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Dynamic modeling and damage analysis of debris cloud fragments produced by hypervelocity impacts via image processing

Key words: Debris clouds; Hypervelocity impact; Image processing; Damage estimation

Corresponding author: Yan Song

E-mail: sonya@usst.edu.cn

 ORCID: <https://orcid.org/0000-0002-9035-9142>

Motivation

- It is always a challenging task to model the trajectory and make an efficient damage estimation of debris clouds produced by hypervelocity impact (HVI) on thin plates due to the difficulty in obtaining high-quality fragment images from experiments.
- To improve the damage estimation accuracy of HVIs on a typical double-plate Whipple shield configuration, we investigate the distributive characteristic of debris clouds in successive shadowgraphs using image processing techniques and traditional numerical methods.
- The aim is to extract the target movement parameters of a debris cloud from the acquired shadowgraphs using image processing techniques and construct a trajectory model to estimate the damage with desirable performance.

Main idea

- An advanced photographer, the hypervelocity sequence laser shadowgraph imager, is used to acquire sequential shadowgraphs of a debris cloud with high resolution.
- Most of the overlapping fragments are separated using the concave point segmentation technique.
- By analyzing the motion characteristics of fragments and conducting image matching in successive frames of the debris cloud, the trajectory model of matched fragments is successfully established.
- Damage to the rear wall is effectively estimated based on the established trajectory model by comparing the actual damage pattern of the rear wall and the estimation based on the established model.

Raw images

In our experiment, eight images were obtained by the hypervelocity sequence laser shadowgraph imager every 5 ns.

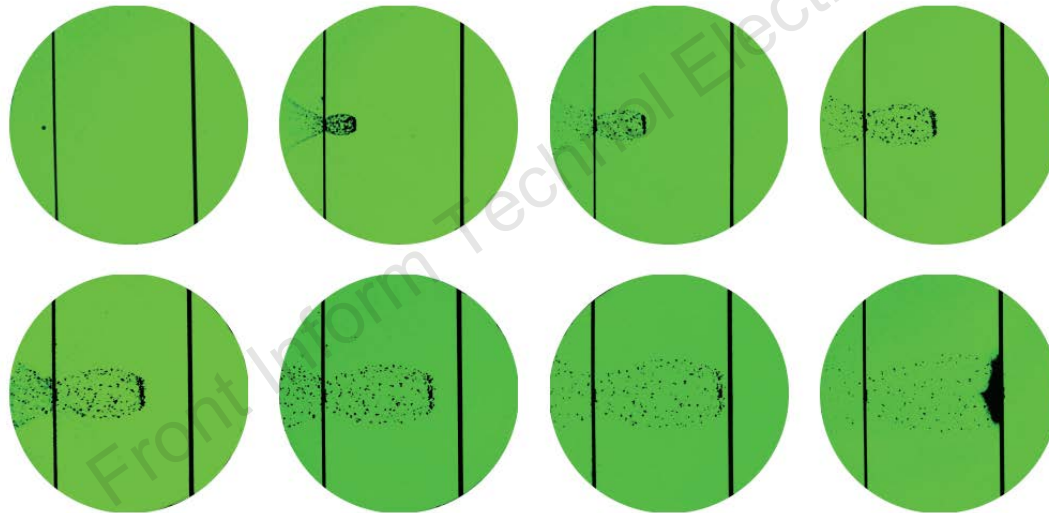


Fig. 3 Raw images of debris clouds (the resolution is 150 mm × 150 mm)

Raw images



Fig. 5 Surfaces of the rear wall after hypervelocity impact (the size is 200 mm × 200 mm): (a) front surface; (b) back surface

Method (Cont'd)

Image processing:

1. Pre-processing including image denoising and threshold segmentation



Fig. 7 Key fragments of debris clouds after pre-processing (the resolution is $80 \text{ mm} \times 53 \text{ mm}$). In (a)–(d), the number of fragments is 60, 90, 109, and 90, respectively

Method (Cont'd)

2. Concave point segmentation of debris clouds



Fig. 8 Results of Fig. 7a by concave point segmentation (the resolution is 80 mm $\times$ 53 mm). References to color refer to the online version of this figure

