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Using embedded fibers to measure the detonation velocity of sensitized nitromethane

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Using embedded fibers to measure explosive detonation velocities

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Abstract

Single-mode fibers were cleverly embedded into fixtures holding nitromethane, and used in conjunction with a photonic Doppler velocimeter (PDV) to measure the associated detonation velocity. These measurements have aided us in our understanding of energetic materials and enhanced our diagnostic capabilities.

ACKNOWLEDGMENTS

The author would like to thank the following people for helping to collect this data: Shawn Parks for setting up and operating the high-speed video cameras fielded during these series and Rudy Navarro for helping to design and fabricate target fixtures and executing the tests.

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1. INTRODUCTION [BEGIN SECTIONS ON ODD PAGES]

Photonic Doppler velocimetry (PDV), also known as heterodyne velocimetry [1], is a displacement interferometer that is commonly found in the shock and dynamic material research communities. Over the past several years, the PDV has been instrumental in our efforts to measure free-surface velocities of explosively-driven metals. One unique challenge is to measure the velocity of a detonation wave inside of an explosive material. This measurement technique demonstrated that embedded fibers could be used to measure the detonation velocities of solid explosives [2]. We chose to test out the measurement technique using a liquid explosive, nitromethane (NM).

Making a PDV Measurement

The PDV system is built using common, off-the-shelf, telecommunication components. Figure 1.1 shows a single channel inside a conventional PDV system. A narrow linewidth (<5 kHz) fiber laser operating at 1550 nanometers is initially split into two paths, a reference path and a probe path. The reference path sends a small portion of un-shifted laser light directly through a frequency shifter (to aid in target alignment) and then to a 2x2 coupler. The probe path sends light into a three-port optical circulator. An optical circulator works much like an optical diode, allowing light to travel from port to port in a specific fashion. In this case, light from the splitter enters port one, and exits out of port two. The light now travels to an optical probe used to illuminate the target of interest. Light reflected off of the target is collected by the probe, and sent back into port two of the circulator. Light exits out of port three, and is relayed to the 2x2 coupler where it is mixed with the shifted component of light. When the target begins to move, the light reflected off of the target surface will undergo a Doppler shift. The Doppler-shifted light mixes with the reference light inside the 2x2 coupler, and is measured with high speed detectors and digitizers operating in the gigahertz range.

Because the PDV is a displacement interferometer, the individual points in a PDV measurement contain no velocity information [3]. The frequency content of the PDV signal is typically derived by using short-time Fourier transform (STFT) methods. In this case, the data was reduced using SIRHEN [4].

Motivation for Work

Explosive detonation waves can travel very quickly (>7 km/sec) through a material. In some cases, the impact of a projectile or fragment into an energetic material can cause a self-sustaining deflagration that eventually transitions into a detonation event [5]. Knowing the exact location and time at which the material begins to detonate can provide useful insight into the behavior of that material. In many explosives, getting an interrogation probe, such as a resistive element, embedded inside the material requires the material to be modified or machined.

An ideal measurement is one that accurately measures the detonation velocity of the explosive and minimizes disturbances to the propagation of the detonation wave. We chose a liquid explosive, nitromethane (NM), for several reasons. A fiber optic probe can easily be inserted and visually inspected while inside a test fixture of NM. Also, NM is well characterized and inexpensive.

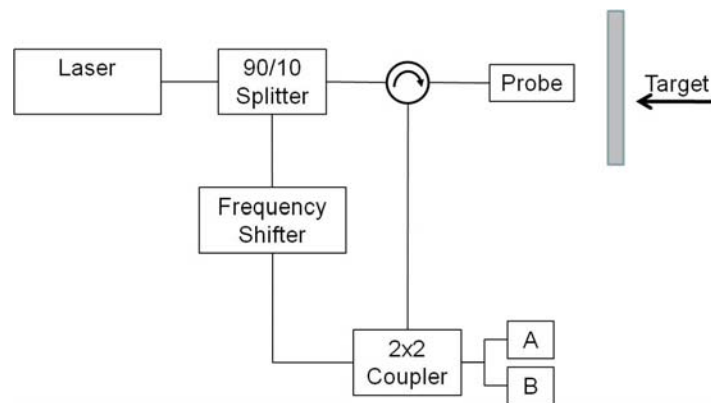


Figure 1.1. A Single Channel of Conventional PDV.

