Non-destructive visualization of linear explosive-induced Pyroshock using phase arrayed laser-induced shock in a space launcher composite

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Abstract. Separation mechanism of Space launch vehicles are used in various separation systems and pyrotechnic devices. The operation of these pyrotechnic devices generates Pyroshock that can cause failures in electronic components. The prediction of high frequency structural response, especially the shock response spectrum (SRS), is important. This paper presents a non-destructive visualization and simulation of linear explosive-induced Pyroshock using phase arrayed Laser-induced shock. The proposed method includes a laser shock test based on laser beam and filtering zone conditioning to predict the SRS of Pyroshock. A ballistic test based on linear explosive and non-contact Laser Doppler Vibrometers and a non-destructive Laser shock measurement using laser excitation and several PZT sensors, are performed using a carbon composite sandwich panel. The similarity of the SRS of the conditioned laser shock to that of the real explosive Pyroshock is evaluated with the Mean Acceleration Difference. The average of MADs over the two training points was 33.64%. And, MAD at verification point was improved to 31.99%. After that, experimentally found optimal conditions are applied to any arbitrary points in laser scanning area. Finally, it is shown that linear explosive-induced real Pyroshock wave propagation can be visualized with high similarity based on the proposed laser technology.

1. Introduction

Pyrotechnic devices have been developed for the success of the critical mechanical functions in launch vehicle programs and missile launching technology over the past decades. Majority of pyrotechnically actuated functions is achieved through piston/cylinder devices which are like linear actuators, valves, separation nuts/bolts, and cutters of guillotines. Other functions are accomplished by linear explosives such as mild detonating cord (MDC) and flexible linear shaped charge (FLSC) [1]. On the other hand, when the pyrotechnic device is operating, the structure is exposed to a shock environment because pyrotechnic devices produce a high structural shock wave, on the order of thousands of g’s, which can physically damage the structure and give rise to contamination [2]. Therefore, the prediction of high shock structural response, especially the shock response spectrum (SRS), is very important for safe operation of pyrotechnic devices. Estimation and prediction of a pyroshock effects on a structure are
performed using numerical simulations [3] and experimental [4]. And, many researchers have been developing a low-impact pyrotechnic mechanical device [5].

In general, an SRS is the most commonly used characteristic and test description for the pyroshock environment. The SRS acceleration is also called the maximum or peak absolute response acceleration. An SRS curve shows the maximum positive and negative absolute response experienced by a single degree-of-freedom system as a function of its natural frequency. The SRS concept has been a very useful tool in pyro-structural design, because it provides a consistent way to compare different shock time histories.

In this study, we propose a non-destructive visualization method of linear explosive-induced pyroshock wave propagation based on a linear explosive-induced pyroshock prediction algorithm. A pyrotechnic device based on a linear explosive is used in CFRP sandwich panel, for real pyroshock measurements. The linear explosive-induced pyroshock is measured by three laser Doppler vibrometers (LDVs) in a noncontact manner. On the other hand, the laser shocks generated at three points by a Q-switched laser (QL) are measured by several accelerometers installed at intervals of 23 mm to describe the linear explosive in the same target structure. In laser shock measurement, various experimental conditions are explored to find the optimal conditions associated with the optical characteristics of the laser beam and the band-pass ranges of in-line and numerical filter. Then, the similarity between the different shock waves is evaluated on the basis of the mean acceleration difference (MAD, %) in their SRS curves. In addition, the propagation of the linear explosive-induced pyroshock wave is imaged.

2. Shock measurement technique and validation method

2.1. Linear explosive-induced pyroshock wave measurement setup

Figure 1 shows the experimental setup. The test structure was a carbon fiber-reinforced plastic (CFRP) sandwich panel with an aluminum honeycomb core. The specimen dimensions were 700 mm × 1140 mm × 12.68 mm and the thickness of both face sheets was 1.34 mm. Three laser Doppler vibrometers (LDVs) were used for noncontact acceleration measurement at Pts 1, 2, and 3 as shown in Fig1 (b).

![Figure 1](image)

Figure 1. (a) Overall experimental setup for the pyroshock measurement, (b) location of the linear explosive and the three LDV sensing points.

