Non-invasive timing of gas gun projectiles with light detection and ranging

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Abstract. We have developed a Light Detection and Ranging (LIDAR) diagnostic to track the position of a projectile inside of a gas gun launch tube in real-time. This capability permits the generation of precisely timed trigger pulses useful for triggering high-latency diagnostics such as a flash lamp-pumped laser. An initial feasibility test was performed using a 72 mm bore diameter single-stage gas gun routinely used for dynamic research at Los Alamos. A 655 nm pulsed diode laser operating at a pulse repetition rate of 100 kHz was used to interrogate the position of the moving projectile in real-time. The position of the projectile in the gun barrel was tracked over a distance of \(\sim 3\) meters prior to impact. The position record showed that the projectile moved at a velocity of 489 m/s prior to impacting the target. This velocity was in good agreement with independent measurements of the projectile velocity by photon Doppler velocimetry and timing of the passage of the projectile through optical marker beams positioned at the muzzle of the gun. The time-to-amplitude conversion electronics used enable the LIDAR data to be processed in real-time to generate trigger pulses at preset separations between the projectile and target.

1. Introduction

Light-gas guns are routinely used to launch projectiles at velocities (100 – 8000 m/s) which are impacted into highly-instrumented targets for dynamic (shock) compression research [1–4]. Critical to the success and analysis of these experiments are the determination of projectile impact timing and velocity at the target. A variety of methods have been used to detect the arrival of the projectile. These include shorting pins, interruption of light beams, breakage of conductive wires, X-ray flash detection [5], and inductive coil detection of a magnet embedded in the projectile [6]. While most of these methods have been used to detect projectiles exiting the muzzle, shorting pins and interruption of light beams have also been used to detect the passage of projectiles at points within the barrel of the gun.

An ability to locate (track) the projectile within the gun barrel at substantial distances from the target provides a means of generating early, pre-event signals useful for triggering high-latency diagnostic probes (e.g., flash lamp-pumped light sources and lasers, pulsed radiography sources, including synchrotron x-ray or accelerator-produced proton bunches) and detectors (e.g., streak and framing cameras). Recently we demonstrated that external-surface mounted...
optical fiber Bragg grating strain gauges can be used for timing the passage of projectiles inside of the launch tubes of single-stage and two-stage light gas guns [7].

Here we demonstrate that Light Detection and Ranging (LIDAR) can be used to detect and time the passage of projectiles inside of the launch tubes of single-stage and two-stage light gas guns routinely used for dynamic shock compression studies at Los Alamos. Figure 1 shows the LIDAR principle in the context of this work. Pulsed laser light illuminates the moving projectile. A fast optical detector registers the arrival of the light pulse reflected from the projectile. The distance, $D$, between the projectile and the LIDAR probe (shown schematically here as the laser and detector) is obtained by dividing the measured laser pulse round trip time, $T$, by two and multiplying by the speed of light ($D = (cT)/2$).

2. Experimental

Figure 2 shows a schematic of the setup used to implement the LIDAR diagnostic in our experiments. A pulsed diode laser (Model LDH-P-C-650, Picoquant) operating at 655 nm was used to illuminate the projectile. The laser pulse width ranged from 100-500 ps, increasing with the laser diode drive current level. Laser pulse energies ranged from 8-80 pJ. The pulse repetition rate was fixed at 100 kHz to accommodate the $\sim 10\mu s$ dead-time of the time-to-amplitude conversion (TAC) electronics (Model TC 863, Tennelec). A suitably delayed synchronization output pulse from the laser driver (Model PDL 800-B, Picoquant) was used to start the TAC electronics. Laser light reflected from the moving projectile was detected with an avalanche photodiode (Model APD-210, Menlo Systems, Inc.). The output of the avalanche photodiode detector (APD) was amplified 10-fold using a fast amplifier (Model 6954, Phillips Scientific), inverted, and then fed into a constant-fraction discriminator (Model TC 454, Tennelec) to generate a pulse used to stop the TAC electronics. Details of the time-to-amplitude conversion process are given in figure 3. As shown in the figure two timescales are measured. The first, referred to here as the “macro” time, is measured in units of $10\mu s$, the pulse period of the 100 kHz illumination laser. The second, referred to as the “micro” time, is the nanosecond timescale delay between the output of the laser pulse and the detection of the laser pulse reflected from the moving projectile. The micro time associated with each laser pulse is converted by the TAC electronics to a voltage pulse of amplitude proportional to the micro time. A single-channel-analyzer (SCA) built into the TAC electronics outputs a logic pulse when the amplitude of voltage pulse is within a preset range (SCA window).