Report Summary

Chapter 2 briefly describes the theory of the measurement technique. The target design and two types of fiber probes used are also discussed. An overview of the additional diagnostics chosen to compliment the PDV measurement, are similarly included in Chapter 2. Chapter 3 presents the data that was collected during this test series including PDV, piezoelectric pins, and high-speed video.

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2. EXPERIMENT DETAILS

This chapter describes the method by which the PDV measurement was made. It also outlines the design of the target fixtures built, describes the two different types of single-mode fibers used, and introduces the suite of support diagnostics used to compliment the PDV measurement.

Theory of Experiment

As previously discussed, the PDV conventionally measures reflected, Doppler-shifted light off of a moving surface. Usually, this surface is somewhat specular so that adequate signal level can be collected by the probe, and relayed back to the PDV. In this experiment, a single-mode, 9/125-micron fiber was used without being attached to a probe. The end of the fiber was cleaved at eight degrees (to minimize back-reflection), and then inserted directly into the NM.

When the NM is detonated, a shock wave is formed, shown in Figure 2.1. This shock wave creates a refractive index discontinuity inside the core of the fiber which reflects the laser light back down the fiber to the PDV [2]. The discontinuity, which is moving at the speed of the detonation wave, creates a Doppler shift traveling at the same velocity. The Doppler shift seen by the PDV is actually inside a transparent material. Thus, it will appear to be traveling $\approx 1.5X$ ($n = 1.4682$ for fused silica) faster than it actually is [6].

Given adequate bandwidth of the recording system, determined by ($f = 2v / \lambda_0$), this Doppler shift can be measured. In the case of NM, which has a steady-state detonation velocity of approximately 6.2 km/sec, the detonation wave will appear to be moving around 9.3 km/sec. Thus, a bandwidth recording capability of at least 12 GHz is required. To satisfy the Nyquist limit, a minimum sampling rate of 24 GS/sec should accompany this required bandwidth.

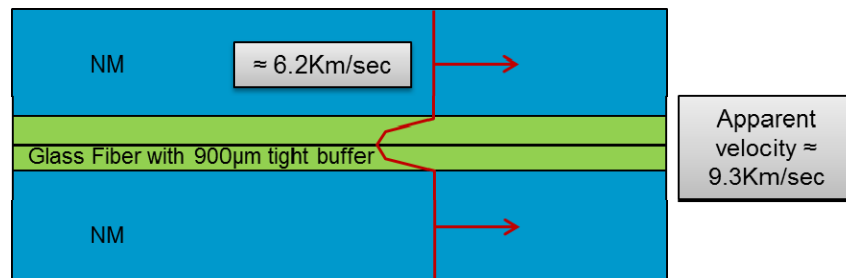


Figure 2.1. Embedded Fiber Measurement.

We have chosen to make this measurement using a Tektronix DPO72004C series digitizer which has a 20 GHz available bandwidth, and a 50 GS/sec sampling rate. This easily satisfies the requirements needed to make the measurement. The digitizer has been paired with Miteq 20 GHz bandwidth detectors. These detectors have a frequency response ranging from 100 KHz up to 20 GHz. Because the PDV system uses a 200 MHz down-shifter in the reference leg to aid in the alignment process, the detectors always see a frequency that is well within their response range.

