A pixel-wise image processing method for shock wave detection in high speed video

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***Abstract*—Even under optimal lighting conditions and with properly chosen settings, shock waves are only scarcely perceived on high speed video recordings of explosive blasts in open air. Usual post-processing methods like contrast, level and curves adjustment have limited effectiveness to improve the visibility of the shock wave as it drifts through the field in the video and have little to no effect making it visible on individual frames.**

A pixel comparison method yielded high contrast images showing well defined wave fronts allowing accurate measurements of the evolution of the wave in single frames.

***Keywords*—high-speed video, shock wave, image processing.**

I. Introduction

Shock waves have been photographed in confined spaces as early as late 19th century using a process known as *Schlieren* method, first devised by Robert Hooke in the 17h Century [1] and later developed by August Toepler in the period 1859—1864[3].

Fig. 1 depicts a supersonic bullet in flight and shows the associated shock waves and the trailing edge shock as published by Ernst Mach in 1887[4] using the *Schlieren* method.

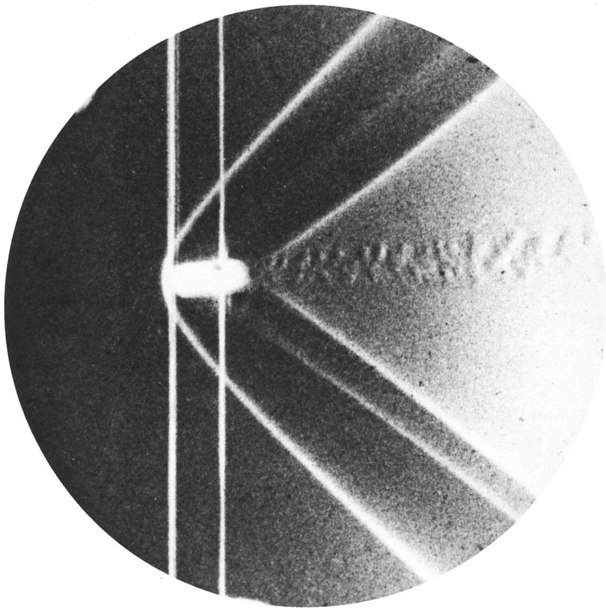

Fig. 1 - Photograph of shockwaves around a supersonic bullet, published by Ernst Mach in 1887.

The *Schlieren* method takes advantage of the refraction of light rays caused by the variable gradient of density in the medium as the wave propagates and is widely used to photograph the flow of air around objects and to study supersonic motion.

However, video recordings of shock waves in open air can't benefit from direct *Schlieren* photography as it requires a collimated light source —obtained with a complex and fragile optical apparatus— rather than the scattered sunlight available in open air blasts.

Nevertheless, the passage of a blast wave produces the same refraction phenomena responsible for the *Schlieren* effect, causing subtle but noticeable distortions on background features as terrain and distant trees illuminated by sunlight, in what is known as Background Oriented Schlieren [BOS]. Fig. 2 describes the behaviour of pressure over time at a given distance from an explosive blast in open air according to [5].

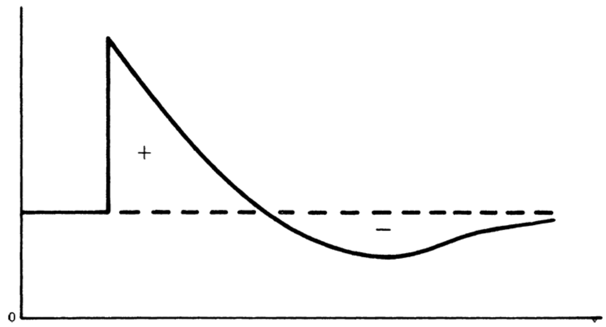

Fig. 2 - Blast wave pressure versus time

As an effect of BOS, the blast wave front generated by an explosive blast in open air is perceived on high speed video recordings as a narrow blurred stripe moving from frame to frame. Fig. 3 is a frame extracted from a high speed video clip recorded with an Olympus i-Speed 3 camera at 5 kfps, shutter speed 100 μs, F=110mm, $f/2.8$ under optimal lighting conditions. The shock wave is present and can be spotted surrounding the explosive blast but lacks contrast and definition.

Accurate measurements are hard to perform as the shock wave is easily missed on static images preventing any direct data analysis to be made on individual frames. Toggling between subsequent frames is often needed to identify the

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position of the wave front. Considering that images recorded with state-of-the-art high speed video camera systems mounted on sturdy heavy-duty tripods on steady surfaces are able to record high-resolution/low-noise/stabilized videos, we can expect that the only perceived changes in the comparison between subsequent frames might correspond to the BOS effect caused by the drifting shock wave front.

Fig. 3 - High speed video frame. Blast wave is present but barely seen.

This comparison between frames —or image correlation— is the basis to the processing technique described in section II.

II. Method

Image correlation algorithms may be implemented on traditional programming languages or mathematical analysis applications as MATLAB in attempt to highlight the BOS effect and detect and enhance the shock wave. A similar routine can be implemented on the popular and wide available image editing application Adobe Photoshop [PS] combining its image editing capabilities and powerful analysis tools.

