

FULL-SCALE SCHLIEREN IMAGING OF SHOCK WAVES FOR AVIATION SECURITY RESEARCH

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Abstract

A multi-flash light source and a large-scale, lens-and-grid-type schlieren system have been used to image shock wave motion generated by small explosions in scenarios representative of terrorist bombings of commercial jetliners. It was demonstrated that even very weak explosions, producing shock waves only marginally faster than the acoustic speed, could be made visible. Stronger shocks due to a few grams of explosive mixture were found to travel at Mach numbers up to 1.2, and thus to have overpressures up to about 1/2 atmosphere. The utility of such explosions to study shock motion in an aircraft cabin has been demonstrated qualitatively by imaging the shock waves due to explosions underneath full-sized aircraft seats. This approach may be of value in aircraft hardening studies for several reasons, including the fact that it provides a physical picture of the phenomenon, it can provide useful quantitative optical data to supplement pointwise pressure sensors, and it can be used to check the accuracy of numerical predictions.

1 Introduction

The rise in worldwide terrorism, especially directed at commercial air transportation, has made it imperative that measures be implemented to harden aircraft against catastrophic in-flight failure due to concealed explosives. The Pan Am

103 disaster has shown that the modern terrorist is sophisticated enough to obtain and use plastic explosives, a small amount of which may be sufficient to bring down an aircraft, and which are very difficult to detect. Accordingly, research directed at making commercial jet airframes and baggage containers less vulnerable to such explosive sabotage has been carried out for several years by the US Federal Aviation Agency and others [1].

The investigation of Pan Am 103 [2] revealed the key role of blast overpressure and shock wave propagation in the disintegration of the aircraft within seconds of the explosion, yet the actual gas dynamics of such an explosion onboard an aircraft is still poorly understood. The more-recent loss of TWA Flight 800 from an onboard explosion (now believed to be accidental) is also poorly understood. Numerical simulation of the blast wave is feasible [3], but coupled gas- and structural-dynamics solutions simulating blast damage are extremely difficult and complicated [4,5].

Full-scale experiments have also been conducted on both baggage containers and airframes [6,7]. These experiments tend to be very expensive. Also, unfortunately, the pointwise instrumentation used in some of these (e. g. individual pressure transducers at various distances from the explosion center) are sparse and not very revealing of the key flowfield phenomena [3]. Small-scale experiments on blast effects, e. g. inside shock tubes, also have their precedents and their limitations [3, 8, 9].

The present work describes an intermediate approach which combines a reasonably-large scale with the principal experimental tool for the study of blast wave propagation: *optical imaging* [10].

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This tool was previously available mainly in small-scale experiments and has yet to be applied at all to aviation security problems.

The very existence of shock waves from explosions and supersonic projectiles was originally a matter of conjecture until Toepler [11] and Mach and Salcher [12] observed actual shock waves, thus removing all doubt. These observations were made using the schlieren technique, which is to this day (along with shadowgraphy and the occasional interferogram) the premier experimental tool for the observation and analysis of explosions, detonations and ballistics.

The optical visualization of shock wave motion yields both a physical picture of the explosive

event and, with a proper multi-flash light source, quantitative data of shock position vs. time. Once the shock speed and thus its Mach number are known, all flow properties behind the shock are available from the Rankine-Hugoniot theory of gas dynamics [13].

The application of this optical technology to aviation security issues does not necessarily require the expense of full scale, but a reasonably-large scale is needed if the complex geometry of the problem is to be well-represented. Penn State's full-scale schlieren flow visualization system was built for such purposes.

