NANOSECOND SCALE OPTICAL PULSE SEPARATIONS FOR HOLOGRAPHIC INVESTIGATION OF HIGH-SPEED TRANSIENT EVENTS

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INTRODUCTION

The dynamics of detonation for dispersed solid particulate explosives are not well understood. These explosives, used for mine neutralization, are comprised of a fine, solid particulate dust which is dispersed as a cloud over a given area. When detonation is initiated in some portion of the cloud, the ensuing detonation wave propagates throughout the entire cloud and results in an explosion, generating a tremendous pressure which serves to destroy any land mines present. However, the mechanism with which individual explosive particles interact to sustain detonation in these solid dispersed particle explosives is not clear. In liquids, for example, it is known that coupling between a propagating shock front and the chemical reaction front which follows is maintained by a "stripping" action of the shock front on the explosive droplets so that an ultrafine mist is produced and swept along in the convective flow behind the shock front [1]. Thus, upon ignition and combustion of this ultrafine mist, coupling is maintained between the shock and reaction fronts. In the case of solid particulate explosives, it is unclear whether it is the shock front alone or a combination of the shock and reaction fronts which initiate subsequent particle detonation. In an effort to more closely examine the generation and propagation of the shock and reaction fronts arising from single particle detonation, and the interaction of these fronts with neighboring particles, high-speed holography is being used to visualize and study these transient phenomena. The shock front generated by detonation of a single explosive particle ($\approx 100\mu m$ diameter) may exist as a true shock front only 10-50 particle diameters away, and may propagate at velocities approaching 5000m/s. As a result, the holographic techniques used to study these dispersed particle explosives need be capable of capturing events with lifetimes shorter than $1\mu s$, thus requiring optical pulse separations between 10 and 200 ns.

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HIGH SPEED HOLOGRAPHY

High-speed holography has been used to study a wide variety of events, from transient Lamb wave propagation in thin plates [2] to turbulent fluid flow in prosthetic heart valves [3]. In general, high-speed holography may be used either as a quantitative interferometric tool, or simply as a high-speed imaging method. In either case, successful application of the holographic technique requires the generation of optical pulses with temporal separations matched to the event being studied. To study an event with a 500 millisecond lifetime may require optical pulse separations on the order of 50 milliseconds, whereas events with shorter lifetimes may require nanosecond pulse separations. Frequently, multiple exposure holography relies on Q-switched lasers to produce optical pulses with sufficient energy for the holographic recording process. For investigations in which the desired pulse separation ranges between a few microseconds and tens of milliseconds, it is possible to repetitively open the laser Q-switch and generate the required optical pulses. However, the rapidity with which optical pulses can be generated in a Q-switched laser is largely dependent upon laser physics. For example, a typical flashlamp pumped Q-switched Nd:YAG laser is limited to pulse repetition rates of less than 50 kHz, corresponding to a lower limit of 20 μs between optical pulses [4]. For shorter pulse separations (i.e. higher repetition rates), it becomes extremely difficult to pump the lasing medium hard enough to create an above-threshold population inversion in the interim between the Q-switch openings. Owing to this limitation, transient events with lifetimes less than 20μs are difficult to study with conventional Q-switched lasers.

To break this 20μs barrier in the generation of optical pulses inherent in conventional Q-switched lasers, it is possible instead to use a mode-locked laser to produce the optical pulses. Mode-locking a laser allows for extremely high optical repetition rates, typically from 75-150MHz (6 to 13 ns between pulses). Although mode-locked lasers operate at repetition rates several orders of magnitude greater than Q-switched lasers, mode-locked pulses are generally of extremely low energy and are ineffective in exposing high resolution holographic film. Additionally, these high repetition rates may be too fast to be of use in many applications.

In examining the operating parameters of typical Q-switched or mode-locked lasers, it is apparent that neither are well suited to the holographic study of transient events with lifetimes less than 10μs. Although it is possible to purchase multiple cavity lasers whose individual outputs may be synchronized together and thus generate optical pulses with virtually any temporal spacing, the cost of such a system can be prohibitive. Hence, in order to study these short-lived transient phenomena, it became necessary to devise an alternate method to produce optical pulses with temporal separations ranging from 10 to 500 ns. The current method incorporates an optical delay line to produce the desired temporal separation.

