Measurement Science and Technology

TECHNICAL NOTE • OPEN ACCESS

Optical flow tracking velocimetry of near-field explosions

To cite this article: J E Higham *et al* 2022 *Meas. Sci. Technol.* **33** 047001

OPEN ACCESS
IOP Publishing
Measurement Science and Technology
Meas. Sci. Technol. **33** (2022) 047001 (5pp)
https://doi.org/10.1088/1361-6501/ac4599

Technical Note

Optical flow tracking velocimetry of near-field explosions

J E Higham[1], O S Isaac[2,*] and S E Rigby[2]

[1] University of Liverpool, School of Environmental Sciences, Department of Geography and Planning, Liverpool L69 7ZT, United Kingdom
[2] Department of Civil & Structural Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, United Kingdom

E-mail: o.isaac@sheffield.ac.uk

Received 15 October 2021, revised 13 December 2021
Accepted for publication 22 December 2021
Published 7 January 2022

Abstract
To better understand the complex dynamics and physics associated with the rapid expansion of the detonation product fireball following an explosion, it is imperative to have a full description of its associated velocity field. Typical experimental techniques rely on simple single-point measurements captured from pressure transducers or Hopkinson pressure bars. In this technical design note, we aim to improve the current state-of-the-art by introducing a means to determine full velocity fields from high-speed video using optical flow tracking velocimetry. We demonstrate the significance of this method from our results by comparing velocity fields derived from high-speed video and a validated numerical model of the same case. A wider use of this technique will allow researchers to elucidate spatial and temporal features of explosive detonations, which could not be obtained thus far using single-point measurements.

Keywords: blast & explosions, optical flow tracking velocimetry, experiments & simulations

(Some figures may appear in colour only in the online journal)

1. Introduction

When an explosive detonates, it converts into a high-pressure, high-energy gas that rapidly expands and displaces the surrounding air at supersonic speeds, causing a blast wave to form. In order to provide adequate and efficient protective systems against blast loading, it is of critical importance that the evolving properties of the explosive products and the emerging blast wave are well characterised and understood. However, in the region close to the source of the explosion, blast pressures are in the order of several hundreds of megapascals (Kinney and Graham 1985), and thus direct experimental measurement is challenging (Rigby *et al* 2015). Research into high explosives (and thus our ability to rigorously validate new numerical modelling approaches for this purpose), is dependent on our ability to provide indirect, yet accurate measurements and quantification of blast parameters.

Currently, in order to experimentally interrogate the physics of near-field explosions, we often rely on pressure transducers[3] that provide single-point temporal data, which can be used to either validate computer models or to provide limited scientific insight. While advances in computer modelling might enable

* Author to whom any correspondence should be addressed.

[3] Whilst imaging techniques such as background-oriented schlieren do exist (Sommersel *et al* 2008, Mizukaki *et al* 2012), they cannot provide information in regions where the light rays from a reference background cannot reach the camera. The other optical methods mentioned in the review article by McNesby *et al* (2016) pertain to tracking only the edge of the blast wave or the fireball.

us to interrogate explosions in three dimensions at high rates, it is known that such models do not capture all of the complex stochastic processes associated with blasts (Rigby *et al* 2018). Thus, to fully interrogate all these processes, it is essential that we capture full-field, high-fidelity data from experiments.

The rapid development of digital image sensors in the recent past led to a dramatic reduction in the price and an enhanced ability to record at higher frame rates. These, combined with the vastly improved processing abilities of modern computing, has allowed us to capture images of the highly unsteady features associated with explosions. The application of image processing techniques can then allow for a quantitative description of the motion within these images. There is a substantive need in this regard for a technique which can robustly track features associated with the aggressive expansions of the turbulent structures within the chaotic fireball.

To determine and quantify motion (i.e. velocity) from a sequence of images, there are three well established image processing based techniques. The most common one is particle image velocimetry (PIV) (Adrian and Westerweel 2011), an Eulerian method typically used in fluid, granular and solid mechanics. This works by subdividing images into smaller interrogation windows and correlating patterns through successive snapshots in an image sequence, typically through Fourier based correlation methods. The reader may refer to Adrian and Westerweel (2011) for a more in depth description of the method and its variants.

