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D. E. Hare, D. B. Holtkamp, O. T. Strand

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D.E. Hare[*], D.B. Holtkamp[f], O. T. Strand[*]

[*]Lawrence Livermore National Laboratory
Livermore, CA 94550

[f]Los Alamos National Laboratory
Los Alamos, NM 87544

Abstract. Detonation velocities for high explosives can be in the 7 to 8 km/s range. Previous work has shown that these velocities may be measured by inserting an optical fiber probe into the explosive assembly and recording the velocity time history using a Fabry-Perot velocimeter. The measured velocity using this method, however, is the actual velocity multiplied times the refractive index of the fiber core, which is on the order of 1.5. This means that the velocimeter diagnostic must be capable of measuring velocities as high as 12 km/s. Until recently, a velocity of 12 km/s was beyond the maximum velocity limit of a homodyne-based velocimeter. The limiting component in a homodyne system is usually the digitizer. Recently, however, digitizers have come on the market with 20 GHz bandwidth and 50 GS/s sample rate. Such a digitizer coupled with high bandwidth detectors now have the total bandwidth required to make velocity measurements in the 12 km/s range. This paper describes measurements made of detonation velocities using a high bandwidth homodyne system.

Introduction

Early attempts to measure detonation velocities inside high explosive (HE) assemblies were performed by Willard F. Hemsing of Los Alamos National Laboratory (LANL) in collaboration with David R. Goosman of Lawrence Livermore National Laboratory (LLNL). The method involved inserting an optical fiber into the explosive assembly and trying to observe the change in position of the shock front in the fiber core. Their work gave hints that the method might be possible, but they were not able to develop a technique that reliably gave usable data. Goosman continued to work on the problem using a Fabry-Perot velocimeter system[1] and, with Rex Avara and others at LLNL, eventually developed two components that yielded reliable results in detonation velocity measurements. The first component was an etalon-based filter[2] that improved the signal-to-noise ratio by effectively suppressing the non-Doppler-shifted light returned from the probe while allowing a large fraction of the Doppler-shifted light from the probe to return to the velocimeter. The design of this filter is elegant in its high throughput of the desired Doppler-shifted optical frequencies and its variable attenuation of unwanted non-Doppler-shifted frequencies, but its eventual success was never in doubt because the notion of using a Fabry-Perot etalon as a frequency filter is well known. The second component developed by Goosman that eventually led to the routine measurements of detonation velocities inside HE assemblies is the probe itself. There was no prior successful work upon which to build in determining the optimal design for a probe that could make this measurement. Goosman spent several years trying various design ideas before hitting upon the basic requirements for a good design[3] and then finally realizing those requirements in a design that could be tested. Goosman's probe is based upon a liquid core waveguide that can be coupled to the multi-mode fiber used by the Fabry-Perot system. The liquid core has a very low (2 km/s) sound speed, which allows this probe to measure a range of velocities from full detonation (8 km/s) to the sound speed of the liquid core (2 km/s). In addition to measuring detonation velocities inside HE assemblies, this probe can also follow decaying shocks in metals, for example. Goosman labeled this probe the embedded fiber optic (EFO) probe.

Even though the Fabry-Perot velocimeter is an excellent diagnostic for EFO experiments, there are certain disadvantages that prompted the attempt to perform EFO experiments using the homodyne method. Here at LLNL, the Fabry-Perot velocimeter uses a large pulsed laser capable of launching 100 watts of 532 nm light into 100-micron core fibers. The filter described above uses a tunable etalon and requires considerable adjustments to perform properly. The light returned from the EFO probe is sent to an analyzer table consisting of another tunable etalon and streak cameras. The total system is very labor intensive and requires skilled maintenance. Furthermore, the Fabry-Perot system cannot be easily moved, which restricts all of our EFO experiments to be performed in our large tank capable of containing experiments with 10 kilograms of HE, even though our EFO experiments generally contain less than 0.5 kilograms of HE. Our facility would be better served if we could perform our EFO experiments in one of our small tanks, and our experiments would be considerably less expensive if we did not need so many people to handle the diagnostics.