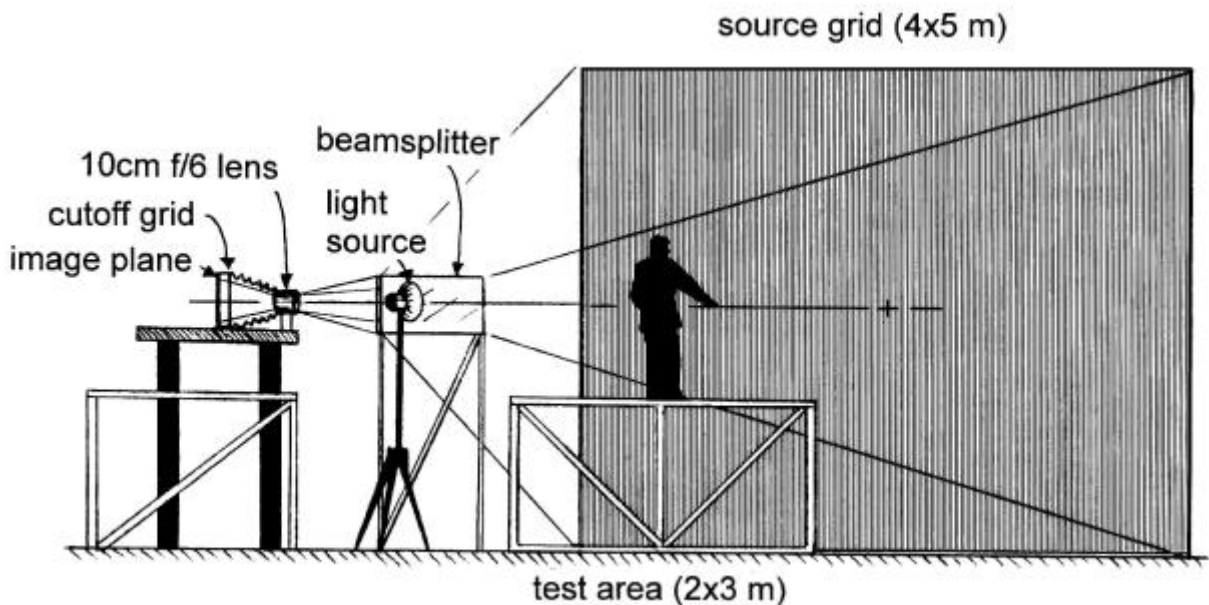


Figure 1. The Penn State Full-Scale Schlieren Facility

2 Experimental Methods

2.1 Full-Scale Schlieren Facility

It first became clear to present investigators [14] in 1993 that it was feasible, given a building of sufficient size, to construct the largest indoor schlieren system in the world. This instrument is based on the lens-and-grid principle first stated by Schardin [15], and recently brought to fruition by Weinstein [16]. The initial challenge, finding suitable housing, was met by obtaining the use of a

university warehouse formerly used for fruit storage. As shown in Figure 1, the schlieren system we designed uses a large front-lit retroreflective source grid mounted against one wall of the building. A beamsplitter is used to fold the optical axis parallel to the opposite wall. A 10 cm diameter f/6 flat-field aerial camera lens produces a cutoff grid size of 20x25 cm (8"x10") and an image plane of about the same size (dictated by the maximum available size of photographic film). The maximum test area is a rectangle 2.1 m high

by 2.67 m wide, or about 7x9 feet. The source grid is made of white 3M retroreflective highway-sign material mounted to aluminum panels which are assembled on a frame. Upon the retroreflective material are silkscreened 5.08 mm (0.2 inch)-wide vertical black gridlines spaced 5.08 mm apart.

The test area lies midway between the source grid and lens, is centered 2.4 m above the concrete floor, and has roughly a 1.2 m depth-of-field. The schlieren image is currently either observed on a ground-glass screen with continuous lighting or flash-photographed using a Polaroid 20 x 25 cm (8x10 inch) film back. Videography is also done with the aid of a Fresnel lens. The image resolution is estimated to be 1.5 mm in the test area, yielding razor-sharp large-format photographs. However, such exposures on 8x10 film require more than 100 J flash energy, which is not available at the microsecond-range exposures required for present purposes.

2.1.1 Camera and Film

The 8x10 film back was thus replaced by a 34 cm focal length Fresnel lens and a Pentax 6x7 medium-format camera with a 106 mm lens. Photography used either ISO 3000 Polaroid film in a Pentax/Polaroid back or ISO 3200 color negative film in a 120 film back. In all cases, photos were taken in the darkened laboratory with the camera shutter held open during the explosive event.

