Characterizing Detonator Performance in Dynamic Witness Plates

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Motivation

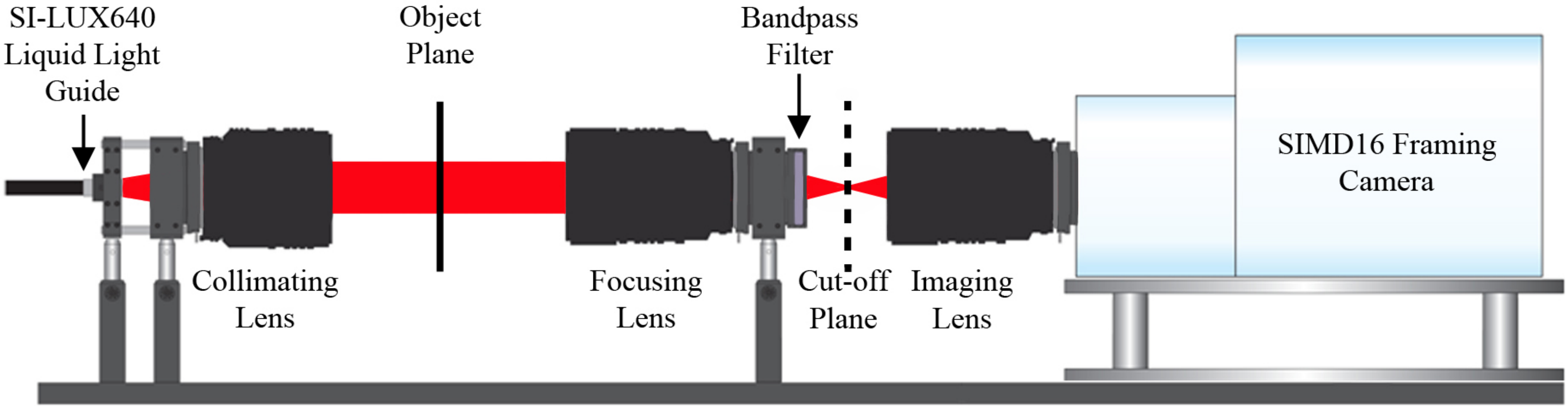
The Detonator Technology group in the Weapon Systems Engineering Division at Los Alamos National Laboratory is characterizing detonator performance by studying detonator-induced shock physics in transparent dynamic witness plates. Current work investigates detonators embedded in polymethylmethacrylate (PMMA) samples, and the shock wave image framing technique (SWIFT) directly visualizes and records explosively-driven shock maturation with high spatial and temporal resolution in PMMA.

Advanced and novel data-reduction procedures are required to accurately extract shock kinematics out of discrete measurements of shock position. The work presented here introduces a new methodology for quantifying centerline detonator shock strength from SWIFT data based on empirical Hugoniot characterization of PMMA.

Outline

- SWIFT
- Historic data-reduction methodology
- New ODE approach
- Example solutions
- Application to varidrive Hiper detonators
- Ongoing work
- Acknowledgments

SWIFT employs spoiled-coherence laser backlighting coupled with schlieren optics and ultra-high-speed image recording



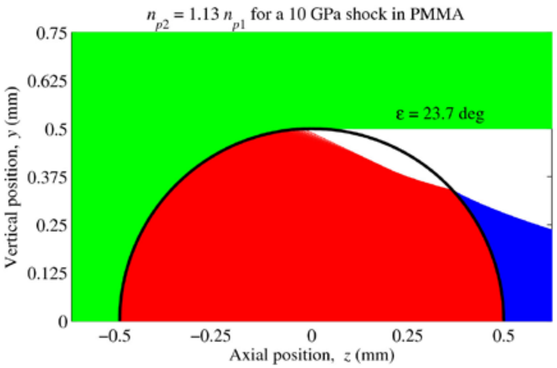
- “SWIFT and Explosive PIV”, **M. J. Murphy**, *Proceedings 15th International Detonation Symposium,* Office of Naval Research, in press, 2015.

- “Preliminary investigations of HE performance characterization using SWIFT”, **M. J. Murphy and C.E. Johnson**, *Journal of Physics: Conference Series,* Vol. 500, pp. 142024-1—142024-6, 2014.

- “Ultra-high-speed imaging for explosive-driven shocks in transparent media”, **M. J. Murphy and S.A. Clarke**, *Dynamic Behavior of Materials, Volume 1: Conference Proceedings of the Society for Experimental Mechanics Series,* pp. 425—432, 2013.

- “Simultaneous photonic Doppler velocimetry and ultra-high speed imaging techniques to characterize the pressure output of detonators”, **M. J. Murphy and S.A. Clarke**, *AIP Conference Proceedings, Volume 1426,* Vol. 500, pp. 402—405, 2011.