The homodyne velocimeter[4] is a small compact diagnostic that has found wide popularity for HE-driven experiments and gas gun experiments. (The homodyne velocimeter is often called the Photonic Doppler Velocimeter, or PDV.) The PDV systems used at LLNL are built into 4-channel units that are packaged into roll-around shipping boxes, and so are easily moved from one facility to another. The PDV measures the beat frequency resulting from mixing the Doppler-shifted light from the moving surface with the non-Doppler-shifted light from the laser. A velocity of 1 km/s generates a beat frequency of 1.29 GHz, so that the PDV must use high bandwidth detectors and digitizers to measure the velocity ranges of interest for HE-driven experiments. As mentioned above, the apparent velocities involved with EFO experiments can be as high as 12 km/s, which corresponds to a beat frequency of 15.5 GHz. To measure the frequencies required for an EFO experiment, the PDV system described in Reference 4 was modified to have detectors and a digitizer with much higher bandwidth. This latest generation PDV was outfitted with 20 GHz detectors built by Miteq, and the latest model Tektronix digitizer (DSA72004) with 20 GHz bandwidth and 50 GS/s sample rate. In theory, these components give the PDV a frequency limit of approximately 14 GHz, but the bandwidth of the Miteq detectors rolls off slowly enough above 20 GHz that the total system bandwidth is high enough to measure the nearly 16 GHz required for the EFO experiments.

The following sections describe a sample of EFO experiments that used the PDV. The next section describes the standard EFO probe used for the Fabry-Perot velocimeter and the modifications that were required to use the EFO probe with the PDV system. The following sections describe three different HE assemblies that were tested and show the results obtained with the PDV.

EFO probe design

The standard EFO probe used with the Fabry-Perot system is built using a hollow Teflon tube with 1.6 mm outside diameter and 175 µm inside diameter. The core of the tube is filled with an aqueous solution of cesium chloride (CsCl). The CsCl has a lower index of refraction than the surrounding Teflon, so the assembly is an effective waveguide. A multi-mode optical fiber with 125 µm outside diameter and 100 µm core diameter (step index) is inserted into the end of the tube. The Teflon tube is then inserted into a hole that has been pressed or drilled into the explosive assembly. (Goosman discovered that the Teflon tube is very important for the operation of the EFO probe. The teflon apparently provides a smoothing layer so that the shock profile inside the core remains relatively quiescent and stable. Attempts to field an EFO probe without some type of smoothing layer, such as a bare fiber inserted into the explosive, were nearly always doomed to failure.) Light is launched from the pulsed laser into the optical fiber to the probe. The light returning from the probe propagates along the same fiber and is split away at the etalon-based filter to be sent to the velocimeter. The dynamic measurement relies upon having sufficient return from the moving shocked interface in the CsCl to record on a streak camera. We have found that the amount of laser light reflected from the moving boundary is approximately $1x10^{-4}$ of the light launched to the probe. For this reason, care must be taken to reduce the reflected or scattered light from all other components in the system. There are several fiber connections that must be made getting from the laser, through the tank feedthrough, and to the probe pigtail. The returns from these may be greatly reduced to approximately $1x10^{-6}$ or less by using angled connectors or by fusion splicing. The liquid-filled Teflon tube geometry, however, represents a large source of non-Doppler-shifted light that can be removed only by the use of the etalon filter mentioned above.

The probe operation relies upon a proper choice of materials. For the standard Fabry-Perot EFO probe, the detonating explosive sends a shock into the Teflon wall. This shock propagates inward at an angle determined by the shock speed in the Teflon versus the detonation speed along the tube wall. As the inward propagating shock enters the CsCl core, another shock angle is established that is determined by the shock speed in the CsCl versus the speed that the shock is dragged along the Teflon-CsCl interface. It is very important that the shock speed in the CsCl core is slower than the shock speed in the Teflon. This condition sets up a shock profile inside the CsCl core that is concave toward the incoming laser light. It is the index change at this moving shock profile that provides the Doppler-shifted return in the EFO probe. Note that if the shock speed in the core material were higher than the shock speed in the Teflon, then the shock inside the core would tend to run ahead of the shock in the Teflon and set up a shock profile that would be convex toward the incident laser light. Such a shock profile would have an extremely low efficiency of returning Doppler-shifted light to the velocimetry system and the measurement could not be made. For this reason, the EFO probe has an inherent minimum velocity that is determined by the sound speed of the core material. The aqueous solution of CsCl used in the EFO probe has a sound speed of only 2 km/s so that the standard EFO probe can be used in measurements that involve speeds considerably slower than detonation speeds, such as decaying shocks in metals. Also note that the EFO probe axis must be relatively parallel to the direction of the detonation front, otherwise the shock front inside the fiber core becomes angled with respect to the fiber axis and will not reflect the laser light within the numerical aperture of the probe to the velocimeter. One of the on-going studies is to determine the maximum usable angle between the probe axis and the direction of the detonation front.