Target Design

Rather simple target fixtures, shown in Figure 2.2, were constructed. One inch ID, cast acrylic tubes, approximately twelve inches long were used to contain the NM. The NM mixture contained a sensitizer, diethylenetriamine (DETA), at a volume of 2%. This was done primarily to ensure an “overdriven” detonation velocity. It is desirable for the NM solution to always be in a detonation state due to the high sound speed (5.5 km/sec) of the silica glass, fiber core. This “overdriven” velocity (≈ 6.7 km/sec), we hope to capture as well as the steady state velocity (≈ 6.2 km/sec).

A standard barbed fitting was used to attach vinyl tubing to the bottom of the NM tube. At the opposite end of the vinyl tubing, a detonator was inserted and was in direct contact with the NM. The entire tube stood atop a platform constructed of Lexan sheet.

Difference in Fiber Types

The fiber probes were bonded into the center of a nylon cap containing several small holes. See Figure 2.3. The center hole held the fiber tip, while the surrounding holes allowed the NM solution to fill both the vinyl tubing and the acrylic tubing at the same time. The surrounding holes also allowed the detonation wave to propagate past the nylon cap. Failure to provide these surrounding holes yielded in an unsuccessful transfer of the detonation wave past the cap, and into the NM-filled acrylic tube. This result is illustrated in Figure 2.4.

Two primary types of single-mode fiber were used. Both fibers contain 9/125-micron fiber. The main difference between the two fibers was the buffer that was used. Three of the tests used what is known as a 900-micron tight buffer surrounding the fiber core. This is a thermoplastic material that is extruded directly over the acrylate fiber coating. Two of the tests used 900-micron loose tubing. In this configuration, the fiber simply “floats” inside of small tubes, and is surrounded by air rather than extruded plastic. It is expected that this air gap around the fiber will yield undesirable results.