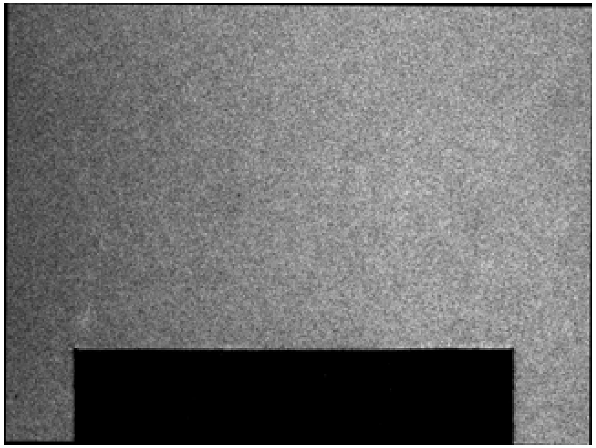
SWIFT images are rich with dynamic performance data useful for characterizing many detonator performance metrics

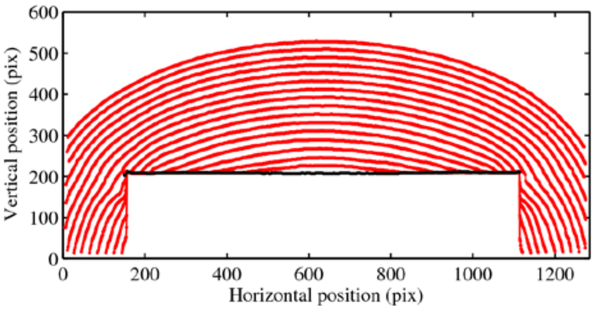


Detonator-driven shock waves are visible in PMMA due to the presence of large discontinuities in density at the shock fronts, as well as the curved shock geometries.

Detonator (into PMMA)

5 ns exposures, 70 ns inter-framing



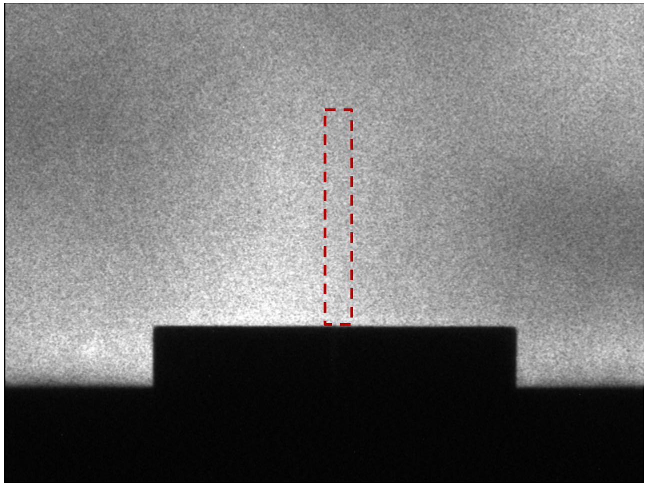


SWIFT images of detonator output provide either direct or indirect measurements of:

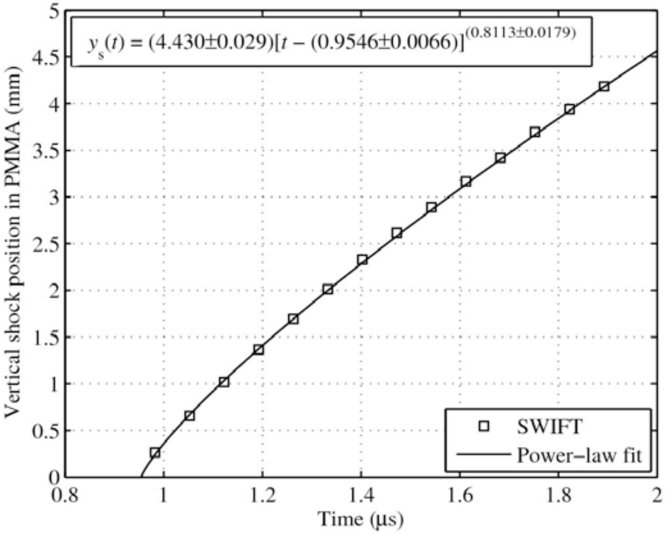
- Function time (indirect)
- Breakout symmetry (direct)
- Axial alignment of flow (direct)
- Output geometry evolution (direct)
- Output reproducibility (direct)
- Interface pressure (indirect)
- Shock pressure evolution (indirect)

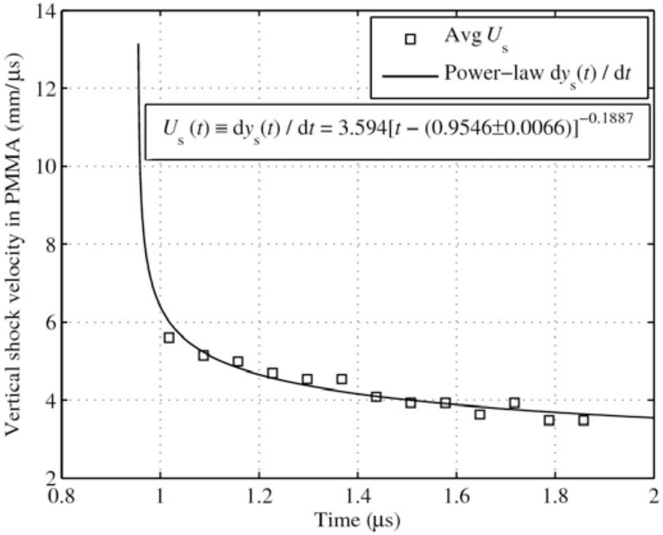
SWIFT data has discrete temporal resolution that must be considered when designing an experiment to measure detonator performance.