The second method is particle/feature tracking velocimetry (PTV), which is similar to PIV, and is also commonly used in fluid, granular and solid mechanics. Unlike the PIV method, this method is Lagrangian, and is used to track individual trajectories of a particle, or of features. There are numerous algorithms used to compute such particle displacements; e.g. based on 2D correlations (Brevis *et al* 2011); using machine learning (Gim *et al* 2020), based on Voronoi diagram (Zhang *et al* 2015), a 3D tracking algorithm (Cui *et al* 2018) and most simply based on nearest neighbours (Malik *et al* 1993). Both PIV and PTV have their benefits and also their limitations, and in more complex cases, an expert user is often required to ensure high-fidelity tracking data.

More recently, in the areas of chemical engineering and granular flows, a third method, called optical flow tracking velocimetry (OFTV) has been successfully used to track complex motions of particles from a high-speed video (Fullmer *et al* 2020, Higham *et al* 2020, 2021, Weber *et al* 2021). The benefit of this method relates to its robustness for tracking. Unlike PIV/PTV, OFTV is based on solving the optical flow equations; a set of equations which describe the motion of regions of image intensity through a sequence of images (Gibson 1950). The application of the method intrinsically suits the tracking of the complex fireball as the method allows for an adaptive change in selected regions in the images between successive images, and this is especially relevant in high-speed video of blast and explosions, where the lighting conditions differ substantially between successive image frames due to decreasing incandescence of the detonation product fireball. The advantages of using OFTV as opposed to PIV further relate to the ability to track at pixel level and resolve Lagrangian statistics, unlike in PIV where the correlation interrogation windows can limit data output resolution and discard Lagrangian information.

The overall aim of this technical design note is to determine if OFTV will be a potential candidate for transitioning the field of blast and explosions from intrusive, point-based measurements to non-intrusive, synoptic, full field measurements derived from high-speed video.

2. Test data and numerical benchmark

In this work, we thus perform OFTV on high speed video footage of near-field free air explosions, and compare the results to those from a validated numerical model. Three blast tests were conducted at the University of Sheffield Blast & Impact Laboratory in Buxton, Derbyshire. 100 g spherical PE4 charges were detonated 355.4 mm clear distance (380 mm to charge centre) from the underside of a nominally rigid, reflecting surface using the COBL (*Characterization of Blast Loading*) (Clarke *et al* 2015). The charges were suspended directly under the centre of the target plate on a super-lightweight glassfibre weave fabric. High speed video data were obtained using a Photron FASTCAM SA-Z camera fitted with a 105 mm Nikon lens, filming at 160 000 fps with a resolution of 256 $\times$ 280 pixels, f/8 aperture and 0.25 µs shutter speed. The tests were self-illuminated by the incandescence of the detonation product cloud. The (vertical) field-of-view was set between the charge centre and the underside of the target plate. Full details of the experimental setup are available in Rigby *et al* (2020).

In this study we apply the FlowOnTheGo code for tracking (for a detailed explanation of the code, the reader is directed to Weber *et al* (2021)); remove camera distortion using piece-wise linear transformation based on calibration plates (Higham and Brevis 2019); and remove any outliers using the PODDEM algorithm (Higham *et al* 2016). For determining the regions of image intensity, we follow the method described in Weber *et al* (2021), where the regions of features in each image are determined based on their eigenvectors and associated roughness. To determine the motion of these regions, we solve the Optical Flow equation using a linear approximation as proposed in Lucas and Kanade (1981) and Lucas (1985).

The multi-material arbitrary Lagrangian Eulerian solver in LS-DYNA was then used to generate the numerical benchmark data, following the methodology outlined in Rigby *et al* (2018). In the same study, LS-DYNA was validated against near-field blast pressure measurements (Rigby 2018) and was shown to be in excellent agreement. Thus, outputs from the model can be used with confidence as benchmark data to assess the accuracy and validity of the OFTV method for measuring the velocity of expanding blast waves. Resultant velocities from the model were output as video files, and a bespoke MATLAB® script was used to read in the videos, convert the pixels to data, and plot against the OFTV results.