Video frames can be imported as separate image layers on PS `(File > Import > Video Frames to Layers)` and later combined according to several blending modes featured in the application. Pixels recorded with bit depth d may assume 2^d values ($0 \geq$ pixel value $\leq 2^d - 1$), where 0 corresponds to black and $2^d - 1$ corresponds to white. For 8-bit images: $2^d = 256$, resulting in pixel values in the range $0 - 255$. 24-bit color images consist of 3 separate 8-bit channels (red, green and blue —RGB— channels) each capable of recording 256 levels.

PS blending modes combine layers performing some mathematical operation between equivalent pixels in the combining layers. As we intend to compare images, blending modes *subtract* and *difference* are a natural choice among the dozens of modes available. Operations performed by *subtract* and *difference* modes are shown in (1) and (2).

Subtract:

$$C = (A - B). \tag{1}$$

Difference:

$$C = |A - B|. \tag{2}$$

As negative values returned by (1) are displayed as black (pixel value= 0), the absolute values returned by (2) make the *difference* mode more suitable for fitting the purpose of enhancing every difference between frames and not only highlighting pixels that shine brighter in the reference frame.

TABLE I
BLENDING OPERATIONS

A	B	Subtraction $(A-B)$	Difference $\|A-B\|$
0	0	0	0
0	128	0	128
0	255	0	255
128	0	128	128
128	128	0	0
128	255	0	127
255	0	255	255
255	128	127	127
255	255	0	0

TABLE II
BLENDING OPERATIONS - COLOR DESCRIPTION.

A	B	Subtraction $(A-B)$	Difference $\|A-B\|$
black	black	black	black
black	50% gray	black	50% gray
black	white	black	white
50% gray	black	50% gray	50% gray
50% gray	50% gray	black	black
50% gray	white	black	50% gray
white	black	white	white
white	50% gray	50% gray	50% gray
white	white	black	black

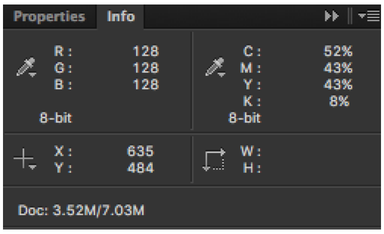

Fig. 4 - Adobe Photoshop Info Panel

Table I shows pixel values resulting from comparisons between black (0), white (255) and 50% gray (128) pixels as returned by blending modes *subtract* and *difference* according to (1) and (2) and inspected using the *info* (Fig. 4) panel on Adobe Photoshop. Table II describes the colours corresponding to values in Table I.

Blending modes can be easily tested combining a solid color 50% gray ($R = G = B = 128$) frame as presented in Fig. 5 and a grayscale bar pattern as presented in Fig. 6.

Fig. 7 and 8 display the outputs of Fig. 5 and 6 blended together using *subtract* and *difference* modes respectively. In Fig. 7 (*subtract mode*) all pixels in the bar pattern brighter than the reference frame result in black pixels in the blended frame. In Fig. 8 only pixels with equal brightness in both the

Fig. 5 - Frame A - Solid Color 50% Gray.

Fig. 6 - Frame B - Grayscale Bar Pattern.

Fig. 7 - Subtract: $C = (\text{Frame } A - \text{ Frame } B)$.

grayscale bar pattern and the solid 50% gray reference frame result in black pixels after blending, preserving and enhancing the differences between frames.

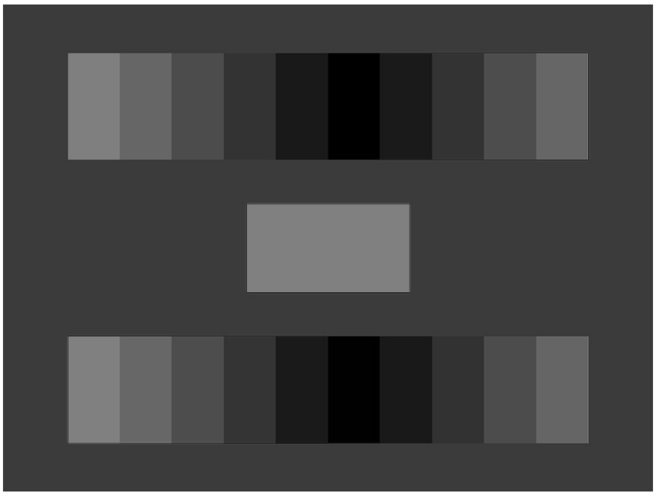

Fig. 8 - Difference: $C = |\text{Frame } A - \text{ Frame } B|$.

Fig. 9 - Reference frame.