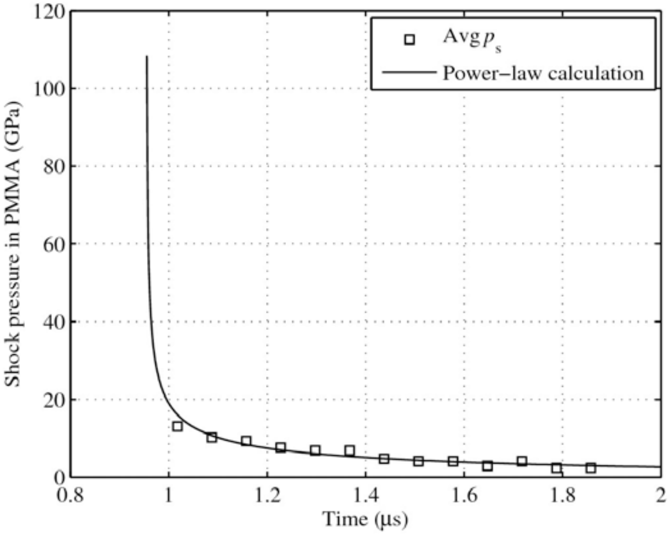
Historically, detonator SWIFT data in PMMA has been investigated along the flow centerline using power-law fitting techniques



5 ns exp, 70 ns IF







Power-law fitting extracts device function time well, but does not allow the interface condition to be determined.

Asymptotic trend in fit results is not physical for finite-strength detonation- and shock-interactions occurring with detonators driving shocks into PMMA witness plates.

New data-fitting approach is required.

Derive a general ODE for shock position evolution in witness plate material by assuming a linear velocity Hugoniot for the material

$p_s = \rho_0 U_s u$ Momentum conservation across 1-D shock wave

$$\left.\begin{aligned} U_s &= C_0 + su \\ u &= \frac{1}{s}\left(U_s - C_0\right) \\ p_s &= \frac{\rho_0}{s}\left(U_s\right)^2 + \frac{\rho_0 C_0}{s} U_s \end{aligned}\right\}$$

Empirical result for many materials over material-specific ranges in shock strength

$U_s(t) \equiv \dfrac{\mathrm{d}y_s(t)}{\mathrm{d}t}$ Definition

$$p_s(t) = \frac{\rho_0}{s}\left(U_s(t)\right)^2 + \frac{\rho_0 C_0}{s}\left(U_s(t)\right) \quad \textbf{or} \quad p_s(t) = \frac{\rho_0}{s}\left(\frac{\mathrm{d}y_s(t)}{\mathrm{d}t}\right)^2 + \frac{\rho_0 C_0}{s}\left(\frac{\mathrm{d}y_s(t)}{\mathrm{d}t}\right)$$

$p_s(t) = p_{pmma}(t)$ Material-specific shock attenuation model is required

$$\Rightarrow \frac{\rho_0}{s}\left(U_s(t)\right)^2 + \frac{\rho_0 C_0}{s}\left(U_s(t)\right) - p_{pmma}(t) = 0 \quad \textbf{or} \quad \frac{\rho_0}{s}\left(\frac{\mathrm{d}y_s(t)}{\mathrm{d}t}\right)^2 + \frac{\rho_0 C_0}{s}\left(\frac{\mathrm{d}y_s(t)}{\mathrm{d}t}\right) - p_{pmma}(t) = 0$$

$$\boxed{U_s(t) = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{\left(\rho_0 C_0\right)^2 + 4s\rho_0 p_{pmma}(t)}\right]} \quad \textbf{or} \quad \boxed{\begin{aligned} &\frac{\mathrm{d}y_s(t)}{\mathrm{d}t} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{\left(\rho_0 C_0\right)^2 + 4s\rho_0 p_{pmma}(t)}\right] \\ &y_s(0) = 0 \end{aligned}}$$

Algebraic equation for shock velocity

ODE for shock position

Example: Use the algebraic equation for shock velocity and temporal exponential pressure decay for detonation-interaction into PMMA

$$U_s(t)=\frac{1}{2}\left[C_0+\frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2+4s\rho_0 p_{pmma}(t)}\right]$$

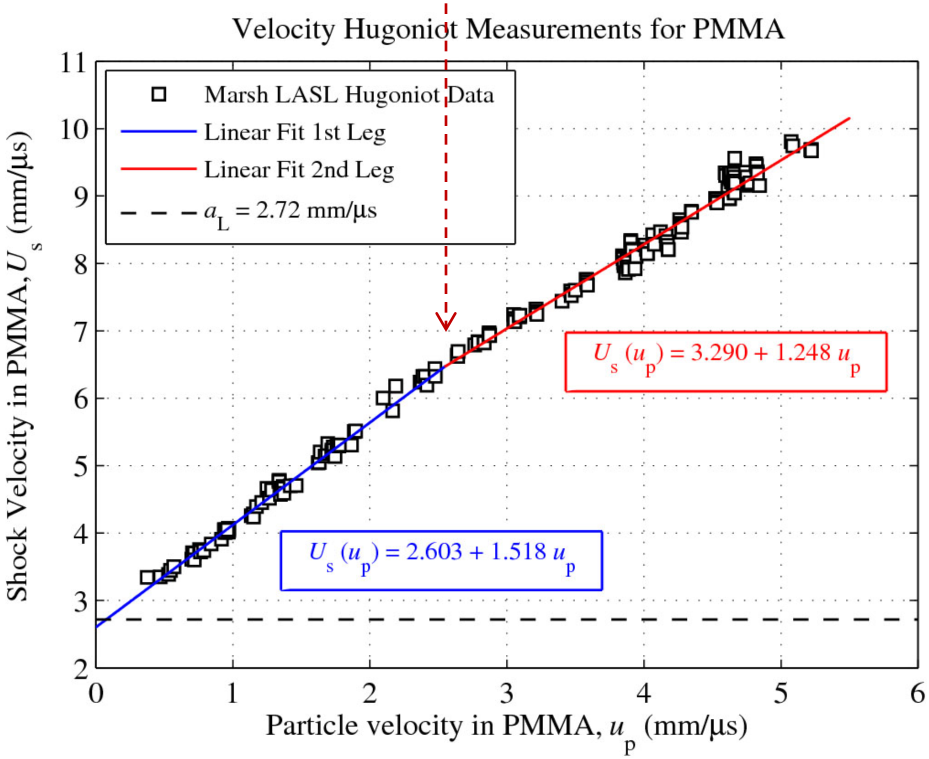
$$p_{pmma}(t)=Ae^{-\alpha t}$$

For 1-D shocks in PMMA under the phase-transition pressure (20 GPa):

