Towards the development of an algorithm for automatic analysis and detection of shock waves in the schlieren visualization technique

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DOI: 10.13111/2066-8201.2024.16.4.12

Received: 13 September 2024/ Accepted: 11 November 2024/ Published: December 2024

Abstract: *This paper presents the development of an algorithm for identifying shock waves formed during the supersonic combustion process, detonation, in a pulsed detonation chamber. The algorithm is based on image binarization techniques, followed by the identification of regions of interest in the images, the detection and isolation of the edges of these regions, and the determination of the wave speed between two consecutive frames. The advantage of this automation process is the efficiency in analysing the repeated detonation cycles of a pulsed detonation chamber. Additionally, it can provide a more accurate evaluation of the data, making it a valuable tool for researchers and engineers in various scientific fields and shock wave applications.*

Key Words: *schlieren imaging, shock wave, detonation, supersonic combustion*

1. INTRODUCTION

In various engineering applications, refractive flow imaging techniques such as the schlieren technique and shadowgraph technique allow for non-invasive investigation of complex flow fields. These visualization techniques are applied in studies of flows where density variations are significant, such as high-speed flows (transonic or supersonic regimes), combustion flows, or flows with large temperature gradients, even at low speeds. The extreme conditions under which measurements are taken in the first case often led to vibrations, poor image quality, or lighting fluctuations, which can compromise the identification of specific structures in high-speed regimes. Therefore, to study the phenomena in question, a very large set of measured data is necessary, which in turn requires the development of methods for automatic image acquisition and post-processing to facilitate the study of experiments. These methods typically consist of decision algorithms and are used in a wide range of fields, from cancer diagnosis to airbag control. Programs are usually created and adapted individually for the specific problem, as creating a computer-assisted decision procedure requires transforming the properties of the particular phenomenon into measurable quantities. To do this, a large dataset is needed to train a software based on neural networks, like the research studies from the Lomonosov Faculty of Physics in Moscow [1, 2], or a strict mathematical representation of the phenomenon that requires identification and analysis [1-4]. In other cases, only a small dataset is available for training the program, such as detecting circumscribed masses in digital mammograms, which can lead to inadequate results since a smaller database can produce errors in decision algorithms based on neural networks. To address this issue, the so-called Augmented Behaviour Knowledge Space (ABKS) method [5] was developed, which deals with the problem by intersecting decisions made by sub-algorithms called classifiers. Each classifier is a dimension that describes a perspective of the analysed case (which is usually an image).

Concerning flow models, the detection of structures with intelligent systems has been studied in relation to combustion in propulsion and power generation systems using schlieren techniques such as Calibrated Colour Schlieren (CCS), Background Oriented Schlieren (BOS), and Rainbow Schlieren (RS) [4, 6] for qualitative and quantitative analyses of compressible flow phenomena, such as shock waves. Background image subtraction and Canny edge detection methods are general methods for identifying and studying the position of the shock wave and its unsteadiness. The present paper focuses on the development of a program based on the aforementioned techniques for the automatic determination of the supersonic flow field topology at the exhaust of a pulse detonation engine. The algorithm has been validated on numerical schlieren images, in which shock waves were generated at the outer surface of the exhaust pipe of the pulse detonation engine.

2. THE PULSED DETONATION ENGINE CYCLE

To attempt automation by implementing a program that can identify, isolate, and determine the main characteristics of the Pulsed Detonation Engine (PDE) cycle, as determined using schlieren visualization techniques, it is necessary to establish a rigorous methodology. Therefore, this section aims to present the main characteristics of the PDE cycle, benchmark images obtained using schlieren visualization techniques, and the methodology of the program, which represents the objective of this article.

The operating cycle of a PDE (Figure 1) begins with the filling of the detonation chamber with an appropriate mixture of fuel and oxidizer. The initiation of the mixture is achieved from one end to the other, of the detonation chamber using an ignition device, which is typically a spark plug. A planar shock wave, characterized by a pressure wave, appears at the open end of the engine and travels towards the exit. In front of the detonation wave, the pressure of the mixture is low, while downstream, the pressure can reach up to 30 bars. The detonation wave not only carries high pressure but also a large amount of kinetic energy, which is converted into thrust. Behind the detonation wave a rarefaction wave forms which, when it reaches the engine exit, reduces the pressure to ambient levels.