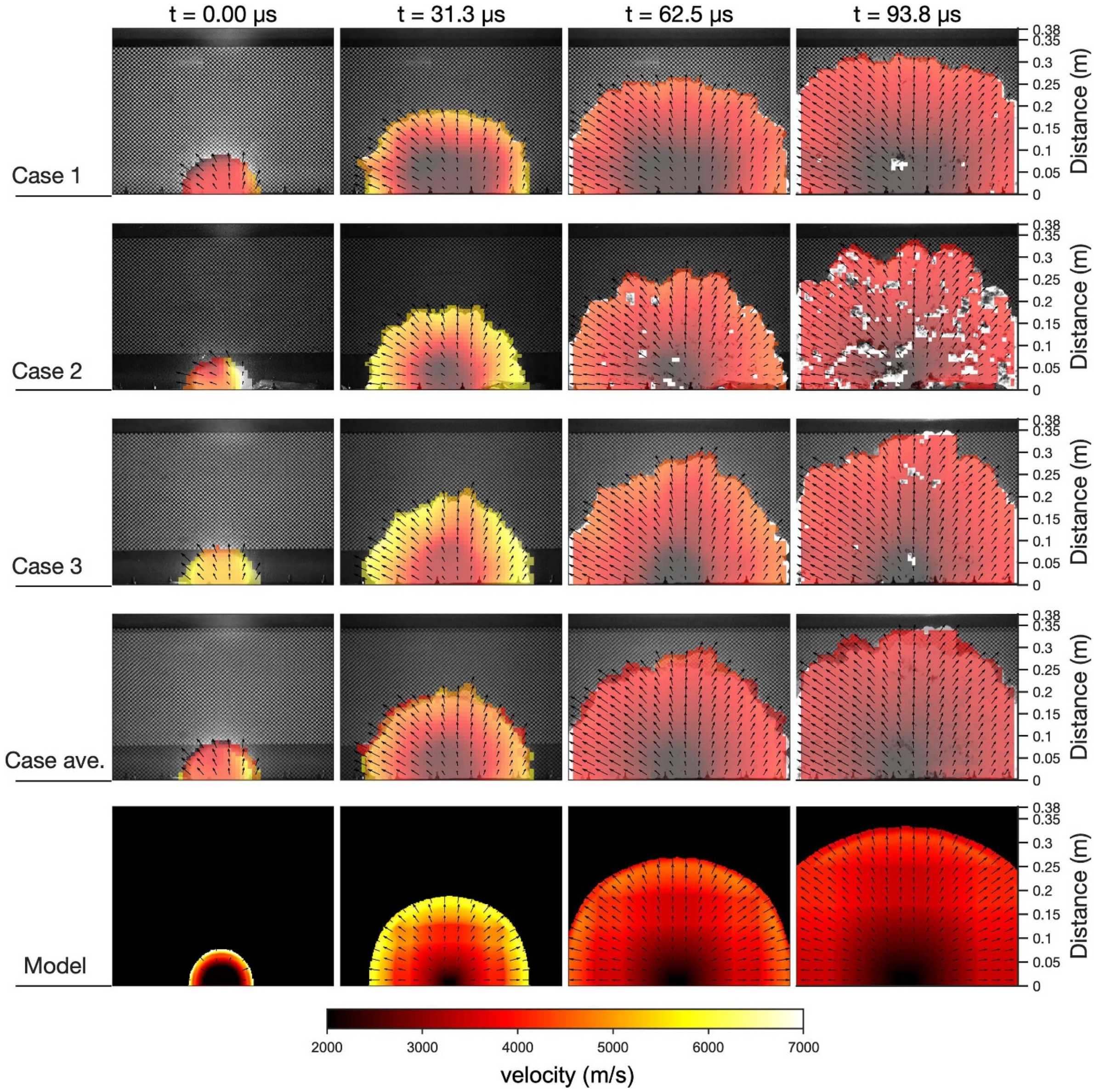

Figure 1. The top four rows show the magnitude of the velocity field tracked using OFTV at four time instances, with the corresponding raw high-speed images underlain. Bottom row shows magnitude of velocity field of LS-DYNA numerical model at the corresponding time instances.