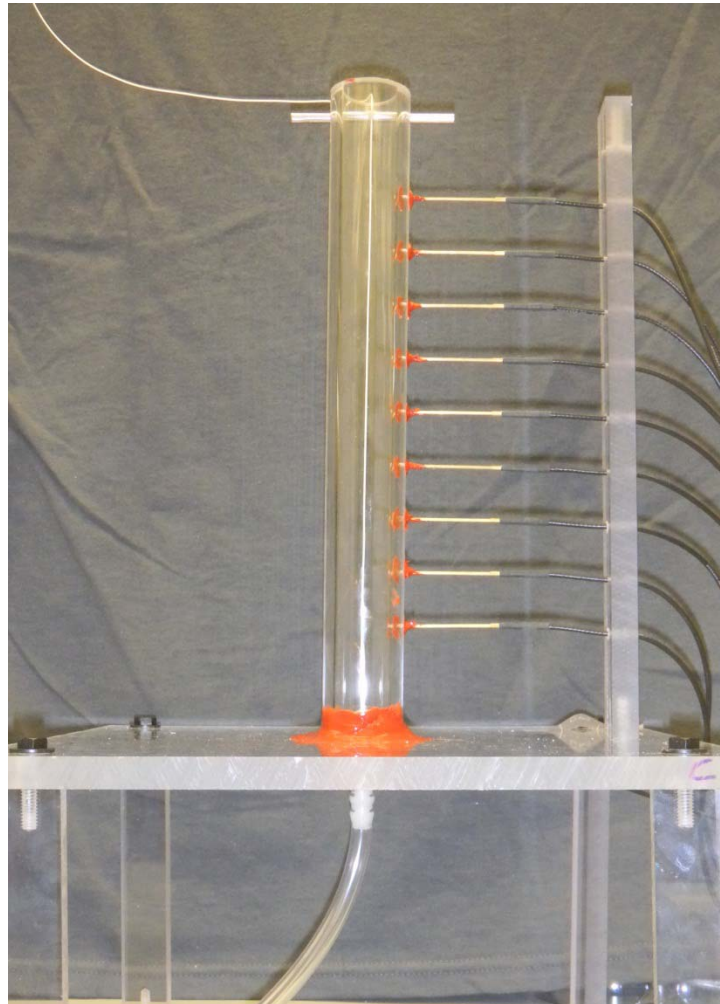


Figure 2.2. Test Fixture



Figure 2.3. Nylon Cap with Holes

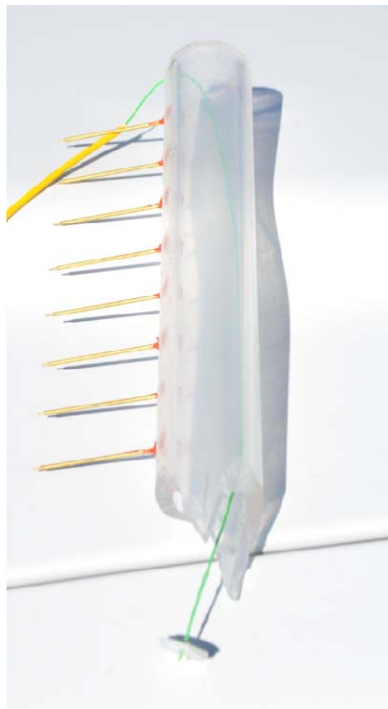


Figure 2.4. Test Fixture Fired Using a Cap without Holes

Supplemental Diagnostics Fielded

To supplement the PDV measurement being made inside the NM solution, piezoelectric pins, spaced one inch apart, were used along the length of the acrylic tube. These will also measure the detonation wave propagating up the tube. A single, high-speed Phantom video camera (utilized at a frame rate of 120,000 f/sec) was used as well in hopes to capture and measure the detonation front.

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3. TEST RESULTS

The experimental test results are presented in this chapter. The PDV, the piezoelectric pins, and the high-speed video data are reviewed and compared.

PDV Velocity Data

Power spectrums for the three tests using the 900-micron tight buffer are shown in Figure 3.1-3.3. PDV results show good repeatability. As expected, sensitizing the NM did indeed overdrive the NM solution. The initial frequency increases up to 12.2 GHz before leveling out at approximately 12 GHz. These frequencies correspond to velocities of 9.4 km/sec and 9.2 km/sec before applying the correction factor. Figure 3.4 overlays the corrected velocity profiles for each of the three shots. The average velocities (≈ 6.2 km/sec) measured is as predicted.

It is noteworthy to add that there is a slight delay after the detonation wave encounters the cap that, the detonation wave is measured. Timing indicates the presence of the cap physically slows the detonation wave down, causing it to “stutter” or delay a bit, before overdriving and finally reaching a steady state. This delay starts around 3 μ sec and lasts until 5.5 μ sec.

Also as anticipated, the test using the fiber surrounded by the 900-micron loose tubing did not yield desirable results. No detonation velocity component was measured by the PDV on either test using this fiber type.