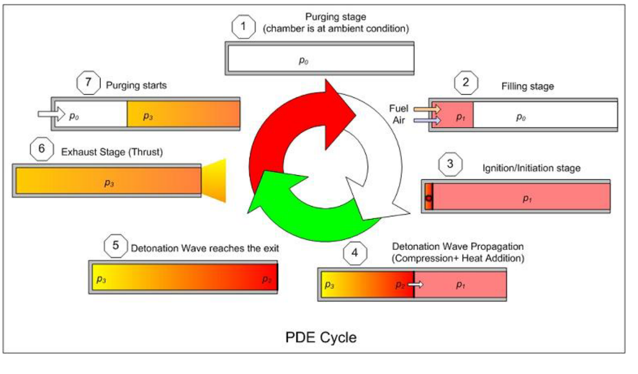


Fig. 1 – Operating Principle of a Pulsed Detonation Combustion Chamber [7]

The phases of this cycle represent the key characteristics that should be identified using the developed program. The pulsed detonation chamber to be analysed in this paper, and its operating cycle are described in detail in reference [8].

3. THE SCHLIEREN VISUALISATION SETUP

The Z-type schlieren visualization technique, similar to the one shown in Figure 2, is used to assess the structure of reaction products from combustion, sensitive to density variations. The system includes a point-like light source (GS Vitec Multiled LT-V9-15, producer Tech Imaging Services, Saugus, MA, USA), two parabolic mirrors (Techspec "10 diameter, 60" focal length, protected aluminium, producer Edmund Optics, East Gloucester Pike Barrington, NJ, USA), a knife-edge (built in-hose), and a high-speed camera (Phantom V2515, producer Vision Research, Wayne, NJ USA), operating at a maximum rate of 77,000 fps. Light from the source is directed to the centre of the first mirror, distributing the light beam onto its entire area. Light is collimated between the two mirrors and afterwards it is focused by the second parabolic mirror, on which the camera is trained.

The knife-edge placed between the second mirror and the camera is intended to reduce the light intensity. Although it is cost-effective and compact, the Z-type schlieren configuration presents some challenges such as non-linear optical alignment and the comet effect, which can distort the image. To minimize these effects, the angles of incidence/emission of the beam (α) are kept below 20°. Another effect is the astigmatism error that can be evaluated based on 'the distance between the sagittal and tangential force - Δf' [9]:

$$\Delta f = f\frac{\sin^2\alpha}{\cos\alpha} \quad (1)$$

or for large f-number mirrors and so, small α angles, the above formula might be reduced to:

$$\Delta f = \frac{d^2}{4f} \quad (2)$$

With the current setup in place, the f/6 parabolic mirrors have 60'' focal length. Imposing an acceptable Δf in the range 4-10 mm [9], the angle α, according to (1), should be in the range 3-5 degrees. With careful alignment procedures for uniform light cutoff, even larger Δf might be acceptable so larger α angles.

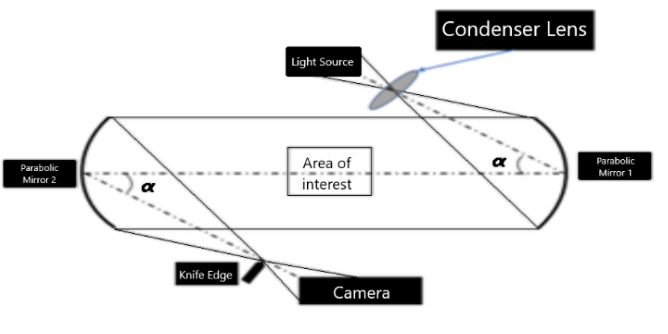


Fig. 2 – Schematic of the schlieren visualization setup applied to PDE [8]

The cited $2\alpha = 20$ deg is more a rule of thumb for large f-number mirrors (larger than f/6) cited in different Schlieren laboratory handouts based on [10]. In the current setup, taking into

account the room constraints as well, one has tried to keep α in the range 5-10 degrees as a trade-off between Schlieren quality and ease of alignment.
All components are mounted on adjustable tripods, allowing the optical axis of the system to be moved in various positions along the three axes for engine exhaust. The high-speed camera, operating at 77,000 fps, captures the unstable phenomena involved in the ignition process as well as the subsequent structure of the waves at the exhaust.

