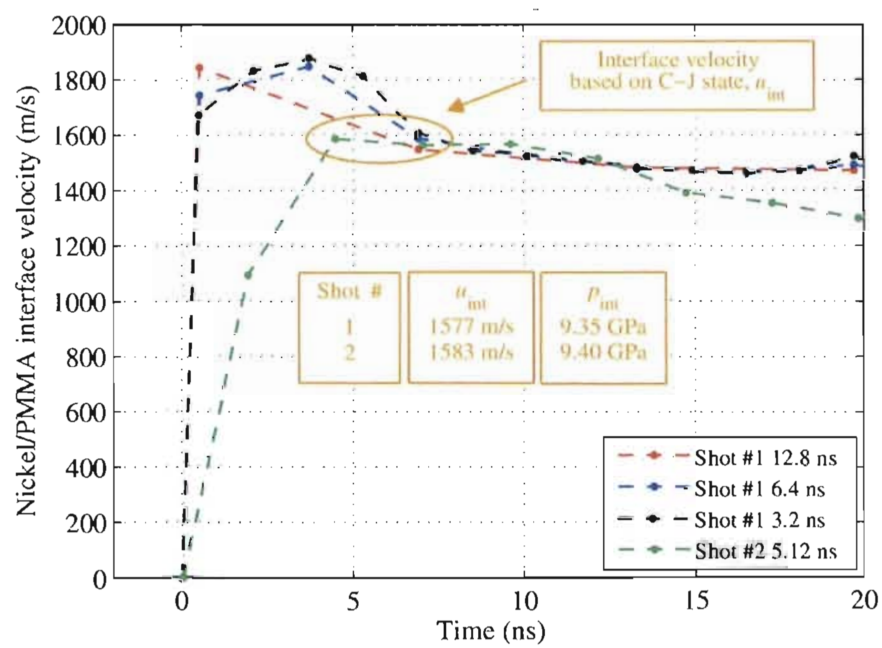




Detonator Output into PMMA – Interface Velocity Determination

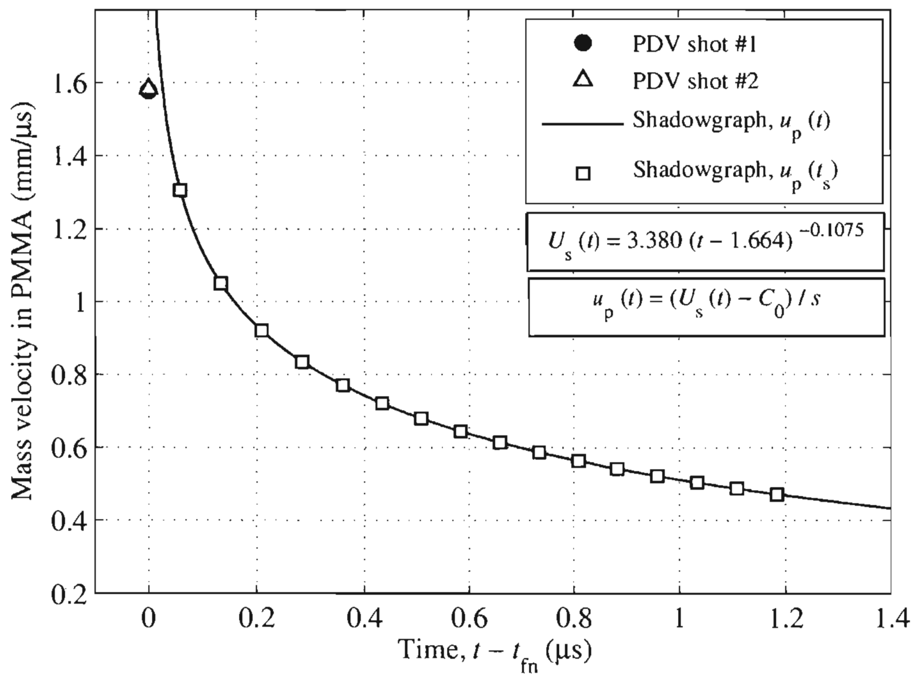


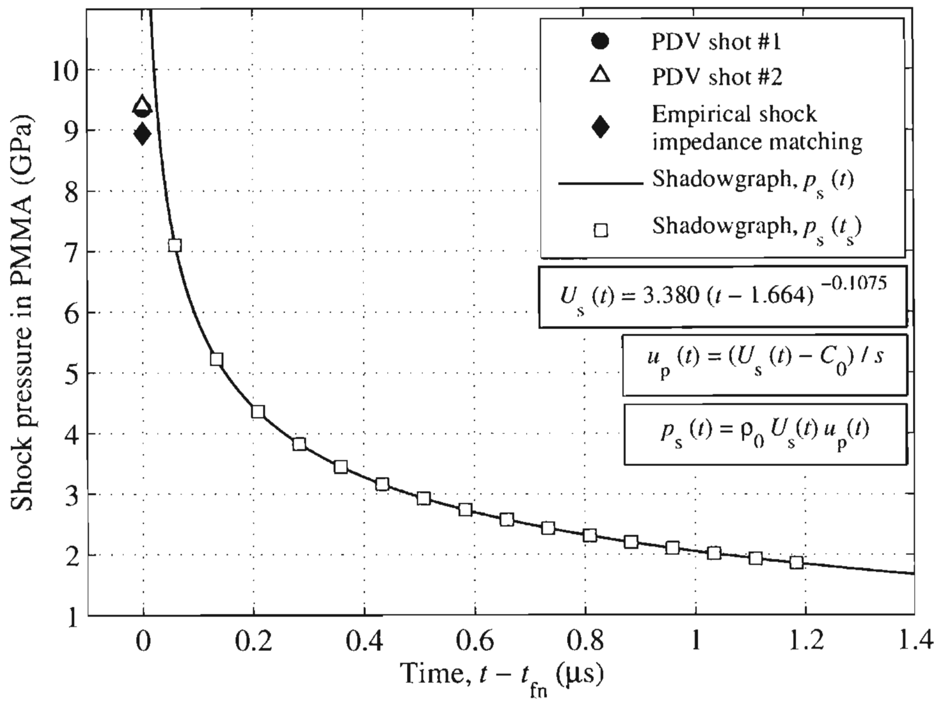
Nickel/PMMA interface velocity histories for two experiments demonstrate close agreement in the region describing the interface velocity based on the C-J state of the explosive. The velocity values in this region are given by 1577 m/s and 1583 m/s, respectively.