2.1.2 Flash Illumination

For present purposes the source grid was illuminated by a Viewstar, Inc. Model 955-5 high-speed triple-flash light source (similar to that described in [17]). Each Xenon flashtube discharged 5-10 Joules in about 5 μ sec through dichroic color filters designed to separate the three flashes via red, blue, and green exposures on a single color photograph. A microphone placed at variable distance from the explosion center was used to provide the electronic trigger signal for the first flash. Time delays for the second and third flashes were adjustable so as to position the successive shock wave images conveniently upon the film. A PIN diode picked up the illumination from the explosion in order to trigger the trace of a Nicolet

digital oscilloscope. A second PIN diode then fed a signal to the oscilloscope, recording the light output of the three subsequent Viewstar flashes. In cases where only a single illuminating flash was desired, the second and third flashes of the Viewstar flashlamp were disabled and the color filter pack was removed.

2.2 Data Reduction

An explosion experiment thus resulted in a single photograph with 3 separate shock wave images in 3 colors and an oscilloscope trace from which the timing of the illuminating flashes could be read. The distance from the explosion center in the image plane was calibrated by way of a meter stick imaged in a tare photo. It was then possible to extract shock wave radii R_1 , R_2 , and R_3 and correlate them with measured flash times t_1 , t_2 , and t_3 after blast initiation. The geometrical correction for non-perpendicularity recommended by Dewey [10] was computed, but was found not to be significant here. For spherical shocks, this procedure yielded three data points of shock velocity $V_i = R_i/t_i$ from each test. (Much more data could be extracted, in principle, from complex experiments involving multiple shock reflections, but such experiments have yet to be performed.)

2.3 Explosives

Since we lack a qualified explosion-proof test facility, current tests were limited to comparatively-small charges, i.e. far smaller than the kg-range high-explosive charges believed to have been used in known incidents of aviation terrorism. Present tests are meant to demonstrate an approach that can later be used, for example, at an explosive test range, to produce images of shock motion in an aircraft setting at realistic scale, and to examine the validity of scaling concepts.

The experiments began with common consumer fireworks of the "penny firecracker" variety, which can be purchased in unlimited quantity at roadside stands in the US. These were found to contain about 0.03 gram of an unknown explosive mixture. They are ignited by a crude fuse and are rather unreliable. Later experiments involved 5-12 gram custom-made charges packed in card-

board cylinders and ignited by an electrically-heated wire. The explosive mixture composition was 50% Potassium perchlorate, 8% Sulfur, and 42% Antimony trioxide by weight. In some tests the latter ingredient was replaced by Aluminum powder, which produced more energy output and a much brighter flash. Some masking or blockage of the direct light was employed in these cases in order to avoid fogging of the film.

3 Results and Discussion

3.1 Fireworks

Despite the drawbacks of the “penny firecrackers,” they produced visible shock waves in our Full-Scale Schlieren facility. A black-and-white single-flash example is shown in Figure 2, with one of us (JDM) standing nearby to lend a sense of scale. The rising turbulence is heat released from the burning fuse prior to the explosion.

Such tiny blasts are innocuous except for requiring ear protection, but Figure 2 nonetheless reveals a realistic primary spherical shock and even the “2nd shock” phenomenon, a characteristic of a blast from an extended source [13,18].



Figure 2. Single-Exposure Schlieren Image of Spherical Shock Wave from “Penny Firecracker”

Triple-flash photos and subsequent data analysis revealed shock Mach numbers in the range of 1.05 decaying to 1.02 within the schlieren field-

of-view. Thus these shock waves – though visible – are only marginally stronger than sound waves. An example color triple-flash image is shown in Figure 3 (note the outermost shock image, nominally in green, is very weak).

3.2 5-Gram Charges

Stronger shock waves were desired, so 5-gram charges with the composition described above were used. Personnel safety was insured by eye and ear protection and appropriate distance from the explosion, though the only difficulty concerned the smoke produced by the explosion. A black-and-white triple-flash example is shown in Figure 4, revealing three spherical shock images. The time delays $\Delta t_{1,2}$ and $\Delta t_{2,3}$ between flashes in cases like this were set to about 400-450 μsec each. Note that direct light from the explosion exposes a portion of the film over a period much longer than the 5 μsec flash duration.