4. THE ALGORITHM

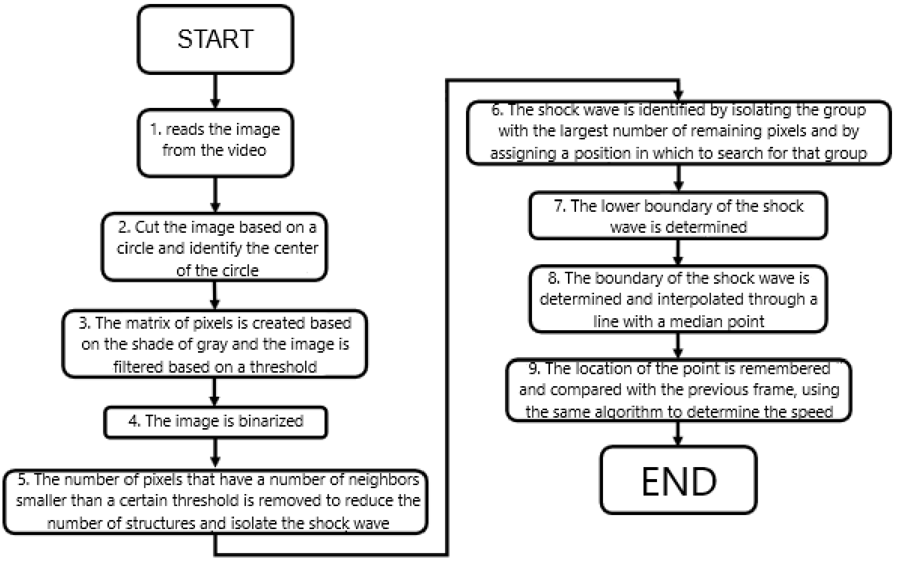
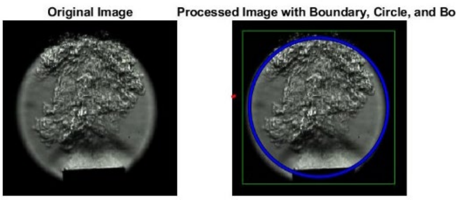


Fig. 3 – Algorithm for identifying and determining shock wave velocity

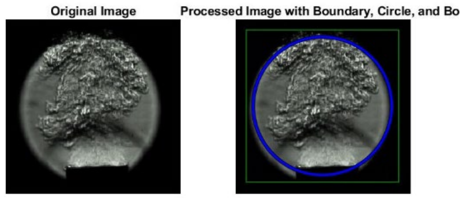
Figure 3 presents the algorithm, for identifying, isolating, and determining the shock wave velocity at the exhaust of the pulse detonation engine. The algorithm does not use numerical methods, as such approach is not required for the purpose, but consists in a sequence of mathematical instructions (Matlab functions and instructions) to be followed to perform the data processing. The algorithm begins by reading images from the saved video. The image is cropped based on a circle with its centre at the origin of the frame to isolate the area of interest. After cropping, each pixel is assigned a grayscale shade using an automatic function, and the image is filtered based on a threshold to retain only the structures of interest. The resulting image is binarized using the Matlab function "imbinarize", and any pixel regions with a number of neighbours exceeding a certain threshold are kept in the frame. This helps in identifying dense pixel areas, where the shock wave is located. Since the shock wave is the densest pixel area, it aids in identifying the detonation wave contour by assigning a location in the pixel matrix and the centre of the circle created in step 2. Once the contour is identified, the southern boundary is isolated, and a line is interpolated to determine the average distance between pixels. In other words, the centre of the southern (inferior) boundary is sought. After identifying the centre, the pixel locations are recorded, and the algorithm is applied to the next frame. Knowing the time difference between two consecutive frames and the distance between the two central points of the boundary (displacement), the shock wave velocity is determined.

5. RESULTS

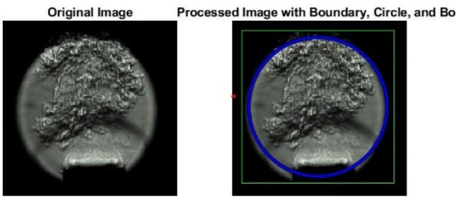
Figure 4shows the process of importing images from the video and generating the circle used to crop the image. To generate the circle centre, the function “fitCircleLSQ” was defined, which applies the least squares method to identify the distance between the circle centre (specified as the origin) and the image boundary. The image cropping based on this function is shown in Figure 5. Figure 6 displays the adjustment of the image based on the grayscale intensity contained in the picture. The “rgb2gray(img)” function from Matlab [11] is used for this purpose.