Adapting the standard EFO probe for use with the PDV presented some issues. The PDV uses single mode fibers with core diameters of only 9 µm, which is a severe mismatch with the 175 µm inside diameter of the Teflon tube. There would be no problem launching laser light into the probe from the fiber, but coupling light back into the fiber would suffer a geometric loss determined by the ratio of the square of the diameters (= $(9/175)^2$ = 0.0026). The outside diameter of the single mode fiber is 125 µm, so the natural choice to try first was to merely insert the single mode fiber directly into the Teflon tube, as shown in Figure 1. There was an immediate, and known, consequence of trying this type of EFO probe design. The sound speed of the silicon dioxide fiber core and clad is over 5 km/s, so that this probe design could be used only for detonation speeds higher than that. It was also not known whether an appropriate shock profile would be established inside such a small core diameter. Fortunately, this was an easy modification to make, so it was certainly worth a try.

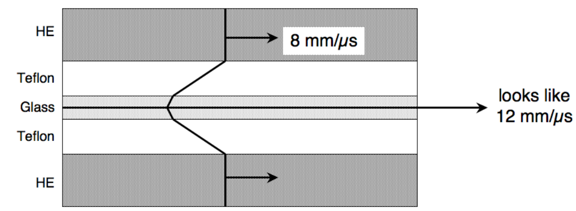

FIGURE 1. The modified EFO probe is built by sliding a single mode fiber with 125 µm outside diameter into a Teflon tube with 175 µm inside diameter and 1.6 mm outside diameter.

Another issue of using an EFO probe with the PDV is whether the proper conditions could be established to generate a good beat signal. It was not known whether the amount of Doppler-shifted light returned from the shocked silica core would be sufficient. The required source of non-Doppler-shifted light also needed to be considered. Two steps were taken to assure a good level of unshifted light. First, the single mode fiber was cleaved at an angle of approximately 8 degrees before inserting into the Teflon tube. This ensured a very low back reflection from the fiber endface and no undesirable signal behavior when the shock crushed the fiber end. Second, a fiber optic splitter and variable reflector were employed to inject the correct amount of unshifted light to generate a good beat signal. The next sections provide three examples of data taken with the modified EFO probe and the PDV.

Overdriven LX-17

Our EFO experiments are generally built using stacks of explosive pellets in the shape of right circular cylinders with a diameter of 25 mm and a length of 25 mm. This size was chosen for the ease of pressing these shapes in a mold that contains a 1.6 mm rod in the middle to provide a hole for the EFO probe. The first example of EFO data taken with the high bandwidth PDV is a stack of three pellets driven by an RP-1 detonator. Figure 2 shows that the first pellet, nearest the on-axis detonator, was made of PBX-9501 and the next two pellets were made of LX-17. This order of pellets was chosen to study the behavior of overdriven LX-17. Note that the single mode fiber was not pushed all the way through the assembly to the detonator, but rather was kept approximately one centimeter from the detonator. This was to reduce the laser fluence on the detonator. It was not known whether the 200 mW launched into the fiber would pre-heat the detonator to the point of exploding prematurely. After igniting this assembly, the time history of the resulting beat frequency shows that the PDV recorded frequencies that were over 16 GHz for the PBX-9501 and were approximately 14 GHz for the LX-17. This data was processed using a sliding Fourier transform method with 41 ns temporal windows, which is approximately the time resolution of the analysis. This yielded a signal-to-noise ratio (SNR) of 20 to 30 dB in the frequency domain, more than sufficient to obtain a good velocity time history. (Higher time resolution (few ns) is achievable for good data sets using alternate techniques.) Converting the measured velocity by dividing by the fiber core index of refraction (1.4682) yields the actual time history of the detonation recorded by the EFO probe[5].

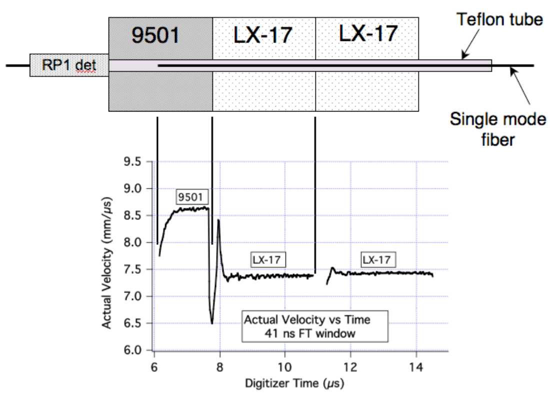

FIGURE 2. This assembly used PBX-9501 to overdrive LX-17.