Method (Cont'd)

3. Image matching of debris clouds by moment invariants

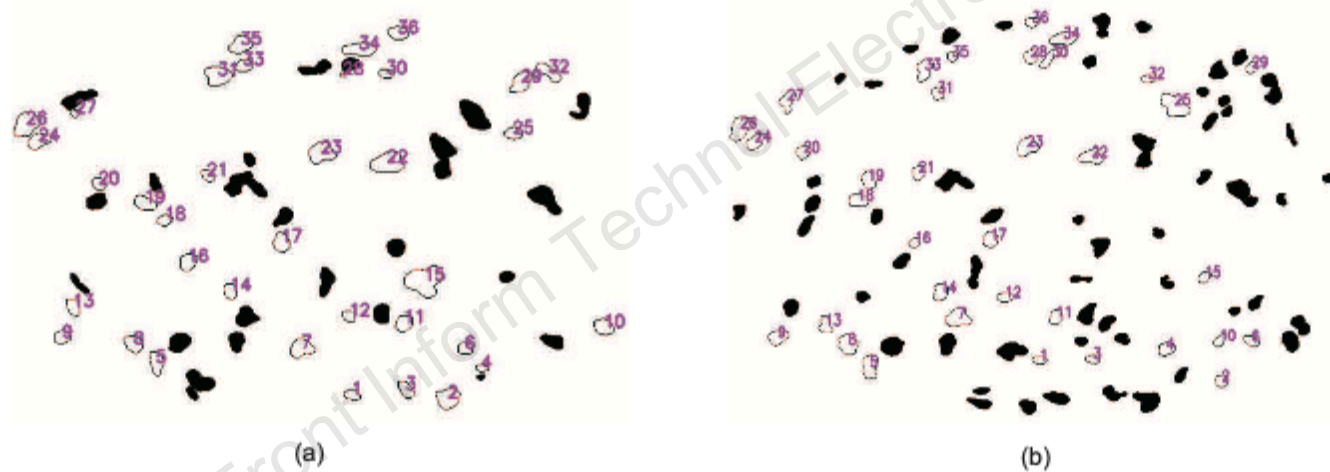


Fig. 9 Image matching of adjacent fragments (the size is 80 mm $\times$ 53 mm): (a) results of Fig. 7a; (b) results of Fig. 7b

Method (Cont'd)

4. By linking these matched fragments based on the centroid coordinates in Fig. 11, the evolutionary trajectories of fragments in the xy plane are desirably obtained (Fig. 12).

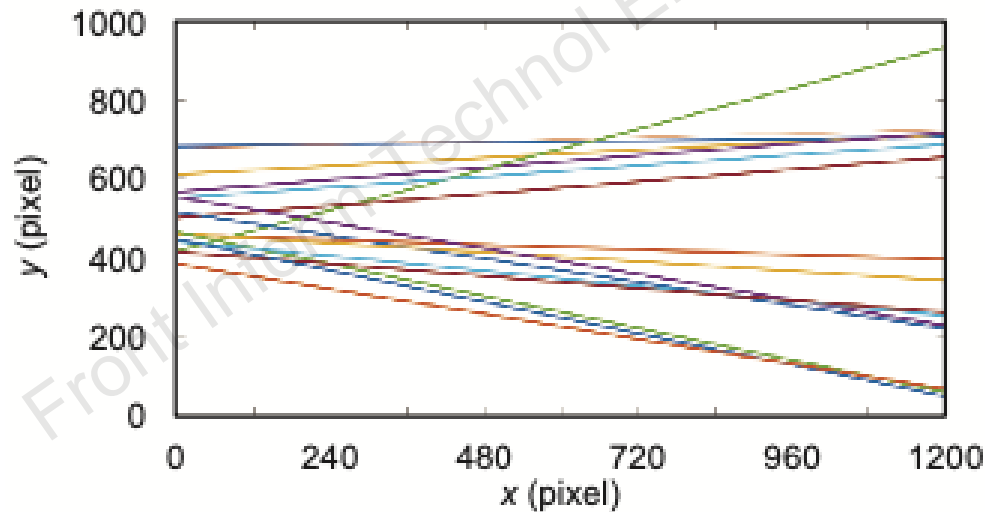


Fig. 12 Trajectory of matched debris

Method (Cont'd)