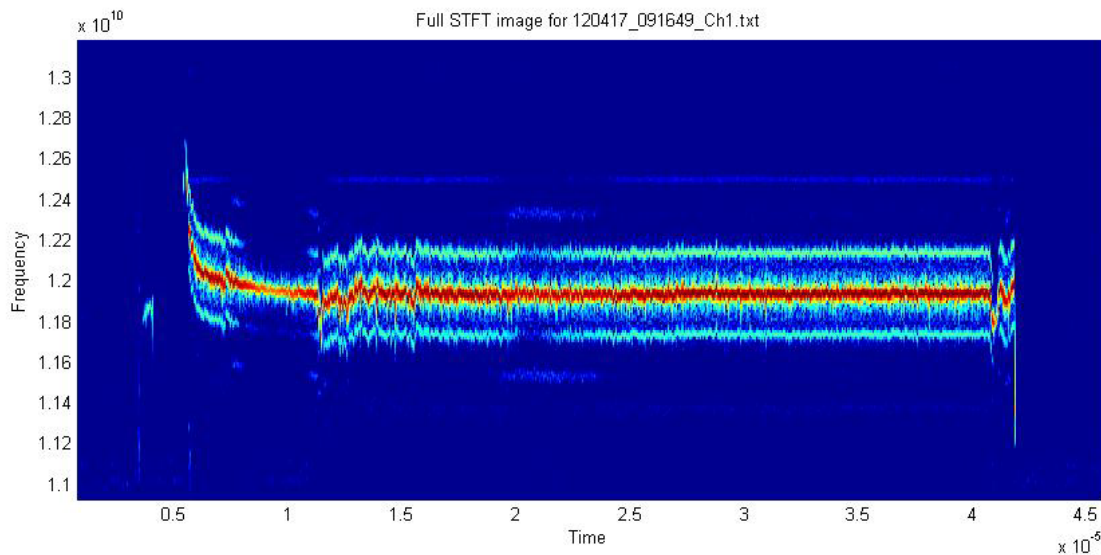


Figure 3.1. Power Spectrum from Test 1 900-micron Tight Buffer

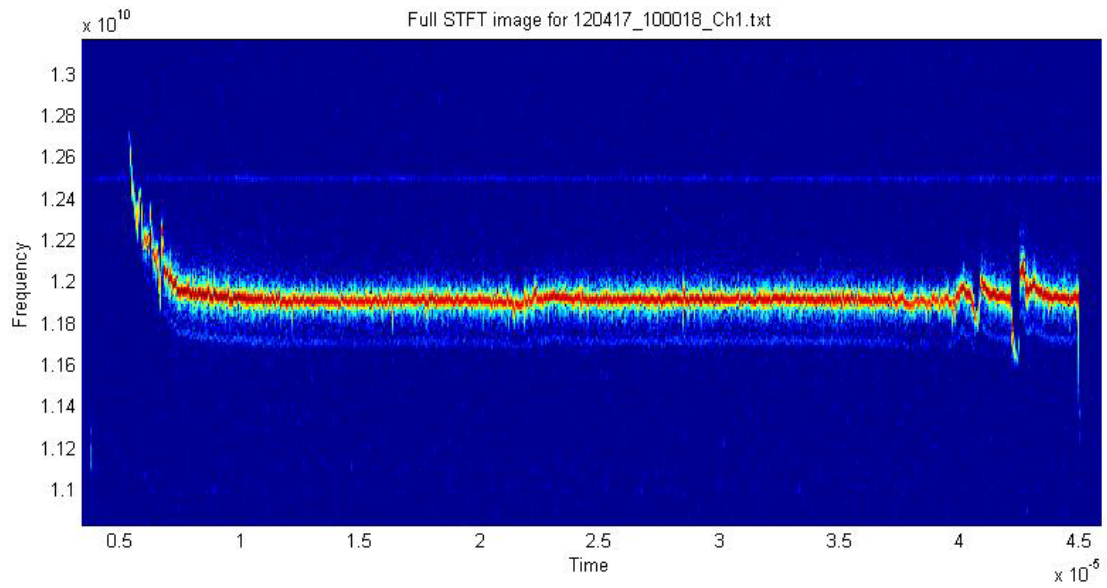


Figure 3.2. Power Spectrum from Test 2 900-micron Tight Buffer