Figure 3. Color Triple-Flash Image of Spherical Shock Wave from “Penny Firecracker”

Analysis of 3 such triple-flash schlieren images from 3 separate explosions yields the shock R vs. t data shown in Figure 5. Also shown in the Figure are R - t curves representing a sound wave ($R = a \cdot t$ where a is the acoustic speed) and a “strong shock” with $p_2 \gg p_1$, where the Rankine-Hugoniot relations take a simplified form leading to the famous similarity law $R \propto t^{2/5}$ [19, 20]. The present data lie much closer to the sound wave limit than

to the strong shock limit, since the shock Mach numbers are only in the range of 1.1-1.2. In that the maximum static pressure rise across these shocks is only about 1/2 atmosphere, they clearly fail to qualify for $R \propto t^{2/5}$ similarity based on the assumption of an intense instantaneous point air-blast. In fact, curvefits show these data to agree instead with the relationship $R \propto t^{4/5}$, which is consistent with Glass's [13] discussion of shock waves too weak to satisfy strong-shock similarity. Note that the three shock experiments represented in Figure 5 do not fall on the same curve, indicating that the energy release varied somewhat from one explosion to the next.

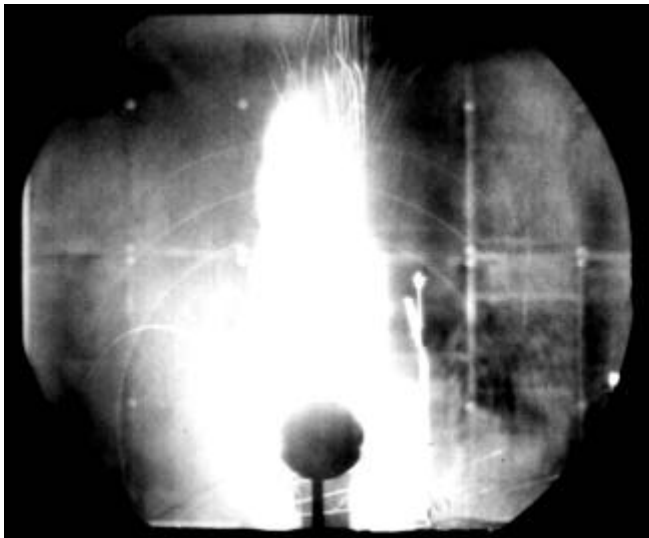


Figure 4. Triple-Flash Schlieren Image of Shock due to 5-gram Explosive Charge (Width of Frame is about 2.5 m)

The explosive charges used here produce less than 1% of the energy of the terrorist bomb responsible for the loss of Pan Am 103. Significant plastic explosive charges would be expected to satisfy the mentioned strong-shock criterion initially. Thus any aircraft-hardening simulations using small charges like those used here will encounter differences in scaling behavior. Briefly, since the $R \propto t^{2/5}$ similarity fails for such small charges, recourse to numerical solutions of the governing equations is required in order to predict shock overpressures [13]. Such solutions are not difficult, however, using modern computers.

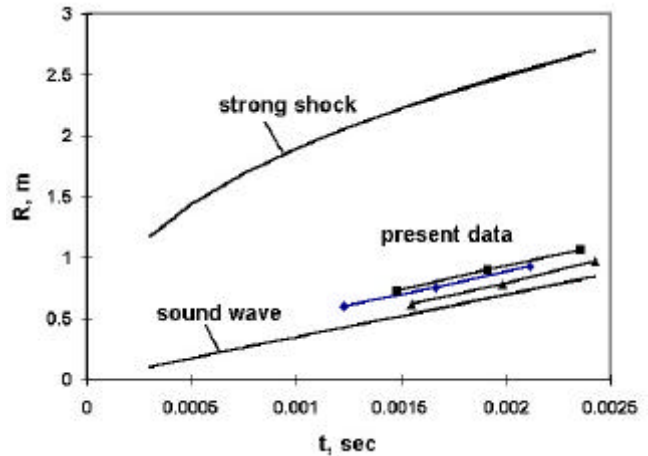


Figure 5. Shock Wave R-t Data from Three Different 5-gram Explosive Charges

On the other hand, the visibility of even very weak shocks in the present study holds promise that stronger blasts can be similarly imaged in blast-proof facilities or outdoor ranges without difficulty. Such results could have been obtained previously using normal-sized optical components, but not on the 2x3 meter scale of the schlieren system used here. The only other known large-scale examples of shock imaging from explosions are Edgerton's [21] Scotchlite shadowgraph and outdoor blasts where the shock is naturally visible by optical radiation [19], the refraction of a distant light-dark boundary [10], or the "sunlight shadowgraph" effect [22].