Shock generation and sensing points in pyroshock and laser shock experiments are summarized in Table 1. Each LDV head was set up on a tripod, and its laser beam was focused normal to the sensing point. Retro-reflective films were used at each sensing point to improve sensitivity. A pyrotechnic device with a linear explosive in a metal tube [6], which is generally used in stage and fairing separation systems, was installed with a steel mount at the bottom edge of the specimen, as shown in
the inset of Fig. 1(b). Two steel blocks were installed at both ends of the pyrotechnic device to protect against debris.

The bandwidth of interest for the pyroshock wave is generally up to 100 kHz; hence, the signals were filtered using a low-pass filter at 100 kHz by the respective controllers of the LDVs. Next, the signals acquired by a high-speed digitizer were stored at a sampling time interval of \( T = 0.72 \mu s \) and a signal length of \( p = 900,000 \) samples in a LabVIEW platform. The pyroshock signals for each sensing point plotted in the time domain is shown in Fig. 2.

Table 1. Shock generation and sensing points in pyroshock and laser shock experiments.

| Point | Coordinate (mm) | Pyroshock measurement | Laser shock measurement |
|-------|-----------------|-----------------------|-------------------------|
| 0     | (230–460, 0)    | Linear explosion       | Accelerometer array sensing |
| 1     | (350, 230)      |                       |                         |
| 2     | (350, 380)      | LDV sensing            | Laser shock              |
| 3     | (200, 380)      |                       |                         |

Figure 2. Pyroshock wave detected: (a) point 1, (b) point 2, and (c) point 3.

2.2. Evaluation of the pyroshock wave propagation direction

The propagation direction of the pyroshock wave formed by the linear explosive can be calculated by using arrival times of the maximum peaks of the measured pyroshock waves. LDV sensing points for the estimation of the speed and direction of wave propagation is shown in Fig. 1(b). The wave propagation direction can be estimated based on previous study [8] as shown in Eq. (1).

\[
\theta = \tan^{-1}\left(\frac{c \Delta t}{d}\right)
\]

Where, \( \Delta t \) is the difference in arrival time between Pt2 and Pt3. The arrival times of the maximum peaks of the measured pyroshock waves were 108,122, 108,135, and 108,179 \( \mu s \) at Pt1, Pt2, and Pt3, respectively. As a result, the wave propagation speed was calculated as 1217.53 m/s. In this case, the wave propagation direction was calculated as 19.57°. The pyroshock wave generation speed was estimated to be 3,700 m/s using the wave propagation direction and speed. Here, it turns out that the pyroshock wave generation speed is much smaller than the detonation speed of the used linear explosive, i.e., 7,030 m/s.

2.3. Laser-induced shock measurement

Figure 3 shows configuration of an experimental setup for laser shock wave measurement. The laser shock measurement system consist of a QL with 1064 nm wavelength, a QL controller, a galvanometric laser mirror scanner (LMS), a laser shock sensing system, and a computer with a LabVIEW platform for data acquisition and synchronization control. The laser shock sensing system
consists of an amplifier-integrated PZT accelerometer and an in-line signal conditioner with filters and amplifiers.

As shown in Fig. 3, the same specimen used was used for the laser shock wave measurement. In this reciprocal setup, the LDV sensing points are now laser shock points and the linear explosive is replaced by the accelerometer array, as summarized in Table 1. Laser shock waves generated at the three points were acquired by the PZT accelerometer array at the coordinate (230–460, 0).

The multiple accelerometer array employed to describe the linear explosive as a set of successive point sources is shown in the inset of Fig 3. Eleven accelerometers were attached at intervals of 23 mm on the bottom of the test structure.

The number of signals for temporal running averaging at each sensing point was set as 10, and the pulse repetition rate (PRR) was selected to be 1.25 Hz. Then, the measured laser-induced shocks were band-pass filtered between 100 Hz and 100 kHz, which was the frequency band of interest to be analyzed for SRS. The time delay was determined to be 6.33 µs. The resulted laser shock wave can be represented as follows:

\[
L(t) = \sum_{i=0}^{M-1} L_i (t + i\Delta\tau)
\]

Where, the measured laser shock wave at each sensing point is denoted as \(L_i\), \(i=0, 1, 2, \cdots, M-1\); \(L(t)\) is the result of the laser shock signal superposition with a time delay; and \(M\) is the number of sensors in the array.