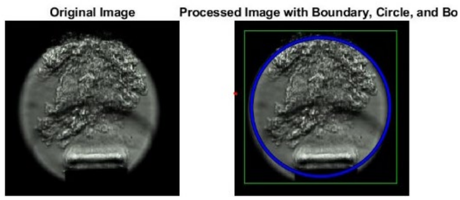
(a)



(b)



(c)



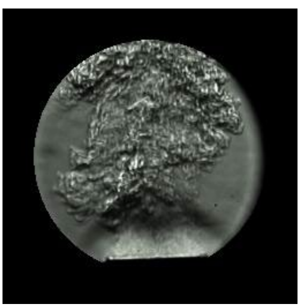
(d)

Fig. 4 – Reading images from video (step 1) and generating the circle for image cropping

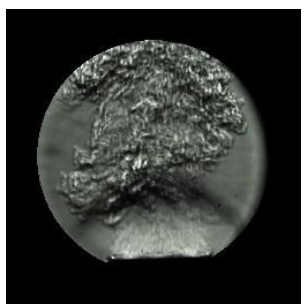
The next step involves binarizing the image based on the previously determined grayscale intensity. Binarization, carried out with the “rgb2gray(img)” function from Matlab, using the “adaptive” option [12], is shown in Figure 7. Figure 8 illustrates the two most critical steps of the created algorithm.

The first step (Figure 8 a-d) involves generating the binary pixel matrix and isolating structures. The image is transformed into a matrix map where each position in the matrix is either 0 or 1, depending on the pixel colour (0 – black, 1 – white).

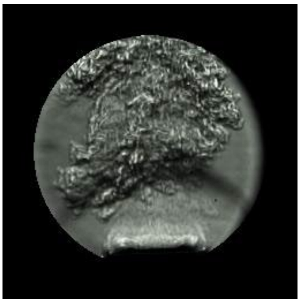
After generating the matrix, the boundaries of the remaining structures are identified using neighbouring pixels (pixels in the matrix) and a user-defined threshold. If a region contains a number of pixels with neighbours above a certain threshold, that region remains in the pixel matrix with a value of 1. Otherwise, the pixels are converted to 0 and removed from the image.



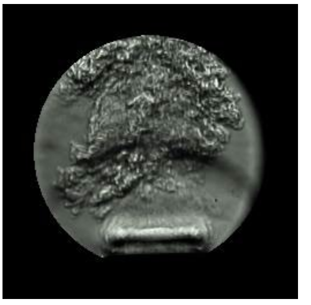
(a)



(b)



(c)



(d)

Fig. 5 – Cropping images based on the generated circle (step 2)

Figure 8e-h represents step number 6 of the algorithm. To achieve the desired images, before cleaning, a filter is applied that acts as a mask, assigning 0 to white pixels inside the boundaries of the identified structures.

Once the image is cleaned in step 5, the image is reconstructed by removing the filter (the mask of pixels inside) to determine if the algorithm has correctly removed unwanted structures.

Thus, only shock waves remain in the image. There is a minor limitation in the program because the exhaust pipe of the engine is not completely removed, but this does not pose a problem for determining the shock wave speed.

Figure 9 illustrates the identification of the southern boundary of the shock wave (red pixels). The boundary is identified using the pixel matrix.

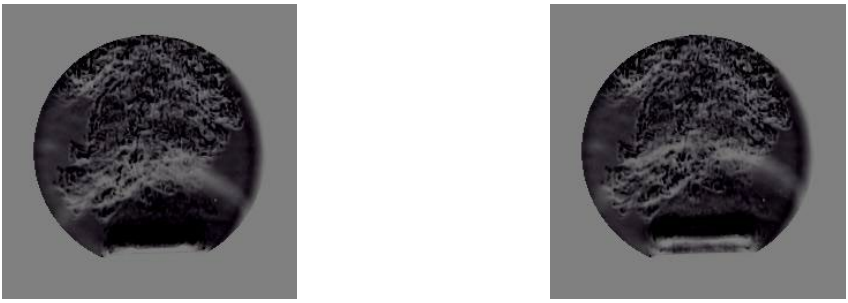
The program determines neighbouring white pixels based on indices i (row number) and j (column number). If the pixel at coordinate (i, j) has a neighbour at i±1 or j±1, both pixels are considered.

The boundary condition for the southern boundary isas follows: if a pixel has a white neighbour at (i, j±2), that neighbour, which is two pixels away on the vertical axis, is no longer considered.

Once the shock wave boundary is identified, Figure 10 shows the linear interpolation (green line) among the pixels forming the southern boundary of the shock wave (red pixels). Figure 11 presents the median point (yellow point) determined using linear interpolation.