3.3 Explosions Beneath Aircraft Seats

To test a plan for a massive attack on US air transportation, Muslim terrorists smuggled bomb components aboard a jetliner, assembled the bomb in the restroom, then planted it beneath a seat. The subsequent explosion killed the innocent passenger sitting there. Fortunately the full-scale attack, "Project Bojinka," was thwarted. Baum, et al. [5] numerically simulated such an explosion in the first-class section of a Boeing 747. Results showed very complex shock wave diffraction, reverberation, and focusing as the blast interacted with the seats and cabin walls. It is known that shock wave coalescence and focusing can lead to significant amplification of the peak overpressure [23]. However, a comparative experiment to the computation of Baum et al. has never been performed.

As a first step in that direction, actual jetliner seats were obtained and placed in the test area of our Full-Scale Schlieren facility in order to simulate an aircraft cabin environment. 12-gram charges of the explosive mixture described earlier were detonated behind or beneath the aisle seat in order to visualize the generation and interaction of the blast wave. Since qualitative visualization rather than quantitative measurement was the goal, only a single 5 μ sec flash was used for schlieren illumination. The seats were also front-lit by a studio flash of longer duration. The seats were also front-lit by a studio flash of longer duration. Two resulting images are shown in Figures 6 and 7.

In Figure 6 the explosive was placed behind the aisle seat at the tray-table level. The spherical primary and secondary shock fronts are clearly visible. Most of the direct light from the explosion was masked by the seat back in this example.

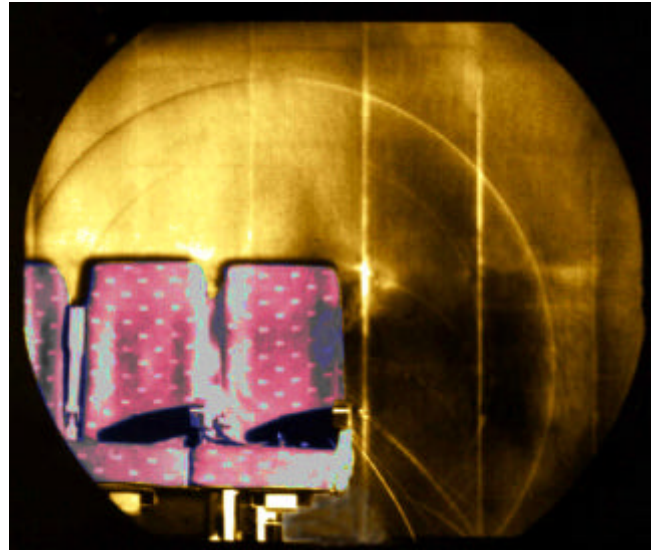


Figure 6. Single-Flash Schlieren Image of Shock from Explosion Behind Aircraft Seat