Optical fibers were used to transport laser light into the target chamber of the gas gun as
well as to bring reflected laser light out and direct it to the avalanche photodiode detector. The first experiment was performed using a 72 mm bore diameter single-stage gas gun (figure 4A). Here a single 400 μm core diameter multimode fiber was used to send and receive the laser light. Linearly polarized laser light was launched into the fiber, a polarizing beamsplitter (not shown), positioned upstream of the input end of the fiber, was used to direct a portion of the depolarized return light to the avalanche photodiode. A relatively large 20 mm diameter, 35 mm focal length lens was used to collimate the fiber output and collect the laser light reflected from the moving projectile. The target assembly (not shown) was instrumented with a fiber-optic photon Doppler velocimetry (PDV) probe operating at 1550 nm that was used to measure the projectile velocity. The central aperture of the target was drilled out to accommodate the LIDAR beam. A set of four optical marker beams positioned between the muzzle and target (not shown) were interrupted by the projectile and triggered the digitizing oscilloscopes used to record the data.

The second two experiments were front surface impact or reverse ballistic experiments, in which a sample was launched by the two-stage gas gun into an oriented LiF window (figure 4B). Here a seven-fiber probe consisting of one send and six receive 100 μm core diameter multimode fibers was used. For this experiment a smaller 5.5 mm diameter, 11 mm focal length collimation lens was used to reduce the size of the LIDAR probe. Retro-reflective tape was applied to the periphery of the projectile to increase the return light level with the smaller probe (figure 4C). These modifications permitted us to position the LIDAR probe off the centerline of the target (figure 4B). This arrangement is useful for the accommodation of opaque targets and the elimination retro-reflections from transparent targets. A set of four optical marker beams (not shown) positioned between the end of the launch tube and target were used to measure the projectile velocity and trigger the digitizing oscilloscopes used to record the data. Figure 4D shows a photograph of the smaller LIDAR probe mounted on back of the target assembly inside of the target chamber of the two-stage gun.

3. Results

The results of the first LIDAR experiment using the single-stage gun are shown in figure 5. The raw data record is shown in figure 5A. The time scales in figure 5 are referenced to the breakage, by the projectile, of an optical marker beam positioned at the muzzle exit. The bottom trace is the output of the avalanche photodiode (APD) constant fraction discriminator (CFD); the
middle trace is the TAC output; and the top trace is the SCA output. As evidenced by the APD CFD record, LIDAR returns were obtained at the laser pulse repetition rate (100 kHz) for $\sim 17$ ms prior to impact of the projectile with the target at $\sim 0$ ms. At times less than $\sim -10$ ms the distance to the projectile results in micro times outside of the TAC range and LIDAR returns from the projectile did not generate TAC pulses; the TAC pulses seen are due to spurious returns from the fiber collimating lens. These spurious returns occurred at a rate of $\sim 20$ kHz in this experiment. Between $-9.8$ ms and $-6.8$ ms returns from the projectile generated TAC pulses with amplitudes that saturated the input of the recording oscilloscope. Between $-6.8$ ms and $0$ ms the amplitudes of the recorded TAC pulses from projectile LIDAR returns tracked the position of the projectile in the barrel of the gun. After impact spurious returns due to laser light reflected from the collimating lens continued to be recorded. Inspection of the SCA record shows that SCA pulses were generated on four successive LIDAR returns starting at -3 ms. The timing and number of the SCA pulses depend on the position and width settings of the SCA window.

Figure 5B shows the change in projectile distance derived from the TAC pulse amplitudes versus time. A linear fit of the distance data over the last 1000 microseconds prior to impact is shown with the solid line. The projectile velocity obtained from the slope of this line, $489 \pm 2$ m/s,
is within 2% of the value, $481 \pm 0.3 \text{ m/s}$, independently determined using PDV. The systematic deviation of the distance data from the line indicates that the projectile was still accelerating significantly over its last 3 meters of travel.

The results of a LIDAR experiment performed on the two-stage gun are shown in figure 6. Figure 6A shows the raw data record. The bottom trace is APD output; the middle trace is the TAC output; and the top trace is the SCA output. The APD record shows that the LIDAR return level increased rapidly with decreasing distance between the projectile and LIDAR probe. This highlights the need for using a CFD to process the APD output. Had a simple threshold discriminator been used, the timing of the LIDAR returns would have been systematically perturbed by changes in APD signal level. The TAC record shows that the position of the projectile was tracked over a period of $\sim 400 \mu$s in this experiment. Figure 6B shows the change in projectile distance obtained from the TAC pulse amplitudes versus time. A linear fit of the data is shown with the solid line. The velocity obtained from the slope of the line, $3510 \pm 14 \text{ m/s}$ is within 4% of the value, $3390 \pm 3 \text{ m/s}$, obtained from optical marker beams positioned at the launch tube exit.

The SCA window setting (figure 3) determines the projectile position at which the first SCA trigger pulse (figure 6A) is generated. In practice, the SCA window settings are fixed by the anticipated projectile velocity and the desired time delay between the SCA trigger and impact.

4. Summary and Conclusions

We have demonstrated the feasibility of using LIDAR to track projectiles inside of the launch tubes of single- and two-stage light gas guns. This capability allows the generation of timing pulses useful for triggering high-latency diagnostics. We anticipate that improvements of the laser light source and LIDAR return detection sensitivity will lead to further reduction in the
size of the LIDAR probe compared to that demonstrated here.

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