$$\rho_0=1.186\ \mathrm{g/cm^3}$$

$$C_0=2.603\pm0.058\ \mathrm{mm}/\mu\mathrm{s}$$

$$\mathrm{s}=1.518\pm0.044$$



The shock-velocity equation becomes

$$U_s(t)=\frac{1}{2}\left[C_0+\frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2+4s\rho_0 Ae^{-\alpha t}}\right]$$

or

$$\boxed{U_s(t)=1.3015+0.4216\sqrt{9.5305+7.201\,A\,e^{-\alpha t}}}$$

Consider the ODE for shock position evolution and exponential pressure decay as a function of 1) time and 2) PMMA thickness

$$\frac{dy_s(t)}{dt} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 p_{pmma}(t)}\right]$$
$$y_s(0) = 0$$

ODE numerically solved in Matlab using a clustering genetic algorithm approach developed by Milano & Koumoutsakos (2002).

1) Exponential pressure decay as a function of time:

$$p_{pmma}(t) = Ae^{-\alpha t}$$

$$\frac{dy_s(t)}{dt} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 Ae^{-\alpha t}}\right]$$
$$y_s(0) = 0$$

2) Exponential pressure decay as a function of PMMA thickness:

$$p_{pmma}(y) = Ae^{-\alpha y}$$

$$\frac{dy_s(t)}{dt} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 Ae^{-\alpha y_s(t)}}\right]$$
$$y_s(0) = 0$$

A genetic algorithm is used to determine exponential decay parameters by solving the ODE numerically and comparing to data

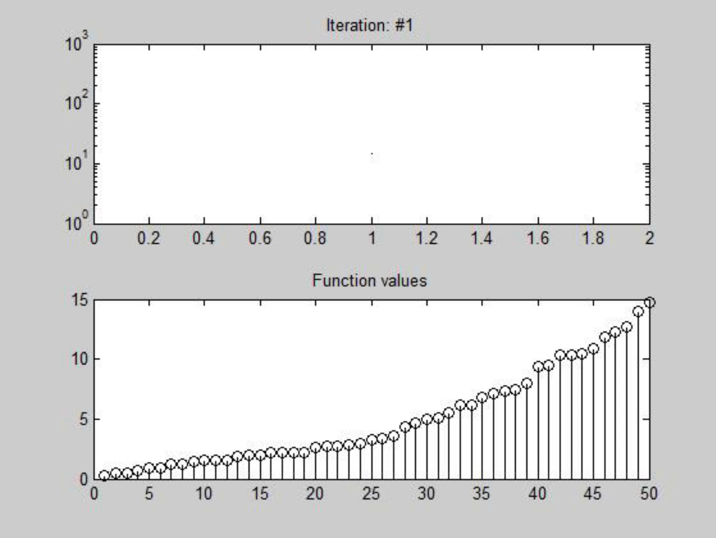
1) Exponential pressure decay as a function of time:

