Small-Scale Experiments in Focusing of Shock Waves Using Timing Delays and Shadowgraphs

E.G. Morris and Aubrey Farmer
NAWCWD
China Lake, California, USA

1 Introduction

The purpose of this test series was to investigate the loading produced on a target by explosive charges fired on either side of a thick steel separator plate with timing delays and identify the potential of this methodology for shock focusing applications. The null hypothesis for this project posited no addition to the wave would be seen with the use of explosive charges fired on either side of a thick steel separator plate with timing delays.

2 Experimental Setup

The setup for this test series utilized two (2) explosive donor charges placed on opposite sides of a thick steel separator plate and fired with various timing delays. The donor charges used for this study were composed of Composition C-4, with a diameter of approximately 3.75 inches and weighing approximately 1 lb. each. Each donor charge was placed on a stand with the centerline at a height of 2 feet, at a distance of 6 inches on either side from the mild steel separator plate measuring 5'7" long and 5'4" feet tall, with a plate thickness of 2 inches.
Three (3) arrays of free-field blast pressure pencil probes (gauges), numbered 1 through 3, were placed at varying distances (3, 7.5, and 12 feet) from the charges. For comparisons measured values were assessed at the centerline gauge of the far measurement point, Array 3. Figure 1 provides a sketch of the overall setup, with the donor charges, separator plate, and arrays of pressure gauges. Timing delays were varied in increments of 1 to 5 milliseconds (ms).

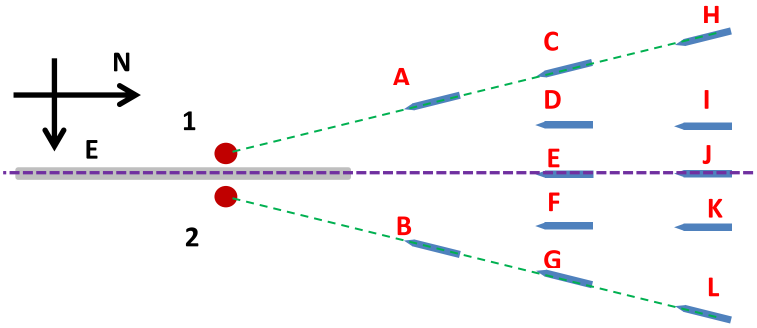

Figure 1. Sketch of Shock Focusing Test Setup

Correspondence to: Erin.G.Morris@navy.mil, Aubrey.Farmer@navy.mil

The arrays of blast pressure gauges were designed to provide quantitative pressure, impulse, and time-of-arrival data at varying target ranges. Exterior gauges were oriented toward the charge center of mass, while interior gauges were oriented orthogonal to the wave. All gauges were placed at heights equal to the centerline of the charges. A photo of the test setup, including the gauge arrays, separator plate, and high-speed photography setup is provided in Figure 2.

Figure 2. Photo of Shock Focusing Test Setup (Facing North)

A high-speed camera recording at 40,000 frames per second (fps), combined with a 150 watt LED light source with a collimating lens and 3M Scotchlite retro-reflective background was used for the shadowgraphy portion of each test. Figure 3 shows an example from a shadowgraph record, a still photo taken from the recording video.

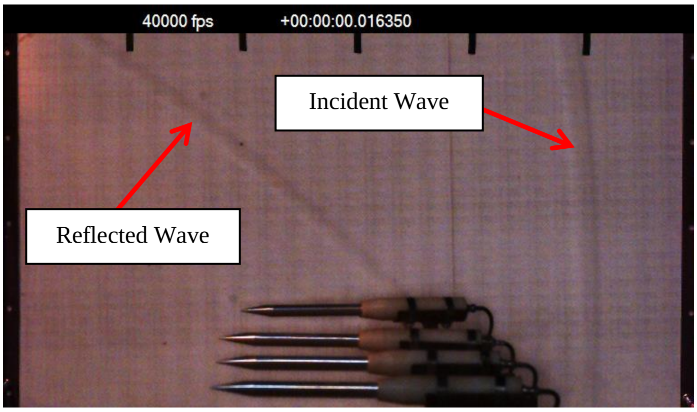

Figure 3. Shadowgraphy Still Photo from Shock Focusing Testing

3 Results

To test the null hypothesis, centerline gauge values for the far-field array, Array 3, were evaluated. Overpressure, impulse, and wave velocity values were compared between the baseline test (dual charges initiated simultaneously on either side of the thick steel separator plate) and each of the timing delay tests.