The beginning of the record starts at 7.7 km/s and ramps steadily upward to 8.6 km/s for PBX-9501. We assume this ramp-up is caused by the shock profile establishing itself at the beginning of the fiber. The EFO probe recorded a velocity of approximately 7.4 km/s for the LX-17, which is 2% lower than the expected value of 7.55 km/s for the detonation velocity of unconfined 1-inch diameters. There are obvious discontinuities and some loss of data at the interfaces between the pellets. The pellets were simply stacked together with no adhesive or grease, so there was probably a thin air gap between pellets. The second LX-17 pellet had a slightly higher density than the first LX-17 pellet and shows a slightly higher velocity. The steady-state portions of both LX-17 pellets show some small, but definite, fluctuations. This behavior is seen in the data taken with the Fabry-Perot velocimeter also and we assume this is caused by the granularity of the pressed HE. The transition from the PBX-9501 to the first LX-17 pellet shows a bimodal structure, which we attribute to the probe response across a gap, before quickly settling into the steady state velocity of the LX-17.

Underdriven PBX-9501

The next example of data taken with a modified EFO probe and the PDV used an RP-1 detonator that was placed off-axis. In this case, a stack of five pellets included, starting at the detonator, PBX-9407, LX-17, LX-17, LX-17, PBX-9501, as shown in Figure 3. The order of the last two pellets was chosen to study how LX-17 might underdrive the PBX-9501, in contrast with the ordering in the previous example. The detonator was placed off-axis so that the EFO probe could be inserted all the way through the stack, which allowed the laser light to be emitted harmlessly away from the detonator. The disadvantage of this layout is that the detonation front is not normal to the axis of the EFO probe until some distance down the stack. It was not known how soon the EFO probe would start to provide a useable Doppler-shifted signal, therefore extra pellets were added to the assembly to allow time for the detonation wave to orient itself parallel to the assembly axis.

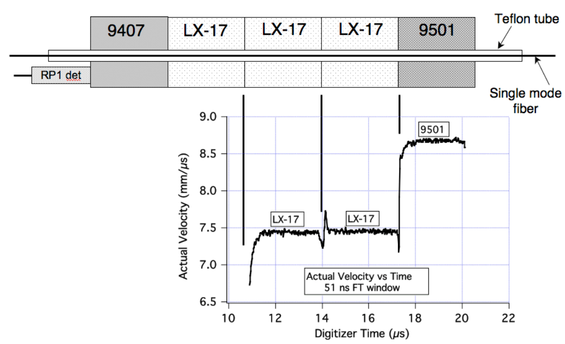

FIGURE 3. This assembly used LX-17 to underdrive PBX-9501

After firing this assembly, the PDV signal had a SNR of approximately 20 dB in the frequency domain, with some occasional fadeouts to a few dB. This data was processing using a sliding Fourier transform method with 51 ns temporal windows. The actual velocity time history shows the familiar ramp-up to the same velocity for LX-17 as observed in the previous example. The rest of the data shows another LX-17 pellet and then the higher velocity expected for the PBX-9501 pellet. This means that the EFO probe did not return signals from the PBX-9407 pellet or the first LX-17 pellet. Integrating the data to obtain the distance versus time, it can be shown that the EFO probe started to return useable Doppler-shifted signals approximately 3.25 mm into the second LX-17 pellet. Thus, it took over 53 mm of detonation run for the shock front to finally align itself sufficiently normal to the EFO probe to return a useable signal. This data also shows the familiar small fluctuations in velocity during the steady state portions of the time history. There are also some slight discontinuities at the pellet boundaries, but no actual loss of data. The transition from the last LX-17 pellet to the PBX-9501 involves an abrupt jump from 7.4 km/s to 8.4 km/s, and then a relatively slow (0.5 μs) increase to the final velocity of 8.7 km/s.

Gap Test

The final example shows a test of the ability of HE to re-detonate after propagating across a gap. The RP-1 detonator was placed off-axis for this experiment as in the previous example. For this reason, extra pellets were added to the stack representing a variety of pellet types to also look at overdriven and underdriven HE. Figure 4 shows the stack-up of pellets, which included, starting at the detonator, PBX-9501, LX-17, LX-17, PBX-9407, PBX-9501, PBX-9407, 2.78 mm gap, LX-17.