**Table 2.** Optimized experimental conditions for prediction of SRS and time-domain signals.

| Laser beam condition | Beam size (cm²) | 0.21 |
|----------------------|----------------|------|
|                      | Energy (mJ)    | 0.72 |
|                      | Fluence (mJ/cm²) | 3.43 |
| Laser shock measurement condition | Pulse repetition frequency (PRF) | 1.25Hz |
|                      | Repetition measurement | 5 times |
|                      | In-line filter | BP: 100 Hz to 100 kHz |
|                      | Numerical filter | BP: 500 Hz to 70 kHz (Butterworth) |
|                      | Time delay (µs) | 6.33 |
2.4. Linear pyroshock reconstruction method

During the measurement of laser-induced shocks, laser beam conditions such as energy, size, and fluence were investigated based on the reconstruction process of the linear explosive-induced pyroshock. Then, the ranges of the in-line and numerical band-pass filters were explored to enhance the similarity of the laser shock wave to the real pyroshock wave. More detailed procedures about this process can be found in the previous study [7]. Optimal experimental conditions to generate laser shock waves similar to the pyroshock are summarized in Table 2.

Figure 4 shows SRS comparison between the conditioned laser SRS and the pyroshock SRS for Pt1–Pt3. The similarity between the SRS curves of the pyroshock and the conditioned laser shock is also quantitatively evaluated based on MAD [7].

The constant gain was found to be 249.5 g/mV and hence the average of MADs over the three points (Pt1–Pt3) was 33.09%. The average of MADs in training points, Pt1 and Pt2, was 33.64% and the conditioned laser SRS at verification point, Pt3, shows an MAD of 31.99%.

Figure 4. SRS comparison between the conditioned laser SRS and pyroshock SRS for the two training points, (a) Pt1 and (b) Pt2, and for one verification point, (c) Pt3.

3. Pyroshock wave propagation imaging results

The laser shock scanning was repeated ten times and averaged for each accelerometer position. Then, the measured laser shock signals were superimposed onto the result. As shown in the inset of Fig. 3 (a), the scan area and interval were 680 mm × 600 mm and 2.5 mm, respectively. Once these resulted signals were ready, constant gain was applied for all the scanned signals. With these converted signals, the linear explosive-induced pyroshock propagation wave can be visualized using the PWPI algorithm. Figure 5 show the freeze-frames of the PWPI generated at three different time delays, Δt = 3.2 and 6.33 μs. The wave propagation directions stand at 9.6°, and 19.6°, respectively. As a result, the more the time delay increases, i.e., when higher detonation speed explosives are used, the more the wave propagation angle increases. The wave propagation direction was determined to be 9.6° at the time delay of 3.2 μs corresponding to the pyroshock wave generation speed of 7,050 m/s, which should be a linear explosive with a higher detonation speed than the one used for the real pyroshock experiment.

Figure 5. PWPI snapshots: (a) Δt = 3.2 μs, (b) Δt = 6.33 μs
4. Conclusions
This paper shows a nondestructive visualization method of linear explosive-induced pyroshock wave propagation using superposition of point source array with a time delay realized by laser shock and multiple accelerometers. For the verification of the proposed testing method, a real pyroshock wave and a laser-induced shock wave were measured in the same CFRP sandwich panel. For the generation of the linear explosive-induced pyroshock, a linear explosive was used, and the pyroshock wave was measured simultaneously by three LDVs at three sensing points. From the measured pyroshock waves, the pyroshock wave generation and propagation speeds of the linear explosive were estimated to be 3,700 m/s and 1,217.53 m/s, respectively, and the wave propagation direction was calculated to be 19.57°. The laser-induced shock wave generated at each training point by the QL was measured by 11 accelerometers installed at intervals of 23 mm on the bottom of the test panel. The waves captured by the 11 accelerometers were superimposed with a time delay of 6.33 µs.

The laser-induced shocks were trained to improve the similarity of the laser shock wave to the real pyroshock wave by using the SRS prediction process. The average of MADs over the two training points (Pt1 and Pt2) was 33.64% and the MAD at the verification point (Pt3) was 31.99%. Next, this process was also applied to the laser shock waves at arbitrary points realized by the laser shock scanning. By applying the measured time delay of 6.33 µs to the PWPI algorithm for the linear explosive, a pyroshock wave propagation video could be generated and it showed a wave propagation angle of 19.57°, which was in agreement with the results of the real pyroshock measurement.

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