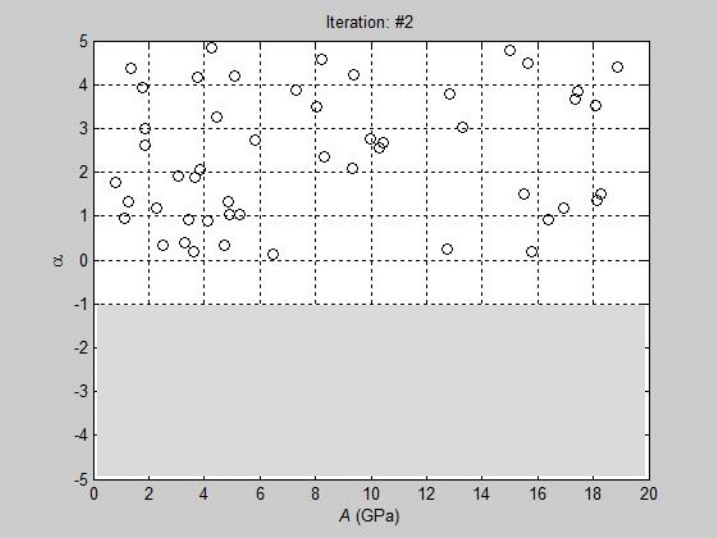
$$p_{pmma}(t) = Ae^{-\alpha t}$$

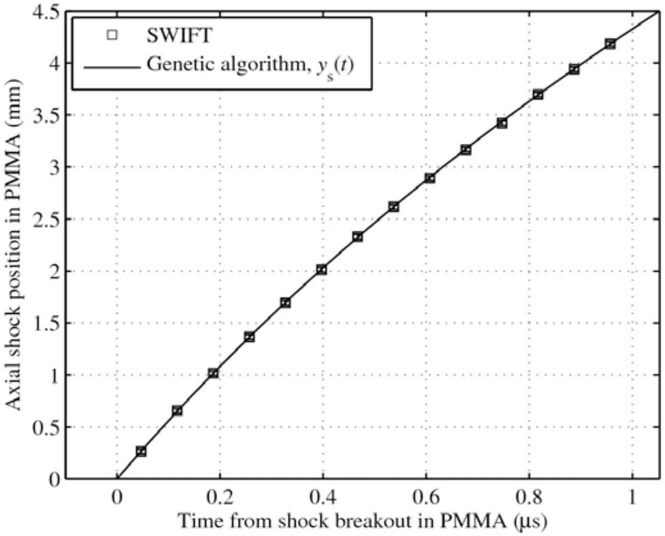
$$\frac{dy_s(t)}{dt} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 Ae^{-\alpha t}}\right]$$

$$y_s(0) = 0$$

$$\boxed{A = 14.54\ \text{GPa},\ \alpha = 2.034}$$







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Exponential decay parameters for temporal decay agree well with SWIFT and PDV results

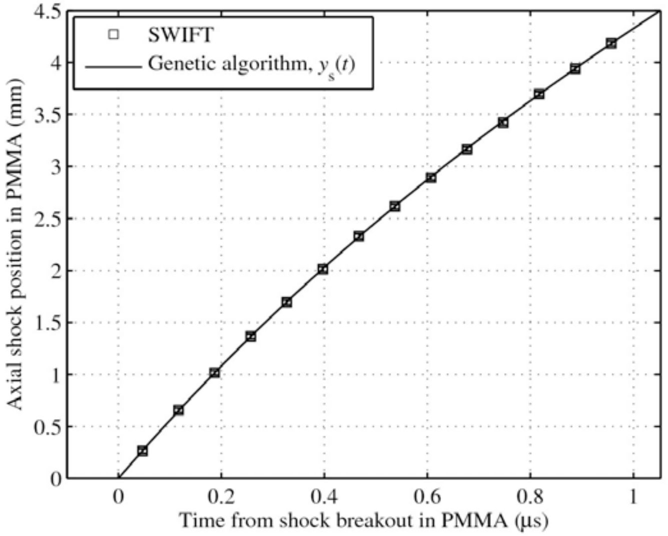
1) Exponential pressure decay as a function of time:

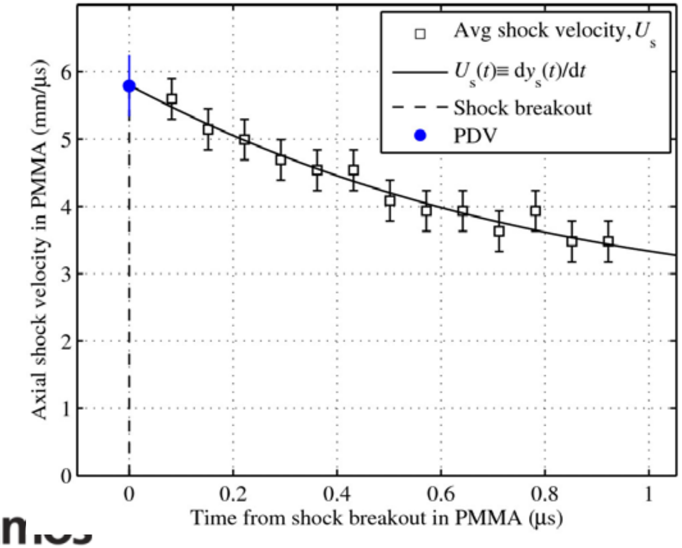
$$p_{pmma}(t) = Ae^{-\alpha t}$$

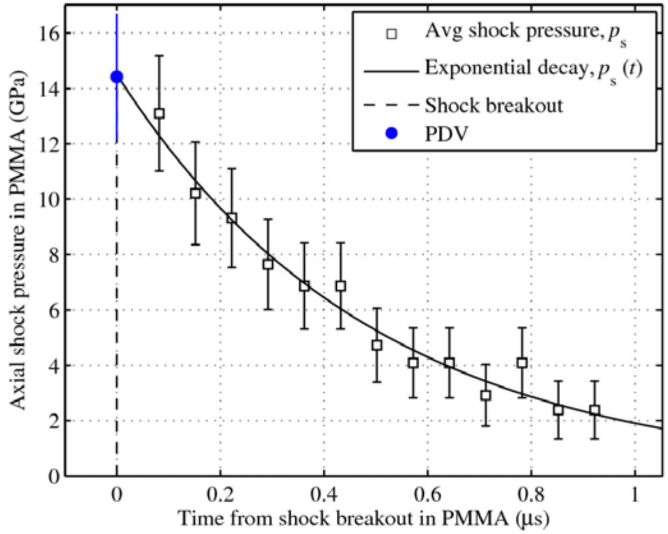
$$\frac{dy_s(t)}{dt} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 Ae^{-\alpha t}}\right]$$

$$y_s(0) = 0$$

A = 14.54 GPa, α = 2.034







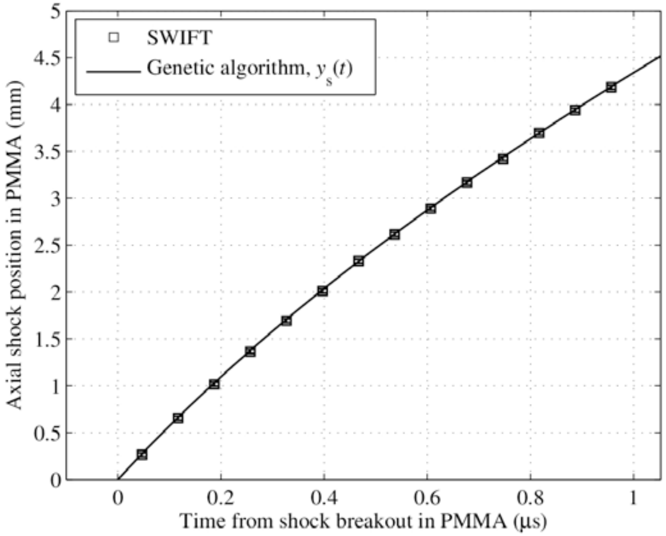
Exponential decay parameters for spatial decay also agree well with SWIFT and PDV results