3. Results

In the first four rows of figure 1 we show the magnitude of the velocity fields derived from the high-speed video. The top three rows show the results from three separate experiments, and the fourth shows the average of these three. On the bottom row, we present the magnitude of the velocity field computed by the LS-DYNA model. In each of the columns, we show four separate time instances, which are consistent across the cases and the numerical model.

Apart from the expected localized variations in surface velocity due to instabilities at the fireball/air interface, it is apparent that the global velocity fields derived between the cases are highly consistent between the OFTV derived cases. In comparison with the numerical model velocity fields, the OFTV results evolve and have the same shape qualitatively. Quantitatively, they have the same velocity magnitudes across the fields at all instances except at $t = 0.0$ μs, where the OFTV is unable to capture finer details, which may be explained by the sudden masking of trackable regions due to the flash of light upon detonation.

A further quantitative comparison is shown in figure 2, where the centreline (vertical line extending from the centre of the explosion) velocity magnitudes are presented. The results obtained from OFTV are in very good agreement with those computed from the numerical model, again with the exception of the first frame.

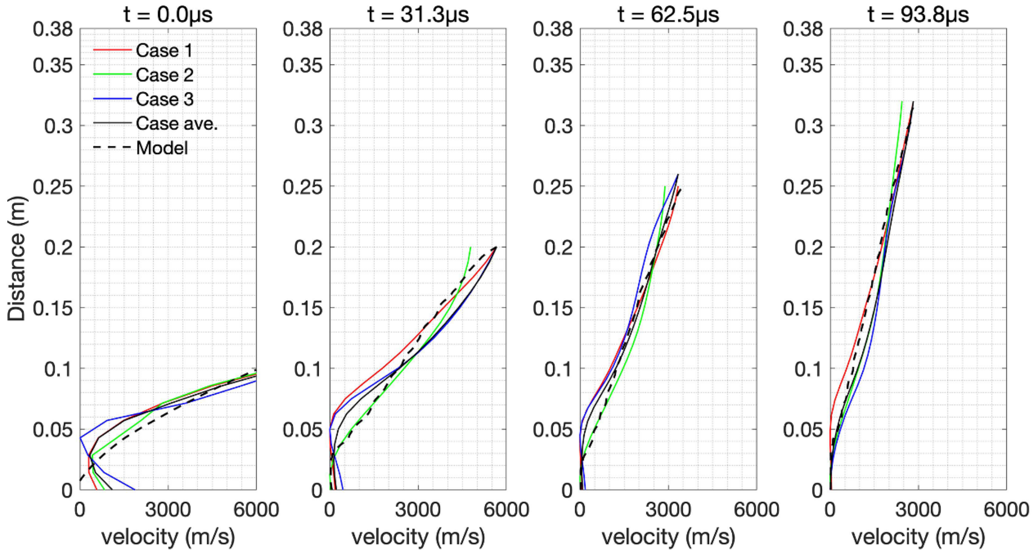

Figure 2. An overlay of centreline plots of velocity magnitudes for the OFTV cases and LS-DYNA model at various time instants.

4. Summary and outlook

This study has demonstrated the feasibility of OFTV on high-speed video footage of explosions. From this preliminary study, it has been possible to show both qualitatively and quantitatively (based on a validated computer model), that it is possible to accurately determine the velocity and motion of a chaotic fireball resulting from the detonation of an explosive material. The OFTV method allows for an instantaneous view of the velocity field of the detonation product fireball. It is envisaged that in future studies, this will allow for a detailed description of the physics of the turbulent chemical reactions occurring within. Without doubt, a successful application is likely to have a significant impact in the field of blast and explosions, as it no longer necessary to solely use an intrusive method, i.e. a Hopkinson bar or pressure transducer, as an experimental diagnostic, but instead, from these data we have a direct measure of velocity which need not be derived from discrete pressure or time-of-arrival gauges.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

O S Isaac https://orcid.org/0000-0003-3621-5903

References

Adrian R and Westerweel J 2011 *Particle Image Velocimetry* (Cambridge: Cambridge University Press)

Brevis W, Niño Y and Jirka G 2011 Integrating cross-correlation and relaxation algorithms for particle tracking velocimetry *Exp. Fluids* **50** 135–47