WHITE CELL FOR OPTICAL DELAY

In 1942, J.U. White devised an optical construct enabling him to obtain very long optical paths for absorption spectroscopy by using three spherical, concave mirrors of equal radius of curvature [5]. Two of the mirrors may be of small diameter, just large enough so that the optical beam is fully contained, whereas the third mirror must be larger, as described below. The two small turning mirrors are placed such that their centers of curvature fall on the front surface of the large field mirror, whose center of curvature is positioned halfway between the turning mirrors. A collimated optical beam entering the mirror assembly, hereafter termed a "White cell", is reflected first by one of the small turning mirrors. This turning mirror directs the beam toward the large field mirror, at the same time focusing it midway between these two mirrors. Upon reaching the large field mirror, the now-expanding beam is again reflected and directed toward the second turning mirror. Upon reflection from the large mirror, the beam becomes recollimated, owing to the spherical, concave nature of the mirrors. In a similar fashion, the beam continues its traversal through the White cell, reflecting between the turning and field mirrors, continually being refocused and recollimated, such that the beam profile upon exiting the White cell is identical to the that which entered.

HOLOGRAPHIC RECORDING CONFIGURATION

Figure 1 is a schematic of the current optical setup used for high-speed holography, incorporating the White cell as an adjustable delay line between two optical pulses. The number of cell traversals possible for a given White cell is determined by the ratio of the field mirror diameter to that of the input beam. Therefore, for a given mirror configuration and input beam diameter, there is a maximum number of cell traversals possible, and a corresponding maximum associated delay time from entrance to exit of the cell. It is possible to vary discretely the number of traversals within the White cell, and thus the total optical delay, by simple adjustment of the two turning mirrors. The current implementation of the White cell uses mirrors of 2 meter radius of curvature.

To obtain two temporally separated pulses, a single 9ns optical pulse was obtained from a Q-switched, frequency doubled Nd:YAG laser, and converted to circular polarization. Using a polarizing beamsplitter, the pulse was split into horizontal and vertical components. The horizontal component passed through a quarter-waveplate/mirror assembly, such that it was redirected back through the same polarizing beamsplitter toward the holographic setup, and became the beam used for the initial holographic exposure. At the same time, the vertical component of the original pulse was directed through another quarter-waveplate and into the White cell. The beam exited the White cell and was retro-reflected, passed a second time through the cell, and emerged along the same path upon which it entered. It then passed through the quarter-waveplate a second time, resulting in a change to horizontal polarization, and continued straight through the first polarizing beamsplitter, collinear with the initial beam, but delayed in time relative to it by the amount determined in traversing the White cell.

Now collinear, but temporally separated, both beams passed through a 50/50 beamsplitter to split each into an object and reference path for holographic recording. The initial and delayed beams in the reference path were separated using another polarizing beamsplitter, and directed toward the film at different angles to give independent control of both the initial and delayed holographic images. In the current configuration, the time interval between the initial and delayed holographic exposures may be varied from approximately 50ns to 450ns.

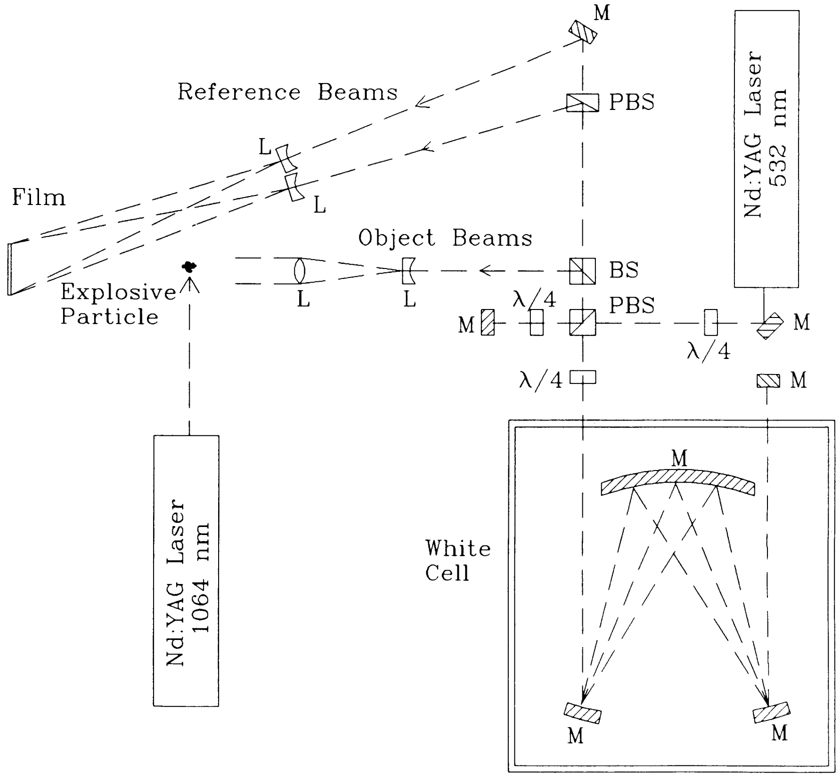
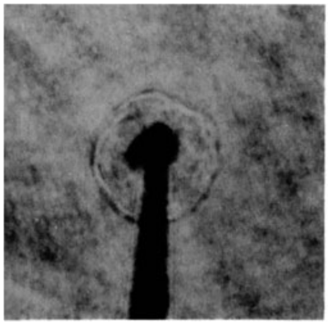


