High-speed digital shadowgraphy of shock waves from explosions and gunshots

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1 Introduction

Shadowgraph and schlieren methods [1] have served to image shock waves for almost 150 years, but the traditional field-of-view of these instruments is often too small for large-scale experiments. On the other hand, optical methods to reveal shock waves in the field (e.g. background distortion and sunlight shadowgraphy) are often crude and weather-dependent. Between these extremes lie some useful but little-used optical approaches for large fields-of-view, two of which are exemplified here.

Shadowgraphy was invented by Robert Hooke around 1672, though centuries went by before it was first applied to ballistics. Toepler, Mach, and C. V. Boys used open electric sparks to illuminate high-speed physics over 100 years ago, and Boys published the first spark-shadowgram photo of a bullet in flight [2]. Cranz and Schardin introduced "focused" shadowgraphy as part of their famous multi-spark high-speed camera [3], and H. E. Edgerton of strobe-lamp fame demonstrated in 1958 a simple and elegant direct-shadow technique for large-scale explosions using a retroreflective screen [4] [5]. The intervening years saw many applications of "focused" shadowgraphy but few of Edgerton's retroreflective-screen technique − henceforth called *Edgerton shadowgraphy* − except in ballistics and helicopter-rotor testing [6] [7].

The "focused" shadowgraph technique differs from direct shadowgraphy in that it produces an optical image by way of a focusing lens, rather than simply projecting a mere shadow. The focusing lens brings the test field into more-or-less sharp focus, for example, on the sensor plane of a camera. This technique is often used in ballistics, where the sensitivity of schlieren is not needed while the robustness of shadowgraphy is required. However, its name has caused controversy since, by definition, the shadowgraph effect disappears in a sharply-focused image [1]. In fact, "focused" shadowgrams are seldom sharply focused, though we will explore that topic further here. "Almost-focused" or "poorly-focused" shadowgraphy better describes the actual case.

Why continue to develop a technique that is so simple and so old as shadowgraphy? Because it is ubiquitous in its utility and, amazingly, it has yet to reach its full potential. The simplest of all the optical flow diagnostics, shadowgraphy is also the best for imaging shock waves. It reveals shock waves clearly while de-emphasizing other, less-abrupt flow features [1]. Yet there is still a need for robust large-scale shadowgraph methods for outdoor testing and explosive events. The most recent development in shadowgraphy is the replacement of the rather-painful traditional high-speed photographic methods by digital imaging, which lends simplicity to high-speed shadowgraphy, promotes quantitative as well as the traditional qualitative analyses, and yields both high-resolution still images and high-speed videography at lower (but still usable) resolution.

The goal of this paper is to combine modern high-speed videography with Edgerton and "focused" shadowgraphy in order to explore the shock waves generated by laboratory-scale explosions and the discharge of firearms. Allotted space permits only a fraction of these results to be shown, but see also [5], [8], and [9], some or all of which are downloadable from `http://www.mne.psu.edu/PSGDL/publicationswebpage.html`.

2 Experimental Methods

2.1 Z-type focused shadowgraph system

Our z-type focused shadowgraph setup is identical to a z-type schlieren system without a knife edge cutoff, as shown in Figure 1. It consists of twin $0.76m$-diameter f/5 schlieren-quality parabolic mirrors, a $1kW$ Oriel xenon arc lamp, and a high-speed digital camera. The focusing ability of these optics is put to good use in what follows. However, this setup requires two expensive, heavy, fragile glass parabolas that make it unsuitable for large-scale outdoor applications.