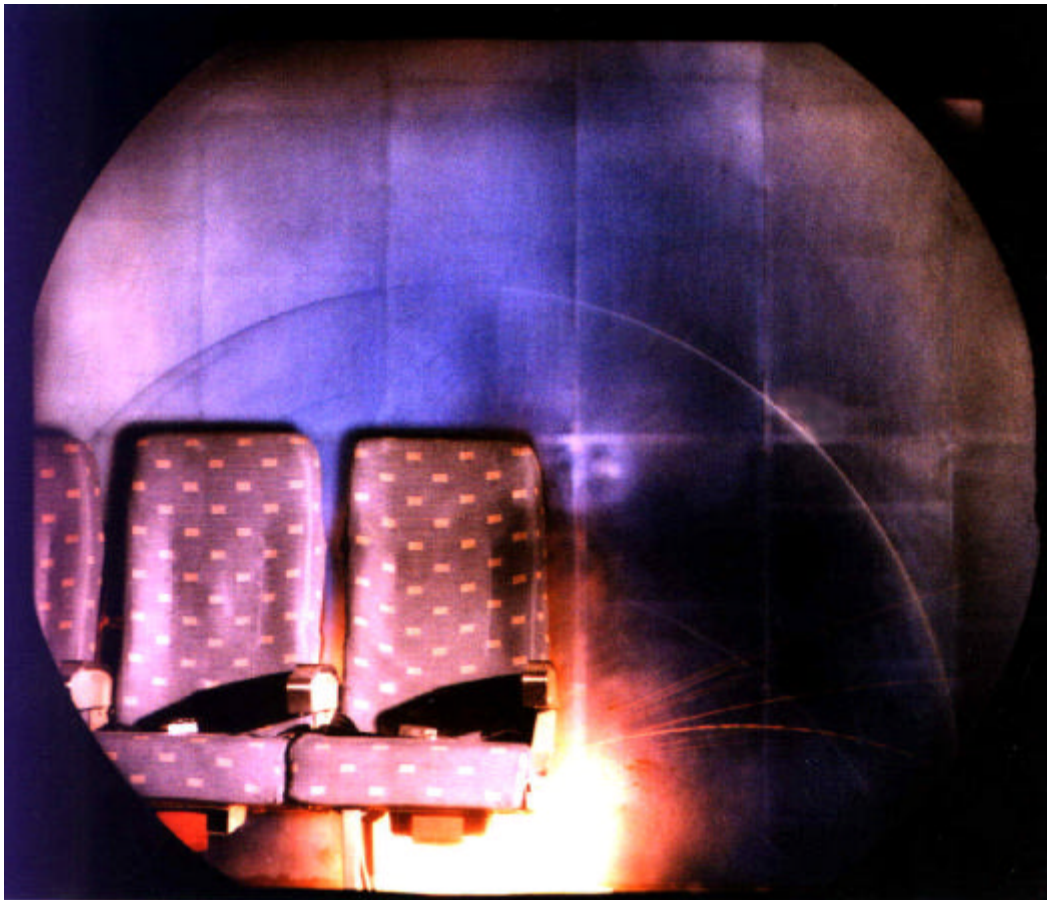


Figure 7. Single-Flash Schlieren Image of Shock from Explosion Underneath Aircraft Seat

Figure 7 shows the case of an explosion beneath the aisle seat in the carry-on luggage space. Again the visible wavefront is still spherical at this early stage. Direct light from the blast is seen underneath the seat. In this case of an explosion on a ground plane, it is known [8] that the reflected shock wave coalesces with the primary shock, boosting the resulting shock strength to about twice that of the primary shock alone. Such results as Figures 6 and 7 demonstrate that experimental verification of numerical results and studies of shock motion in a realistic aircraft cabin environment are feasible by way of the approach described here.

4 Observations and Conclusions

A multi-flash light source and a large-scale, lens-and-grid-type schlieren system have been used to image shock wave motion generated by small explosions in scenarios representative of terrorist bombings of commercial jetliners. It was demonstrated that even very weak explosions, producing shock waves only marginally faster than the acoustic speed, could be made visible. Stronger shocks due to a few grams of explosive mixture were found to travel at Mach numbers up to 1.2, and thus to have overpressures up to about $\frac{1}{2}$ atmosphere. However, these are still weak shock waves, far from satisfying the criteria for intense airblast similarity. The use of such small explosions to study shock motion in an aircraft cabin has been demonstrated qualitatively by imaging the shock waves due to explosions underneath full-sized aircraft seats. The results obtained here are expected to be of value in aircraft hardening studies for a variety of reasons, including the fact that they provide useful quantitative optical data to supplement pointwise pressure sensors, they provide a physical picture of the phenomenon, and they can be used to check the accuracy of numerical predictions. The effects of shock wave focusing and concentration inside a baggage container or an aircraft cabin are of special interest due to their implications for structural failure.

Future work includes taking high-speed “movies” of explosive tests like those described here.

A drum camera or digital camera is required to meet the need for a framing rate in the 100,000 frames/sec range. These frames must then be assembled into a “movie” after the fact.

5 Acknowledgments

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