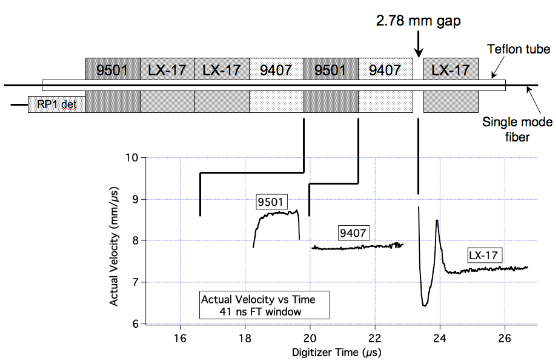

FIGURE 4. This assembly tested the ability to detonate LX-17 separated by a 2.78 mm gap.

This data was processed using a sliding Fourier transform method with 51 ns temporal windows. The velocity record shows that the EFO probe did not start returning signals until approximately 13 mm into the second PBX-9501 pellet, so that it took nearly 115 mm for the detonation front to align sufficiently with the probe axis to be recorded. Unfortunately, this means there is no information regarding overdriven and underdriven conditions from this test. There are interruptions in the data between the last three pellets, but the velocity observed for each pellet is similar to previous experiments. Of particular interest is that the final LX-17 pellet detonated after the detonation front crossed a 2.78-mm gap. The probe shows large velocity oscillations as the signal appears in the last LX-17 pellet. Integrating the velocity for the last section of data, starting at the beginning of the large oscillations and ending at the end of the LX-17 pellet, yields a distance of 24 mm, compared with 25 mm for the actual length of the pellet. This suggests that the large oscillations occurred after the detonation front entered the last pellet after crossing the gap. This bimodal behavior has been seen before and may be caused by the probe response.

Conclusions

Upgrading the homodyne velocimeter with higher bandwidth electrical components has allowed the observation of beat frequencies greater than 16 GHz. This new capacity, along with the modified embedded fiber optic (EFO) probe, has enabled the study of detonation speeds inside high explosive (HE) geometries using the PDV. Alternating the order of the different types of pellets allows a study of overdriving and underdriving different HE samples. During the steady-state portion of the velocity profile, there are small fluctuations in the velocity that are suggestive of the granular structure of the HE. Finally, this type of HE assembly allows a gap-crossing study that would be difficult without the use of the EFO probe.

There is still work to be done to understand details of the EFO probe performance. Basic issues such as probe time response still need to be studied. Another question concerns the absolute timing delay of the shock front inside the fiber core compared to the position of the detonation front in the HE. There is some thought that the bimodal behavior at the pellet interfaces might be caused by variations in this delay. Perhaps the time response and bimodal behavior can be minimized by using Teflon tubes with thinner walls, although this may result in loss of data as the smoothing layer is reduced. Finally, another limitation of the EFO probe is the narrow range of angles between the probe axis and the direction of the detonation front that return data. Investigations of modified probe designs and, perhaps, different fiber materials may allow a broader range of usable angles, which would make the EFO probe adaptable to more interesting HE geometries in addition to stacks of right circular cylinders.

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References

1) Goosman, D.R., “The Multibeam Fabry-Perot Velocimeter: Efficient Measurement of High Velocities”, Science and Technology Review, July 1996.

2) Goosman, D.R., Wade, J.T., Rivera, A.T., “Optical filters to exclude non-Doppler-shifted light in fast velocimetry”, Proceedings SPIE, v 4948, 152 (2003).

3) Goosman, D.R., Wade, J.T., Garza, R., Avara, G.R., Crabtree, T.R., Rivera, A.T., Hare, D.E., Tolar, D., Bratton, B.A., “Optical probes for continuous Fabry-Perot velocimtry inside materials”, Proceedings SPIE, v 5580, 517 (2005).

4) Strand, O.T., Goosman, D.R., Martinez, C., Whitworth, T.L., Kuhlow, W.W., Rev Sci Instr **77**, 083108 (2006).

5) The index of refraction for Corning single mode fiber (SMF-28) is 1.4682. Subsequent analysis indicates that the effective mode index, with a value of 1.4472, may be the more appropriate value to use. More study is required to confirm the proper correction factor to use.