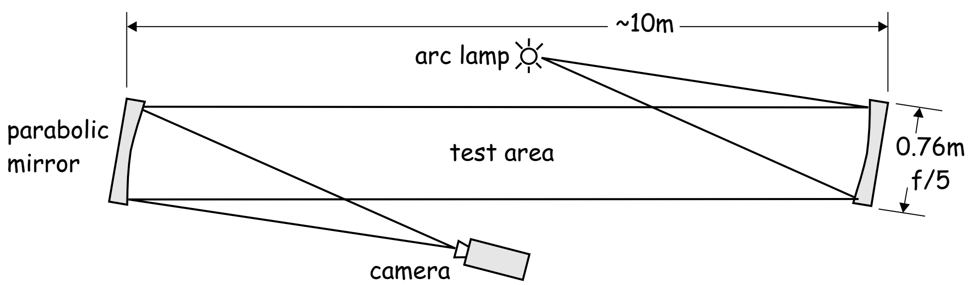

Fig. 1. Z-type focused shadowgraph system, top view

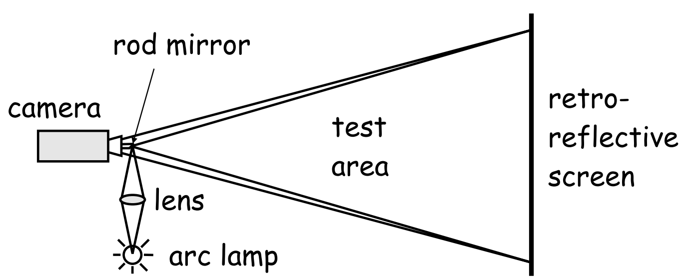

Fig. 2. Edgerton retroreflective shadowgraph system, top view

2.2 Edgerton retroreflective shadowgraph system

Our Edgerton shadowgraph setup, Figure 2, is distinct in several ways from the z-type approach. Its simplicity, robustness, and ease of use make it appealing for large-scale and even outdoor applications, e.g. [9]. It consists only of a retroreflective screen, high-speed digital camera, and $1kW$ Oriel xenon arc lamp, the latter two components being conveniently mounted on a small optical breadboard. However, the Edgerton shadowgraph cannot be focused and is not capable of the previous system's razor-sharp results.

The slight double-imaging inherent in Edgerton's original setup [4] was avoided by fitting the camera lens with a clear filter having a centered 45^o rod mirror to direct the illuminating beam toward the screen without seriously blocking the coincident reflected light. The retroreflective screen is made of 3M Scotchlite^{TM} 7610, a high gain, industrial grade, exposed-lens, plastic-based material pre-coated with a pressure-sensitive adhesive. Screens made of this material can be provided by an industrial supplier [10]. The present screen is $2.4m$ square and cost about $4000US, but we also have a $4.9m$ square screen that provides a $2.4m$ square test area [9].

More detail and setup images of the Edgerton shadowgraph are provided in [5], and are thus omitted here due to space limitations.

2.3 Photron APX-RS high-speed digital camera

Serving both shadowgraph systems is a Photron APX-RS digital video camera. Its CMOS image sensor provides 1024x1024 (i.e. 1 Mb) frame resolution at frame rates up to 3000/s. It can record at 10,000 frames/s with 512x512 pixel resolution and is capable of 250,000 frames/s at further-reduced image size. Frame exposure is independently controllable down to 1 μs, the value used here. A fiber-optic link connects the APX-RS to its controlling laptop computer, upon which the results are viewed. The camera acquires 18 Gb of image data in 6 real-time seconds of memory. Rapid events thus require no triggering, since the camera records continuously and overwrites its memory until stopped. Results are immediately available for viewing. The camera is rated for a 100g shock and has survived powerful explosions at close range [9]. Similar cameras are available from other manufacturers, e.g. the Vision Research Phantom camera. Compared to the now-obsolete high-speed photographic cameras, these modern digital wonders can be operated by anyone after a few minutes training.

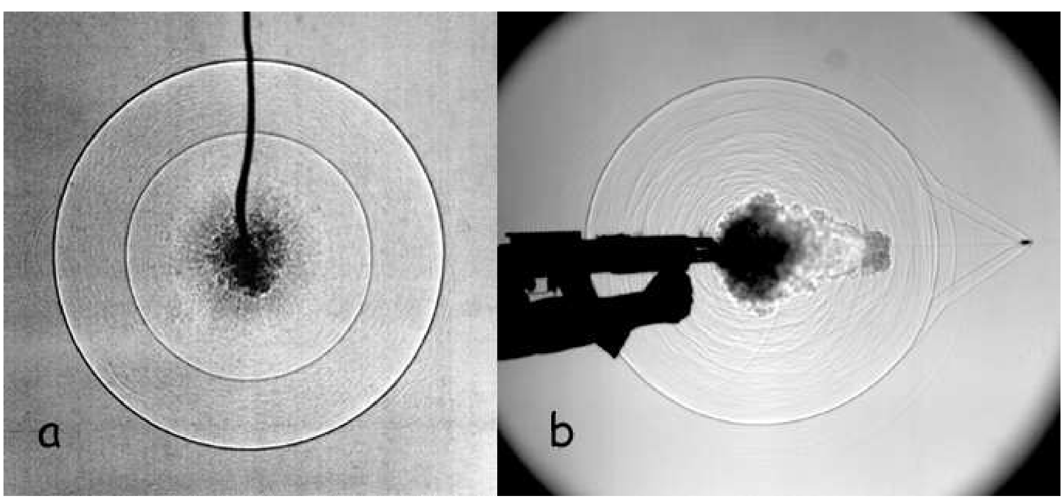

Fig. 3. Edgerton shadowgrams from [5], **a** the explosion of $1g$ of TATP, revealing primary and secondary shock waves, **b** firing the infamous AK-47 submachine gun in single-shot mode

3 Results and discussion

In our previous work along similar lines [5], gram-range explosives and the discharge of several firearms were imaged by Edgerton shadowgraphy. Two examples from this earlier work are reproduced in Figure 3.