2) Exponential pressure decay as a function of PMMA thickness:

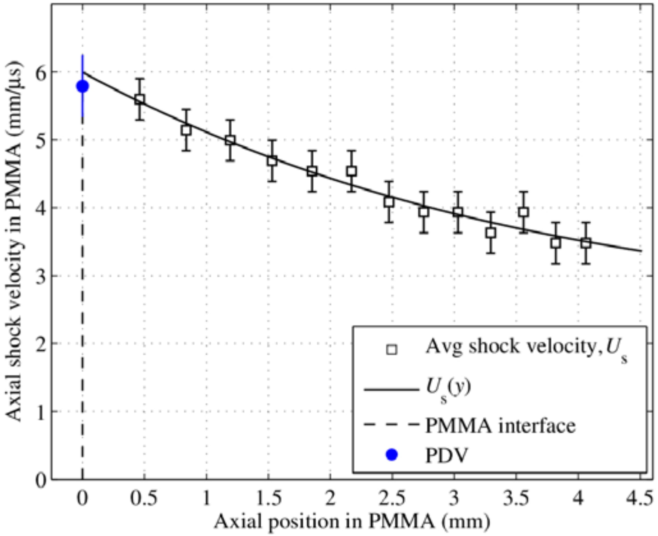
$$p_{pmma}(y) = Ae^{-\alpha y}$$

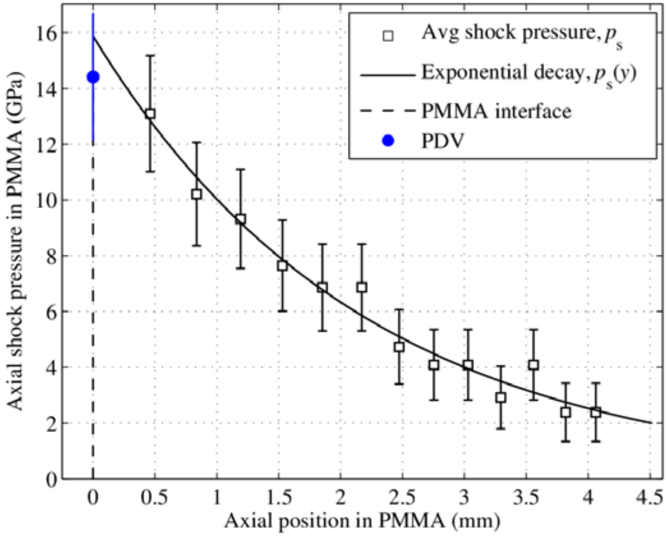
$$\frac{\mathrm{d}y_s(t)}{\mathrm{d}t} = \frac{1}{2}\left[C_0 + \frac{1}{\rho_0}\sqrt{(\rho_0 C_0)^2 + 4s\rho_0 A e^{-\alpha y_s(t)}}\right]$$

$$y_s(0) = 0$$

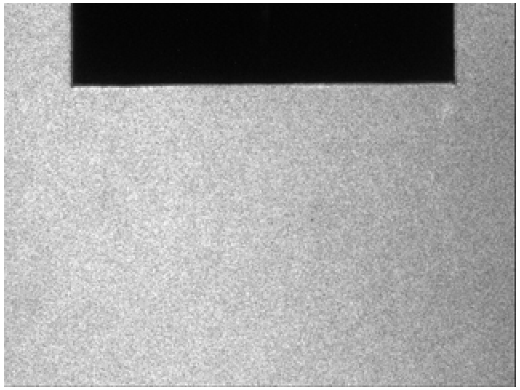


A = 15.88 GPa, α = 0.4595

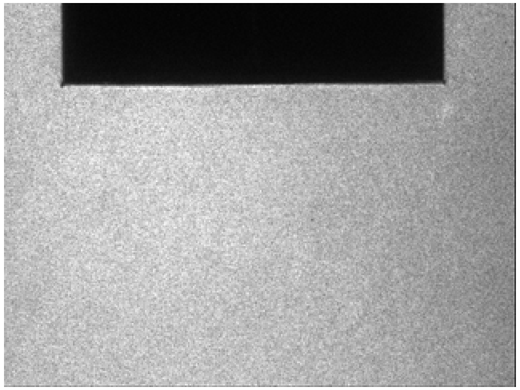




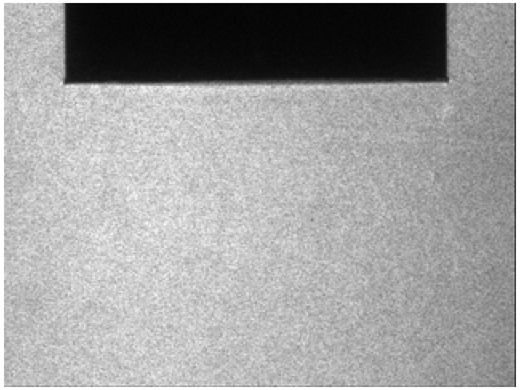
Application: SWIFT data recorded to characterize dynamic performance of standard and varidrive Hiper detonators in PMMA