These values are in good agreement with the 1.53 km/s calculation arrived at through shock impedance-matching analysis, whereby percent difference values are given as 3.0% and 3.4% for the two experiments.

Detonator Output into PMMA – Centerline Imaging and PDV Results Combined





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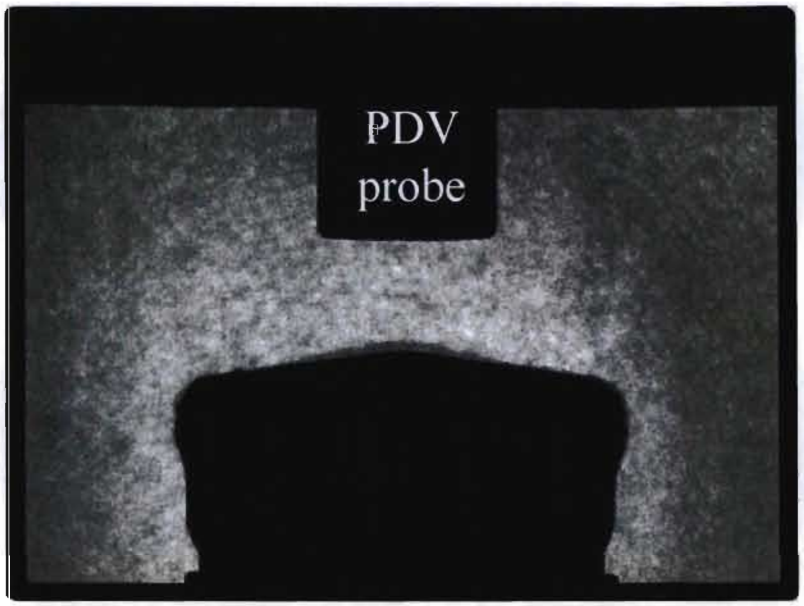
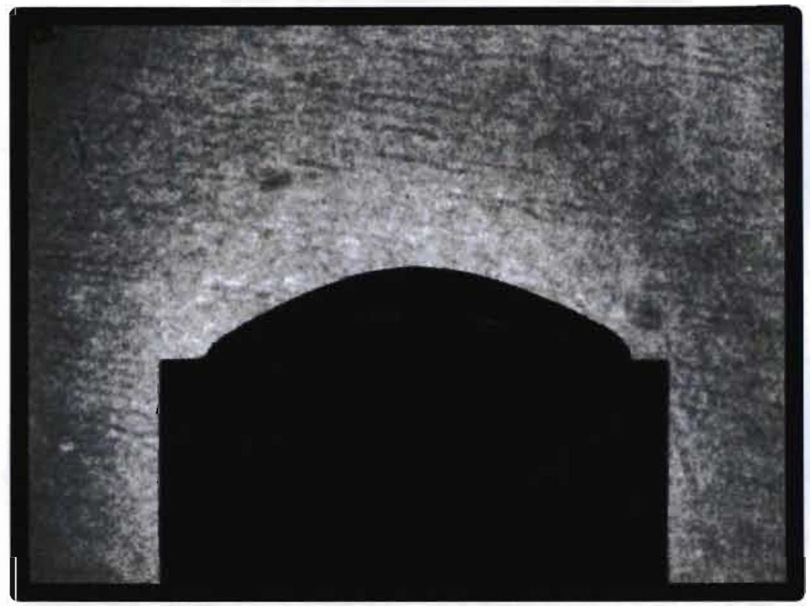
Detonator Output Comparison – Air vs PMMA

Air



Material accelerating into air – bow shocks visible upon formation

PMMA



Shock wave driven into PMMA – leading shock visible

Summary

- Simultaneous PDV and ultra-high speed, time-resolved imaging techniques provide a means of experimentally characterizing centerline output of a detonator
- Validation of the measurement results is obtained by comparing reduced data from each technique
- Output calculations using detonation interaction and shock impedance-matching analyses are in good agreement with experimental measurements to within the accuracy of the empirical parameters used in the equations of state
- Simultaneous imaging and PDV *inside* a PMMA window is successfully implemented
- Results provide time-resolved measurements describing the shocked state of the window material from development of the interface pressure to late-time decay of the shock pressure