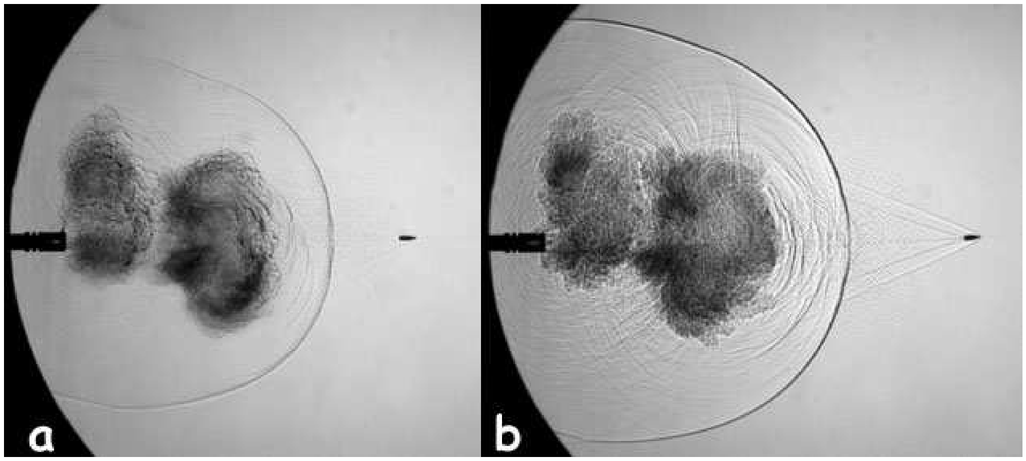

Fig. 4. "Focused" shadowgrams of .223 automatic rifle fire, **a** sharply focused, **b** defocused $1m$

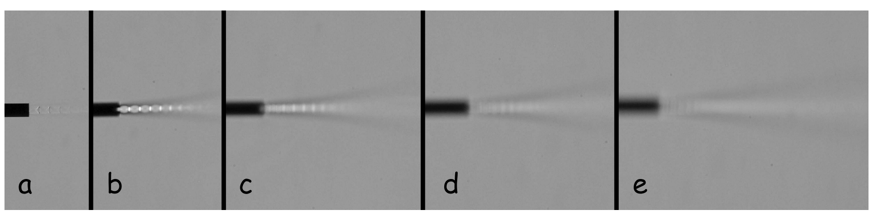

Fig. 5. Effect of defocusing on a small jet of 1,1,1,2-tetrafluoroethane in air, **a** sharply focused, **b** defocused $0.25m$, **c** defocused $0.50m$, **d** defocused $0.75m$, **e** defocused $1.0m$

3.1 Z-type focused shadowgraph results

Theoretical considerations notwithstanding, strong shock wave shadows are visible with this optical system even when sharply focused, as illustrated in Figure 4a. The muzzle blast of the automatic rifle clearly has sufficient lateral extent to be visible even when the muzzle is in sharp focus. However, many weaker flowfield features only appear upon defocusing, Figure 4b. To understand this, refer to Sec. 6.2.2 of [1]: The shadowgraph sensitivity is proportional to the defocus distance times the Laplacian of the refractive index, e.g. $\partial^2 n/\partial y^2$. The size of the arc-lamp source is about $3mm$ compared to the $3.8m$ mirror focal length, yielding a depth-of-field of about $1m$ within which to resolve features $1mm$ or larger. We observed a $1mm$-diameter jet of "dust-off" gas (1,1,1,2-tetrafluoroethane) across the optical axis in order to focus the shadowgram image. As shown in Figure 5, this jet is almost invisible when sharply focused, but its shock diamonds are clear when defocused $0.25m$, where there is finite sensitivity but the blur is only $0.25mm$. However, when defocused $1m$ the blur defeats the shadowgram sensitivity and the shock diamonds are no longer seen. This compromise among sensitivity, blur, and feature size is always an issue in shadowgraphy.