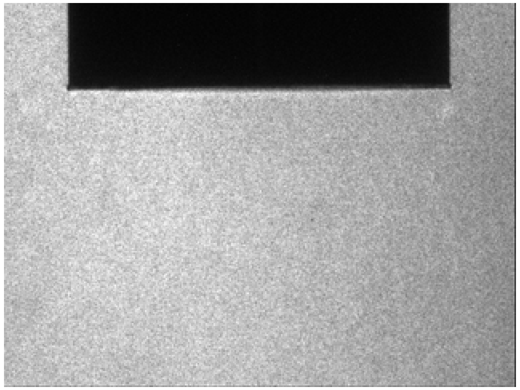
HE pellet 1.45 g/cm^3



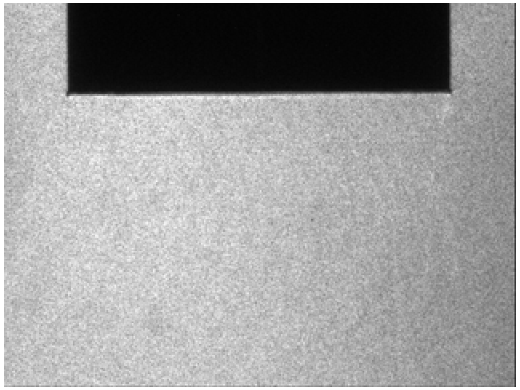
HE pellet 1.50 g/cm^3



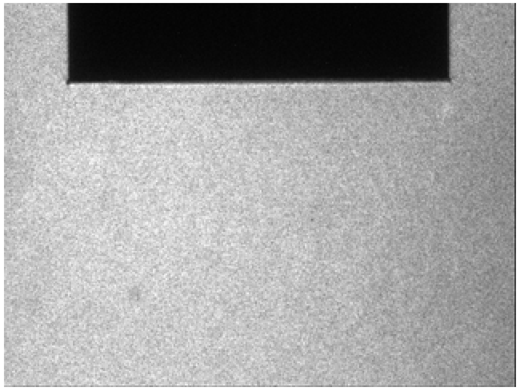
HE pellet 1.55 g/cm^3



HE pellet 1.60 g/cm^3



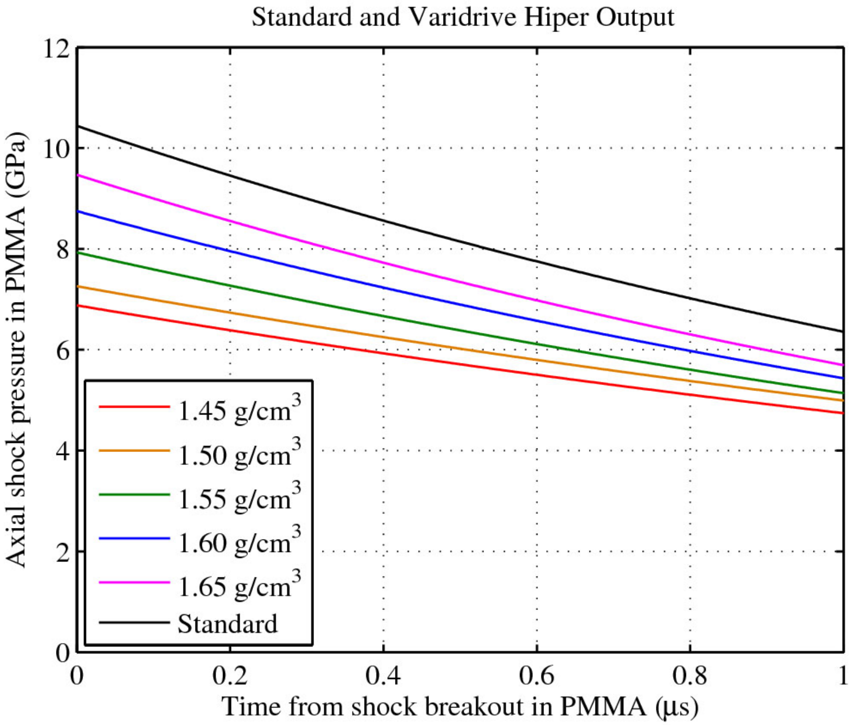
HE pellet 1.65 g/cm^3



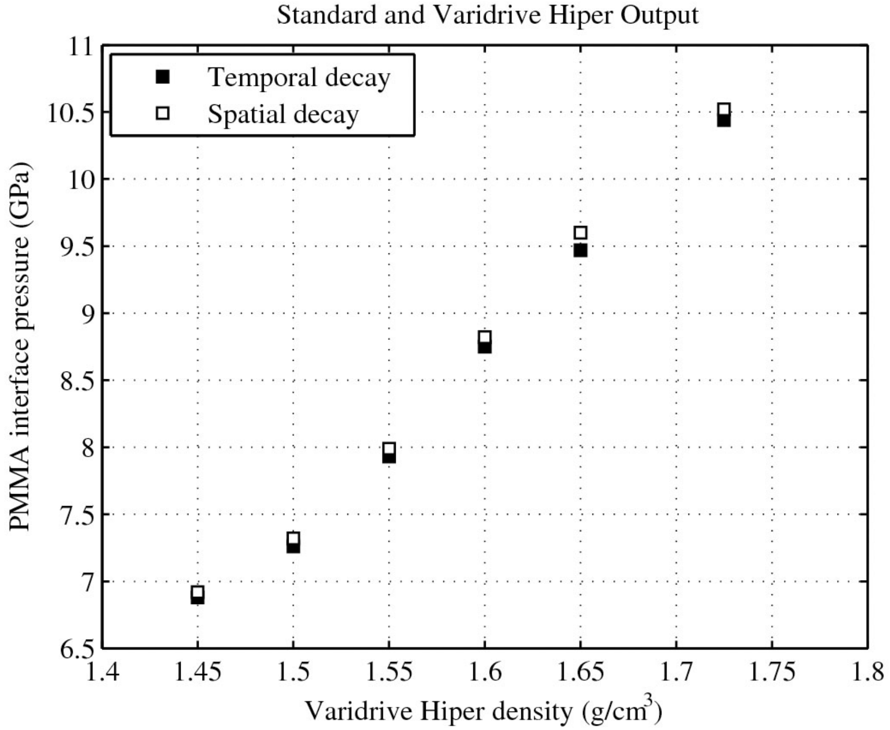
HE pellet 1.70-1.75 g/cm^3
(standard part)

5 ns exposures / 70 ns inter-framing

Varidrive Hiper detonators provide a good testbed for evaluating SWIFT data-reduction procedures



Standard and Varidrive Hiper Output

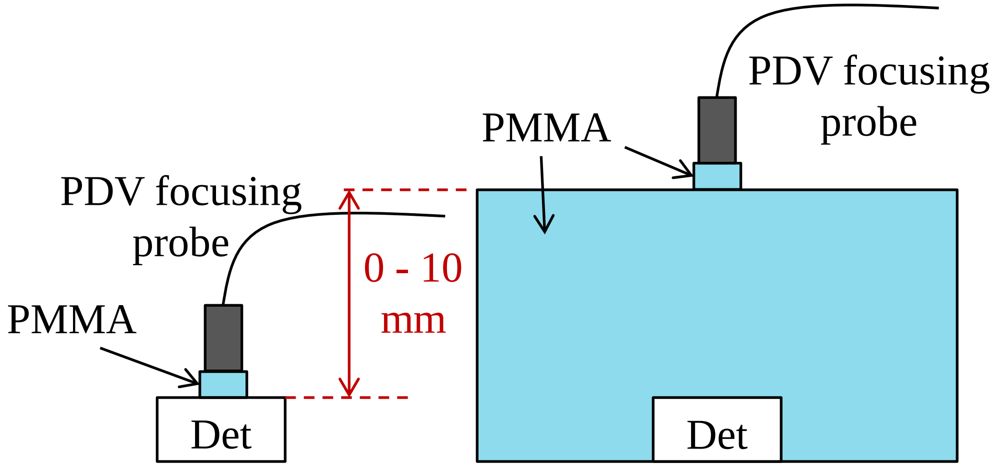


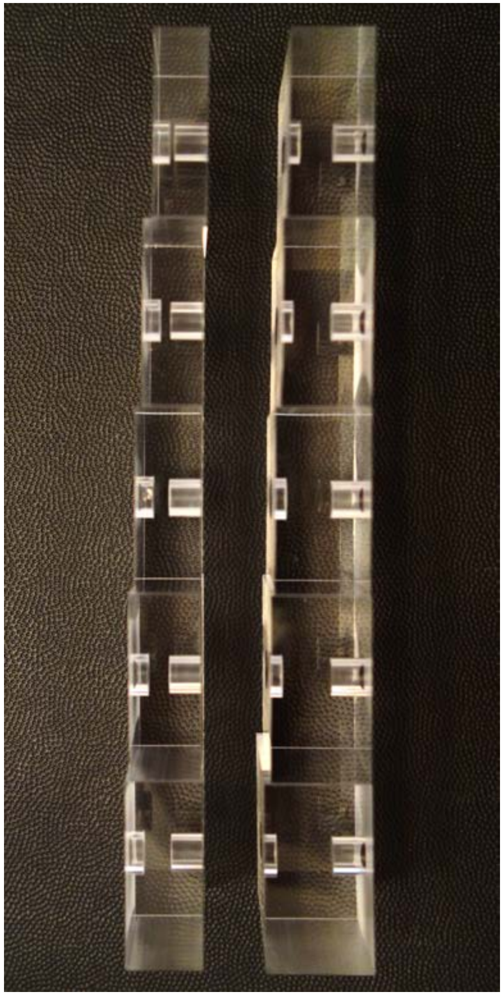
Standard and Varidrive Hiper Output

Results suggest SWIFT can be used as a sensitive tool for comparing fine details in output performance of detonators, e.g. technique is sensitive enough to quantify centerline output performance variations based on 0.05 g/cm^3 changes in HE pellet density.

Ongoing Work

Currently designing a set of dual SWIFT/PDV experiments to measure shock position, shock propagation time, and PMMA jump velocities for PMMA gap thicknesses between 0 and 10 mm. Shock pressure data as a function of both shock propagation time and PMMA thickness will be obtained and used to validate assumptions made in this data-reduction approach.





Acknowledgments

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  - ✓ Michele Milano (MAE University at Buffalo) for providing genetic algorithm
  - ✓ Mark Lieber (W-6) for assistance with implementation of Milano's genetic algorithm