Clarke S, Fay S, Warren J, Tyas A, Rigby S and Elgy I 2015 A large scale experimental approach to the measurement of spatially and temporally localised loading from the detonation of shallow-buried explosives *Meas. Sci. Technol.* **26** 015001

Cui Y, Zhang Y, Jia P, Wang Y, Huang J, Cui J and Lai W 2018 Three-dimensional particle tracking velocimetry algorithm based on tetrahedron vote *Exp. Fluids* **59** 31

Fullmer W, Higham J, LaMarche C, Issangya A, Cocco R and Hrenya C 2020 Comparison of velocimetry methods for horizontal air jets in a semicircular fluidized bed of Geldart Group D particles *Powder Technol.* **359** 323–30

Gibson J J 1950 *The Perception of the Visual World* (Boston: Houghton Mifflin)

Gim Y, Jang D, Sohn D, Kim H and Ko H 2020 Three-dimensional particle tracking velocimetry using shallow neural network for real-time analysis *Exp. Fluids* **61** 26

Higham J and Brevis W 2019 When, what and how image transformation techniques should be used to reduce error in Particle Image Velocimetry data? *Flow Meas. Instrum.* **66** 79–85

Higham J, Brevis W and Keylock C 2016 A rapid non-iterative proper orthogonal decomposition based outlier detection and correction for PIV data *Meas. Sci. Technol.* **27** 125303

Higham J, Shahnam M and Vaidheeswaran A 2020 Using a proper orthogonal decomposition to elucidate features in granular flows *Granular Matter* **22** 86

Higham J, Shahnam M and Vaidheeswaran A 2021 Anomalous diffusion in a bench-scale pulsed fluidized bed *Phys. Rev.* E **103** 043103

Kinney G and Graham K 1985 *Explosive Shocks in Air* 2nd edn (New York: Springer)

Lucas B 1985 Generalized image matching by the method of differences *PhD Thesis* Carnegie Mellon University

Lucas B and Kanade T 1981 An iterative image registration technique with an application to stereo vision *Proc. 7th Int. Conf. on Artificial Intelligence (IJCAI)* (*Vancouver*, *BC, Canada*) pp 121–30

Malik N, Dracos T and Papantoniou D 1993 Particle tracking velocimetry in three-dimensional flows *Exp. Fluids* **15** 279–94

McNesby K, Homan B, Benjamin R, Boyle V, Densmore J and Biss M 2016 Invited article: quantitative imaging of explosions with high-speed cameras *Rev. Sci. Instrum.* **87** 051301

Mizukaki T, Tsukada H, Wakabayashi K, Matsumura T and Nakayama Y 2012 Quantitative visualization of open-air explosions by using background-oriented schlieren with natural background *28th Int. Symp. on Shock Waves* (Berlin, Heidelberg: Springer)

Rigby S, Fuller B, and Tyas A 2018 Validation of near-field blast loading in LS-DYNA *Proc. 5th Int. Conf. on Protective Structures (ICPS5)* (*Poznan, Poland*)

Rigby S, Knighton R, Clarke S and Tyas A 2020 Reflected near-field blast pressure measurements using high speed video *Exp. Mech.* **60** 875–88

Rigby S, Tyas A, Clarke S, Fay S, Reay J, Warren J, Elgy I and Gant M 2015 Observations from preliminary experiments on spatial and temporal pressure measurements from near-field free air explosions *Int. J. Prot. Struct.* **6** 175–90

Rigby S, Tyas A, Curry R and Langdon G 2019 Experimental measurement of specific impulse distribution and transient deformation of plates subjected to near-field explosive blasts *Exp. Mech.* **59** 163–78

Sommersel O, Bjerketvedt D, Christensen S, Krest O and Vaagsaether K 2008 Application of background oriented schlieren for quantitative measurements of shock waves from explosions *Shock Waves* **18** 291–7

Weber J, Higham J, Musser J and Fullmer W 2021 Critical analysis of velocimetry methods for particulate flows from synthetic data *Chem. Eng. J.* **415** 129032

Zhang Y, Wang Y, Yang B and He W 2015 A particle tracking velocimetry algorithm based on the Voronoi diagram *Meas. Sci. Technol.* **26** 075302