Figure 1. A schematic of the optical setup for high-speed dual exposure holography using a White cell as an optical delay line.

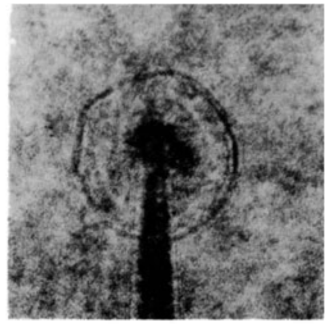
EXPERIMENT

The high-speed holographic technique described above is currently being used to study the generation and propagation of shock fronts resulting from single explosive particle detonation. In this study, single explosive particles approximately 100μm in diameter are supported on a 50μm radius needle tip. A low energy pulsed Nd:YAG laser operating at 1.06μm is used to detonate the explosive. A second, high-energy pulsed Nd:YAG laser with a frequency doubled output (532nm) is used to produce the optical pulse necessary for the holographic recording. The two Nd:YAG lasers are synchronized such that the output of the high energy laser used for the holographic recording follows that of the detonating laser by an amount adjustable between 0 and 10μs in 100ns steps.

Since only one initial and one delayed recording pulse can be obtained for a single event using the current system, it is necessary to repeat the experiment a number of times to view the entire development of the shock front. Accordingly, a given experiment yields only two holographic images of the shock front, as shown in Figure 2. The time at which the first exposure is taken, relative to the initiation of detonation, is determined by the detonating-to-recording laser pulse interval. The time at which the second exposure is taken, relative to the first, is determined by



(a)



(b)

Figure 2. Holographic images of propagating shock front (a) 215ns after particle detonation and (b) 113ns later. The shock front has grown 83μm between exposures.

the number of traversals within the White cell that the delayed beam makes. By changing the detonating-to-recording pulse interval, it is possible to obtain a time series of dual-exposure holograms visualizing the propagation of the shock front. For a given experiment, a single shock front velocity value can be determined from the two holographic images. For example, the first image shown in Figure 2 (a) was taken 215ns after particle detonation, the second (b) 113ns later. During this interval, the shock front has grown radially by 83μm, corresponding to a shock front velocity of 735m/s (Mach 2.1).

After performing a number of these experiments, it became evident that the explosive particles exhibit an initiation time between deposition of laser energy and detonation that varies from particle to particle. Additionally, the particles are nominally 100μm diameter, but any variation in particle size affects the total stored energy within the particle, and therefore the magnitude, velocity, and lifetime of the associated shock front. As such, it is difficult to obtain a relationship between shock front velocity or overpressure as a function of time after detonation, owing to the variability between particles.

FUTURE WORK

In an effort to overcome the timing problems and particle size variability inherent when performing multiple experiments, a new method is currently being developed which will allow multiple holographic exposures (<10) of a single event, with separations between holographic exposures ranging from 25 to 100ns. The system under development uses a White cell as an optical delay line between exposures as described above, but also incorporates a geometrically graded beamsplitter to sample the beam and redirect it back into the White cell in a cyclic fashion. This should allow for 10 optical pulses of equal energy to be obtained, separated both temporally and spatially. Using this, it should be possible to follow a single transient event in both space and time, thereby eliminating variability owing to particle size and imprecise timing of detonation. Ultimately, it should be possible to introduce multiple particles within the test volume, detonate one, and study the interaction of the resulting shock and reaction fronts with neighboring particles.

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