Table 1 provides a comparison of overpressure, impulse, and wave velocities produced by the baseline and each of the timing delays tests at the far (Array 3) measurement point. Values in green represent timing delays which produced values exceeding the baseline, values in blue represent recovery of 95% or greater of the baseline value.

Table 1: Measured Overpressure, Impulse, and Wave Velocity – Array 3

Array 3 - Gauge J	Peak Overpressure (psi)	Peak Impulse (psi-ms)	Wave Velocity (ft/s)
Baseline (Dual Charge)	9.23	11.00	1675
3 ms	8.40	13.97	1697
5 ms	6.65	12.61	1517
7 ms	5.56	12.86	1552
9 ms	6.57	9.77	1568
10 ms	7.25	10.93	1509
11 ms	7.01	9.32	1576
12 ms	7.44	8.44	1594
15 ms	6.13	12.34	1449
17 ms	5.80	13.29	1511

No direct addition to overpressure was observed from any of the timing delays. A very short timing delay of 3 ms produced 91% of the baseline overpressure. Increasing timing delays produced decreasing overpressure up to moderate timing delays of 10 to 12 ms, where recovery of up to 80% of the baseline overpressure was observed.

At the far measurement point (Array 3), a very short timing delay of 3 ms produced an increased wave velocity; i.e. a very short timing delay did add to the wave velocity.

The most significant differences were seen for peak impulse values. Figure 4 presents a visual representation of the comparative impulses produced by the baseline and each of the timing delays tests at the far (Array 3) measurement point.

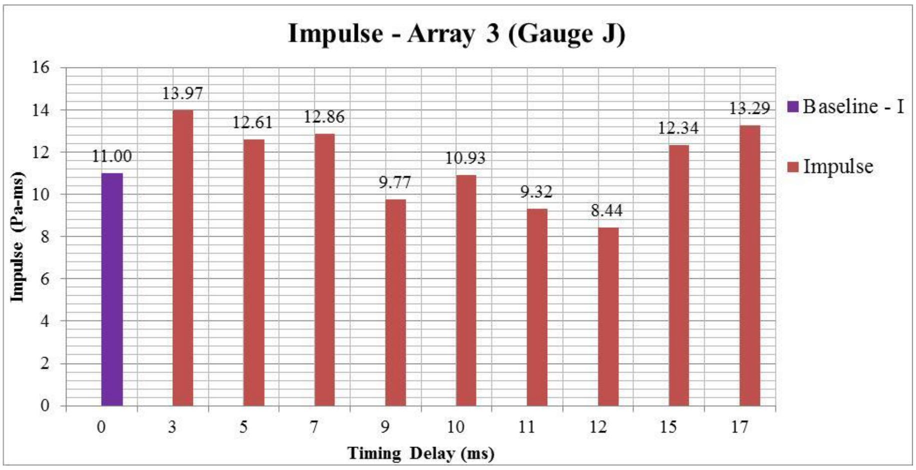

Figure 4. Measured Impulse – Array 3

At the far measurement point (Array 3), timing delays of 3, 5, 7, 15, and 17 ms produced increased impulse; i.e. the short and long timing delays added impulse to the wave. The greatest increase of impulse was achieved at the very short timing delay of 3 ms.

Measured values for baseline tests were compared with predicted values from scaling data developed by G.F. Kinney[2]. The baseline test was conducted using the full test setup, with a single 1 lb. charge placed on one side of the steel separator plate. Predicted values from Kinney's scaling data were based on a single 1 lb. charge in free-air. Variation between predicted and measured values was expected due to the additional reflective surfaces introduced in the full test setup. Table 2 presents the Kinney predicted values and measured values at the far measurement point (Array 3) for a 1 lb. charge baseline test.

Table 2: Kinney Predicted and Measured Values – 1 lb. Charge Calibration Test

Timing Delay (ms)	**Kinney Predicted Value**	**Measured Value**
Peak Overpressure (psi)	5.06	5.76
Peak Impulse (psi-ms)	3.75	6.90
Time-of-Arrival (ms)	5.310	5.347
Wave Velocity (ft/s)	1995	1476

Peak overpressure values showed relative agreement with the Kinney predicted values, a percent error of approximately 14%. Peak impulse values showed significant variance, with measured values registering 1.8 times the predicted value. Time-of-arrival (ToA) values demonstrated very good agreement with the Kinney predicted values, a percent error of approximately 1%. Wave velocity values also showed significant variance from the predicted values, with a measured wave velocity approximately 73% of the predicted wave velocity, a percent error of approximately 26%.