Figure 6 shows 7 frames of Colt 9mm submachine gun fire (124-grain American Eagle ammunition) observed at 75,000 frames/s. These frames are not sequential, but rather cover an interval of 300 μs between Figs. 6b and 6g. This closeup view reveals shock wave emergence from the muzzle brake attached to the weapon prior to the exit of the bullet. After firing five previous rounds, unburned powder is seen emanating from the muzzle of the gun. Some of these powder grains are hurled at supersonic speed as revealed in Figs. 6e-6g. Shock wave diffraction through the multiple orifices of the muzzle brake is also revealed in Figs. 6b-6d. As discussed previously in [5], the gas-dynamic understanding of muzzle brakes, suppressors, and other issues of firearm design could benefit from the sort of high-speed imaging shown here.

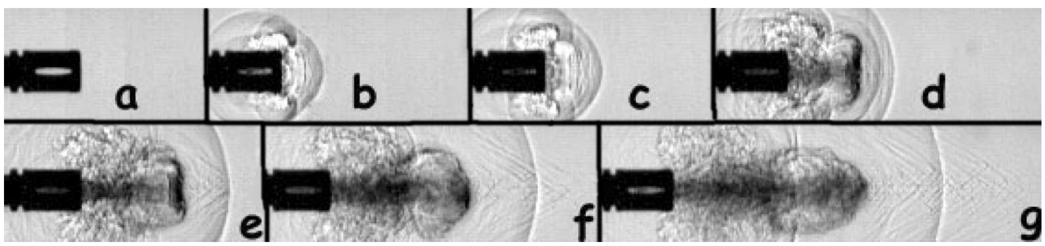

Fig. 6. Sequence of frames from $9mm$ submachine gun fire, muzzle closeup view observed by focused shadowgraphy

3.2 Edgerton retroreflective shadowgraph results

Gram-range explosive charges of TATP were observed using Edgerton shadowgraphy at 10,000 frames/s, e.g. Figure 7. The shock wave radius vs. time can be measured from such a frame sequence by way of a length calibration, yielding shock Mach number vs. radius. Such quantitative results are very useful in gram-range explosive testing, as described in a companion paper [11].

4 Acknowledgment

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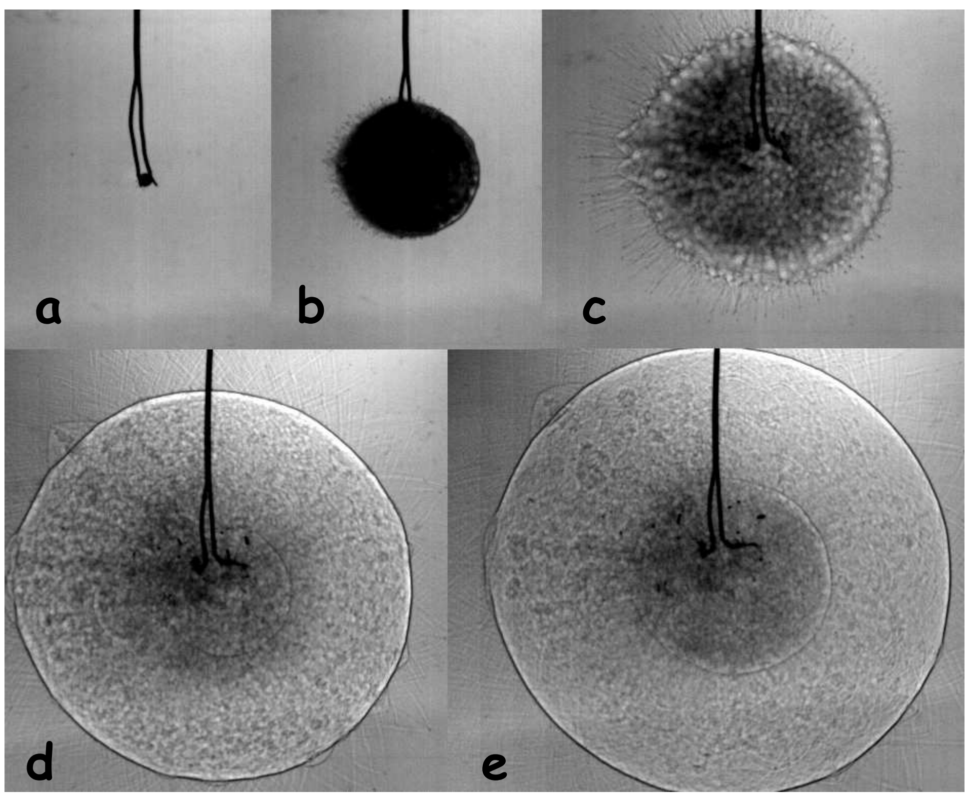

Fig. 7. Selected frames from the explosion of a 1g spherical TATP charge observed by Edgerton shadowgraphy