(a)

(b)



(c) (d)

Fig. 6 – Adjusting images based on grayscale and inverting the colour palette (step 3)

(a) (b)

(c) (d)

Fig. 7 – Binarization of images (step 4)

(a) (b)

(c)

(d)

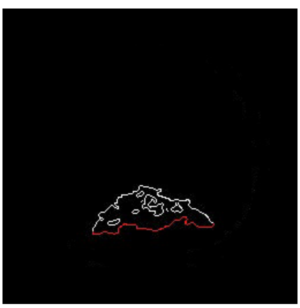
(e)

(f)

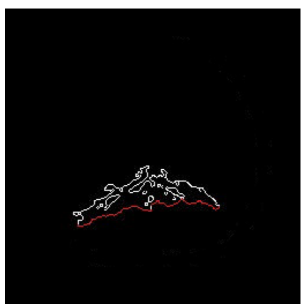
(g)

(h)

Fig. 8 – Assignment of remaining structure pixels (a,b,c,d) – Step 5. Image cleaning to identify and isolate the shock wave (e,f,g,h) – Step 6

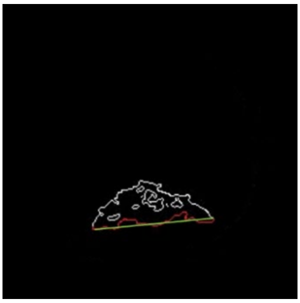


(a)

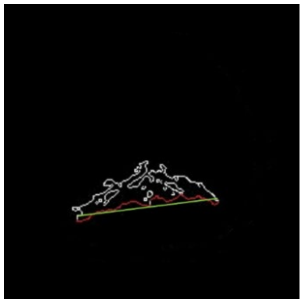


(b)

Fig. 9 – Step 7 - Determination of the southern boundary of the shock wave (red pixels)



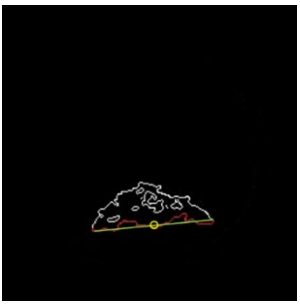
(a)



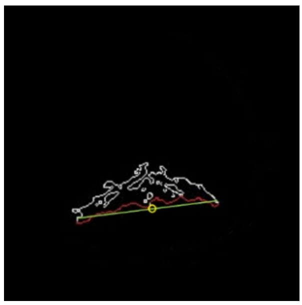
(b)

Fig. 10 – Step 7 - Linear interpolation (green line) of the shock wave boundary

The displacement calculation of the median point between two consecutive images is determined as follows. The location of the pixel (i, j) in Figure 11a and the location of the pixel (i, j) in Figure 11b are recorded. The displacement is calculated using the norm. With the help of the software provided by the camera manufacturer, the relationship between the number of pixels and a known distance can be calibrated, determining in this case how many pixels represent 1 mm. Thus, the distance can be determined, and knowing the time between two different frames, the velocity of the shock wave can be calculated. In the case presented in this paper, the displacement is 16.9706 pixels, 1 mm = 0.2645833333 pixels, and the time between two frames is 74,9309µs.



(a)



(b)

Fig. 11 – Step 8 - Determination of the median point (yellow point) of the southern boundary

The speed obtained using the algorithm is 856 m/s, while for the same test, the speed determined with Kulite pressure probes (shock wave) is 909.09 m/s, and that determined with photodiodes (combustion wave) is 252.7 m/s.

6. CONCLUSIONS

In this paper, an algorithm for analysing schlieren images in Matlab has been developed to a stage where it allows the isolation and identification of the shock wave exiting a PDE. The developed algorithm utilizes various Matlab functions for pre-processing and cleaning the images before identifying the shock waves, where linear interpolation was employed to complete them, and is capable to determine the shock wave velocity can be determined from the schlieren images. The algorithm has been validated against schlieren images resulted from a hydrogen / air experimental campaign. The accuracy of the wave velocity determination by this method is found to be reasonable, the difference with respect to the shock wave velocity determined by pressure measurements along the PDC exhaust channel being below 6 %. Further development of the presented algorithm is required in order to automatize the process of image selection and shock wave identification, minimizing the required user input. However, the present paper is focused on the isolation and identification algorithm, which is the current algorithm development stage. The final software package, under development will focus on refining the wave tracking procedure such that lower quality images can be accurately processed, and on the isolation and identification of other relevant flow features, such as the flame front, vortex cores, and rarefaction waves. The development of a marketable software product, assisted by a Graphical User Interface allowing the user to select multiple masks and tailor the interface settings to fit the images is not part of our research interest.

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