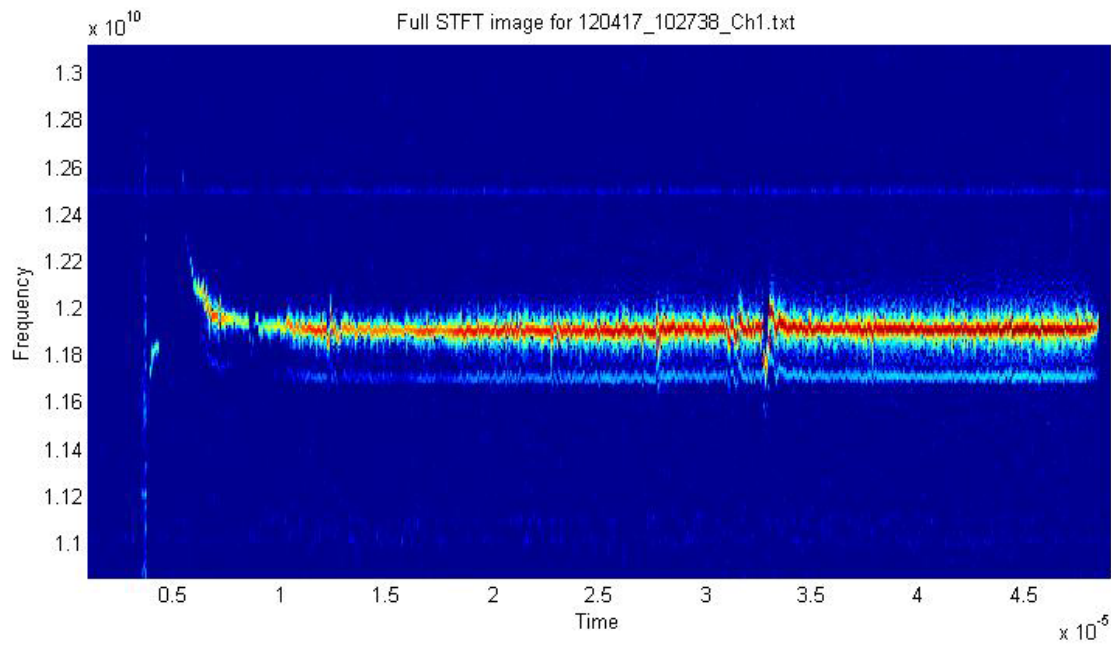


Figure 3.3. Power Spectrum from Test 3 900-micron Tight Buffer

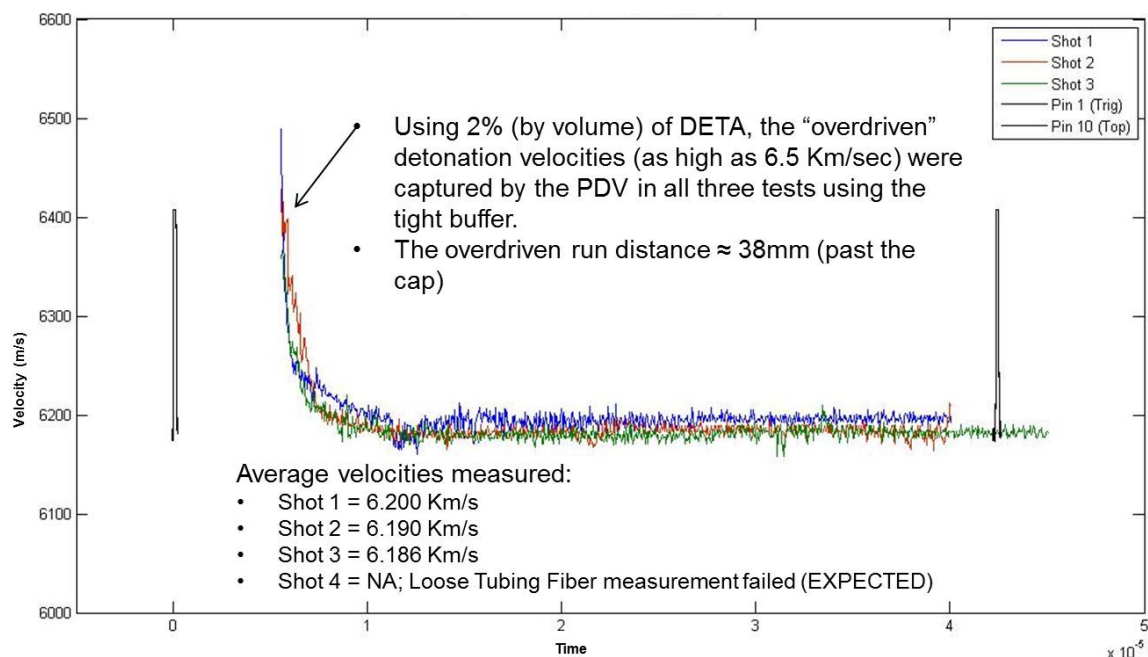
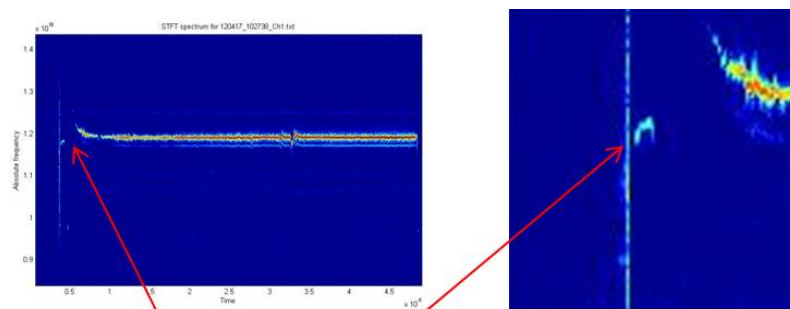