4 Shadowgraphy

The shadowgraphy setup was aligned perpendicular to the far measurement point (Array 3) to visualize wave behavior. With the introduction of a timing delay between the two charges, the second incident wave was expected to arrive at the gauges at a time approximately equal to the timing delay. Shadowgraph records were analyzed using a set location (gauge farthest from the camera) to evaluate the arrival times of the first and second incident waves for each timing delay. Incident waves were selected for analysis due to the complex reflections created in the test environment.
It was observed that the time between arrival of the first and second incident waves increased asymptotically for each successive timing delay. Short, moderate, and long timing delays are included in Table 3 to illustrate this behavior.

Table 3: Time Between Incident Wave Arrivals and Proportion of Timing Delay

Timing Delay (ms)	**Time Between Arrival of Incident Wave 1 and Wave 2 (ms)**	**Proportion of Timing Delay**
3	1.875	62.5%
7	6.075	86.8%
10	7.175	91.8%
12	11.050	92.1%
17	16.200	95.3%

A very short timing delay of 3 ms produced increased impulse and wave velocity compared to the baseline dual charge. Shadowgraph records for the 3 ms delay are presented in Figure 6.

Figure 5. Shadowgraph Records, 3 ms Timing Delay

Waves from both charges are visible in the shadowgraph records, with the wave from the second charge arriving at the gauges approximately 1.8 ms after the first wave. The significantly reduced time between incident waves compared to the timing delay indicates the wave is moving faster than would be expected. This supports the measured data, indicating the 3 ms delay produced an addition to the wave. The 3 ms shadowgraph results also lend evidence toward a theory posited by Robert G.S. Sewell[6] that the second blast wave could potentially accelerate through the vacuum created by the first blast wave, effectively "catching up" so that both waves strike a target at the same time, increasing the load on the target. Additional testing at very short (< 3 ms) timing delays is required to further investigate this theory.

5 Conclusions

The null hypothesis was refuted; the use of timing delays produced additions to the blast wave compared with the baseline test of charges detonated simultaneously on either side of a thick steel separator plate.

Increased impulse loading and increased wave velocities were observed on a target at the far measurement point (Array 3) with timing delays. The optimum delay found in this test series was 3 ms. This very short timing delay provided the greatest increase in both impulse and wave velocity, along with recovery of approximately 91% of the baseline overpressure.

The time between arrival of the first and second incident waves was observed to increase asymptotically for each successive timing delay, with the wave arrivals ranging from 62.5% of the timing delay for the shortest (3 ms) delay tested to 95.3% of the timing delay for the longest (17 ms) delay tested.

The significantly reduced time between incident waves compared to the timing delay observed for the 3 ms test indicated the wave moving faster than would be expected. These observations supported the measured data; demonstrating the 3 ms timing delay produced an addition to the wave.

Though limited in scope, the methodology employed in this test series demonstrated a potential for shock focusing applications. The shadowgraph records provided qualitative evidence toward supporting Sewell's theory that a second blast wave could potentially accelerate through the vacuum created by an initial blast wave. The "catching up" portion of Sewell's theory was not observed in this instance; further investigation of focusing of shock waves using very short (< 3 ms) timing delays would be worthwhile.

References

[1] Kinney G, Graham K. (1985). Explosive Shocks in Air. Springer (ISBN 3-540-15147-8)

[2] Kinney G.F. (1968). Engineering Elements of Explosions. Naval Postgraduate School. Technical Paper NWC TP 4654.

[3] Nelson R, Morris B, McGarvey J. (1970). Shock-wave Focusing Studies. Science and Technology Laboratory Research and Engineering Directorate, U.S. Army Weapons Command. Technical Report RE-70-169.

[4] Grönig H. (1986). Shock Wave Focusing Phenomena. Proceedings of the 15th International Symposium on Shock Waves and Shock Tubes: 43.

[5] Settles, G.S. (2001). Schlieren and Shadowgraph Techniques, Visualizing Phenomena in Transparent Media. Springer-Verlag (ISBN 3-540-66155-7).

[6] Sewell, Robert G.S. Personal communications. August 2014.