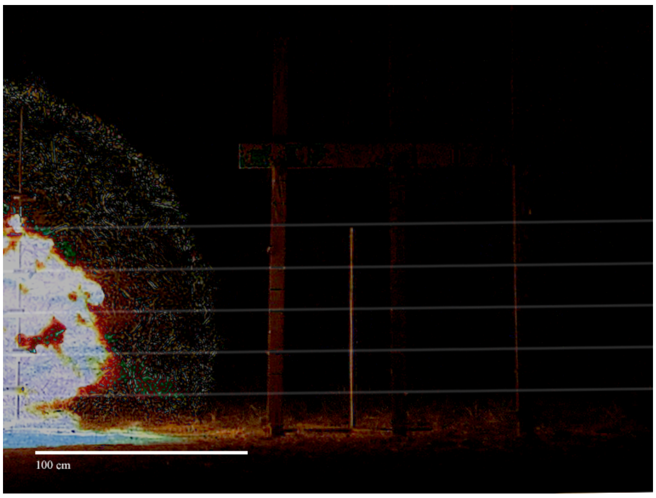

Fig. 10 - Processed video frame. Blast wave sharp and well defined.

Applying this method to blend the frame shown in Fig. 3 with a reference frame (Fig. 9) shot immediately prior to the explosion we get the result in Fig. 10.

Unchanged features appear darkened while the blast wave is highlighted showing sharp and well defined contours, suitable for precise and accurate pixel measurements and analysis if calibration data is available to determine a scale factor to convert pixel count into length units. Target marks properly aligned and spaced on reference bars provide trustable reference axes to set a scale factor and coordinate system for measurements in the final image.

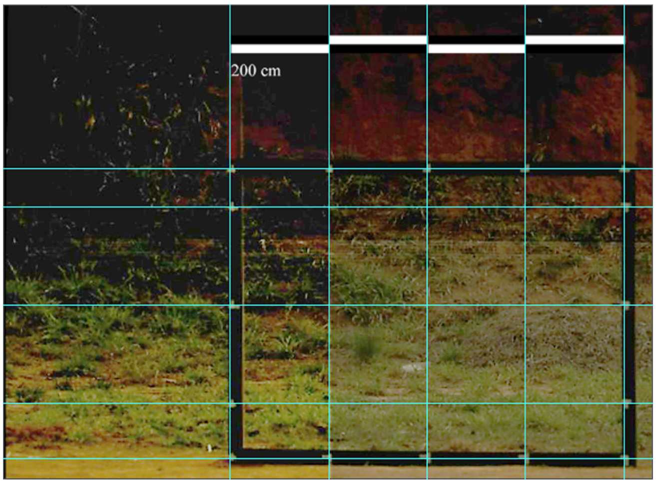

Fig. 11 - Target stickers, aligned and spaced with the assistance of a total station combining electronic theodolite and electromagnetic distance measuring instrument improve the accuracy of position measuring in the final image.

III. Final Considerations

Adobe Photoshop is an widely available and friendly tool to conduct a straight-forward image correlation process capable of highlighting the effects of BOS on high speed video recordings of explosive blasts in open air, bringing shock waves into sharp view.

Multiple reflections and Mach stem (Fig. 12) formation can be easily tracked on the processed images in a manner that could not be achieved solely by the use of arrays of pressure transducers [6].

Precise and accurate visual data on blast waves are an useful counterpart to data gathered by pressure transducers, providing an additional tool to study the effects and evolution of shock wave fronts.

To ensure accurate distance measurements, the experiment must be designed to avoid —or keep to a minimum— parallax effects and optical distortions caused by short focal lengths. Telephoto or zoom lenses set to $F \geq 85$mm, covering a 10° or less field of view show no noticeable barrel distortion. On-camera high gain settings (High ISO/Enhanced Sensitivity) should be avoided as it increases random noise that appears highlighted in the blending process.

Typically, an entire high speed video recording of an explosive blast recorded at a frame rate $\leq$ 10kfps spans for no more than a few dozen frames, making it possible to highlight interesting features by tweaking levels and curves for each frame or to perform frame-by-frame analysis and annotations. However, manual adjustments and frame selection becomes an

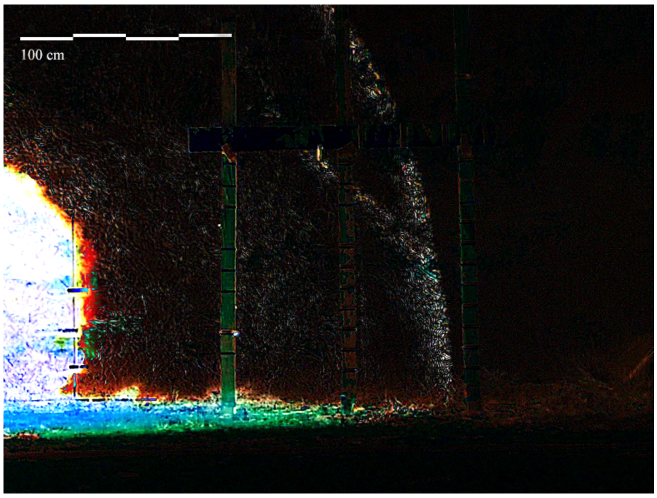

Fig. 12 - Mach stem formation.

exhaustive task for longer videos and the processing technique described herein can become considerably time-consuming. Fortunately, the same blending modes are featured in the non-linear video editing application Adobe Premiere and a similar process can be done by loading the clip to be processed and the reference frame on separated video tracks and mixing them down using the *difference* blending mode. Further analysis can then be done by importing the processed frames to PS.

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