Figure 3.4. Velocity Overlays for 900-micron Tight Buffer Shots

An interesting feature captured by the PDV is presented in Figure 3.5. Because the fiber tip is inserted into the hole in the cap, shown in Figure 3.6, there is a short length of fiber that extends out past the cap into the NM solution. It appears that the PDV was able to measure the initial detonation in this short section of fiber before the detonation transferred fully through the cap. The timing of this measured event seen in SIRHEN lines up with the piezoelectric pin timing (discussed in Section 3.2.). Future testing is planned to validate this theory.



Short duration, low contrast signals seen by the PDV between the fiber tip and cap.

Figure 3.5. Velocity component measured early in time

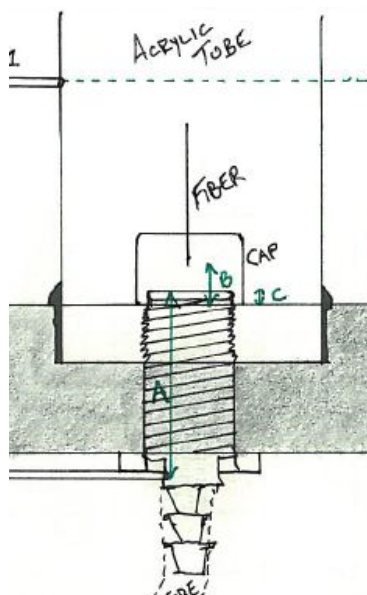


Figure 3.6. Sketch showing fiber extending through cap

Piezoelectric Pin Data

The piezoelectric pins situated along the outer wall of the NM-filled tube provided useful results that agreed extremely well ($< 0.5\%$) with the PDV data. All four tests conducted yielded similar results proven below in Figure 3.7. There were pins located both before and after the cap where the fiber was attached to. The pin timing data indicates that the cap does indeed introduce a delay where the detonation wave slows down a bit before reaching a steady state. This helps to reinforce that the PDV is accurate.

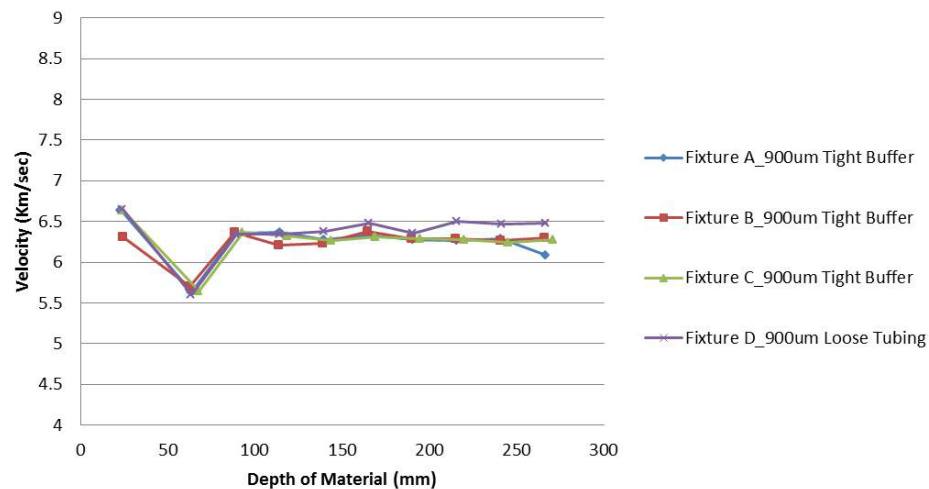


Figure 3.7. Piezoelectric Pin Data (Velocity vs. Depth)

High-Speed Video Results

High-speed video also agrees very well with the PDV and pin results over the entire series. Figure 3.8 displays six frames taken during a single experiment. The frame rate of this particular camera was 120000 frames/sec, which gave us a frame roughly every 8-9 μ sec. An agreement with the PDV and the pins of $< 1.0\%$ was noticed. The measured average velocities were 6.234 km/sec, 6.263 km/sec, 6.251 km/sec, and 6.326 km/sec respectively for the four tests by the high-speed camera.

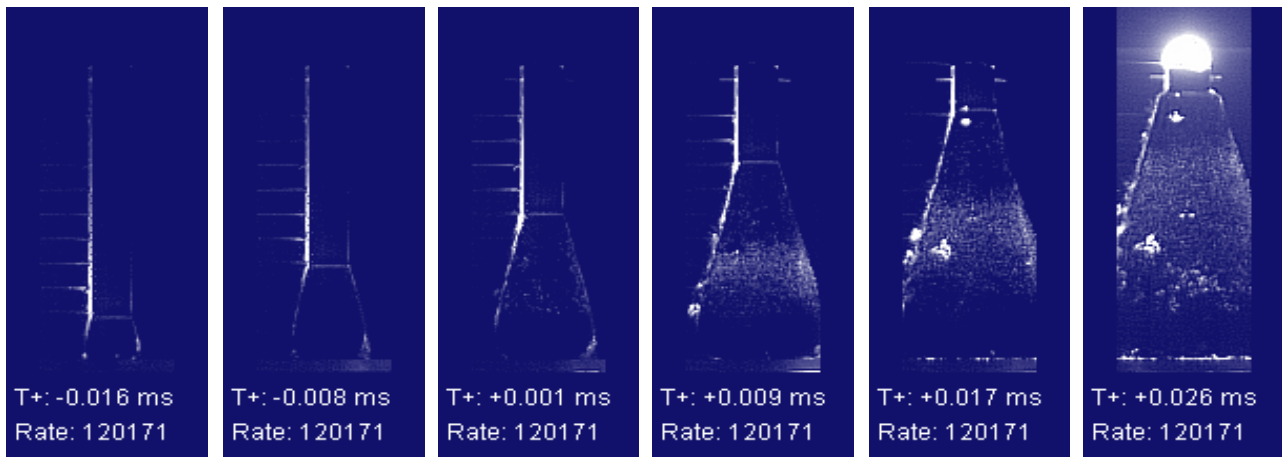


Figure 3.8. Results from the high-speed video

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4. SUMMARY

It has been demonstrated that the PDV can be used as an embedded velocity diagnostic in sensitized nitromethane. Nitromethane was an ideal choice to try and apply this measurement technique because of its availability, and associated detonation velocity (higher than the sound speed of the glass). Two independent diagnostics, piezoelectric pins and high-speed video, were fielded alongside the PDV and provided results that agreed to a fraction of a percent. Further work will be done to look at the feasibility of using probe materials that have a lower sound speed, i.e. plastic or liquid-filled fibers so that non-ideal explosives with lower detonation velocities can be investigated.

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