5. Image processing of the front surface of rear wall



Fig. 13 Binary image of the rear wall (the size is 2000 mm × 2000 mm)

Major results

1. Distribution of debris velocity

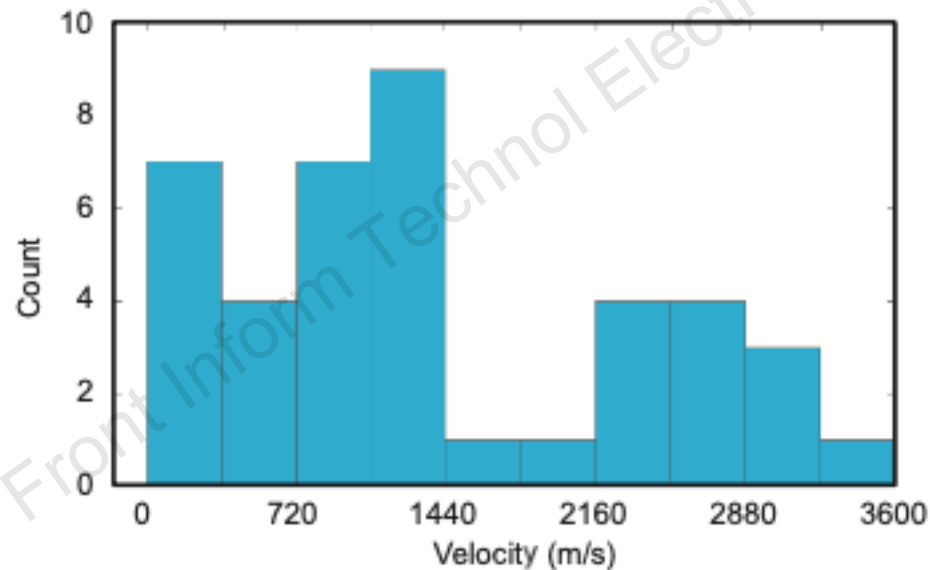


Fig. 18 Velocity distribution of fragments

Major results

2. Distribution of the debris leap angle

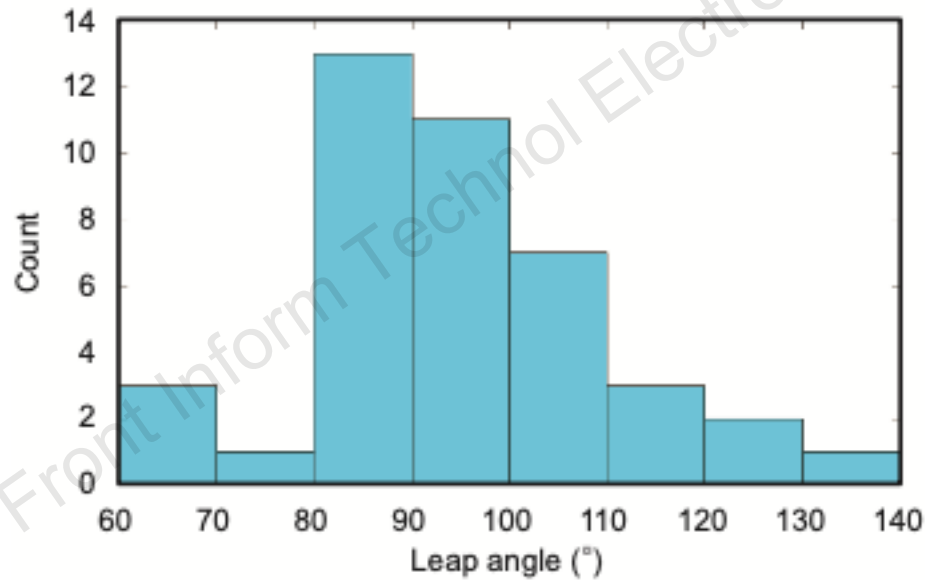


Fig. 21 Distribution of fragment leap angles

Major results

3. Matched fragments with k -means clustering

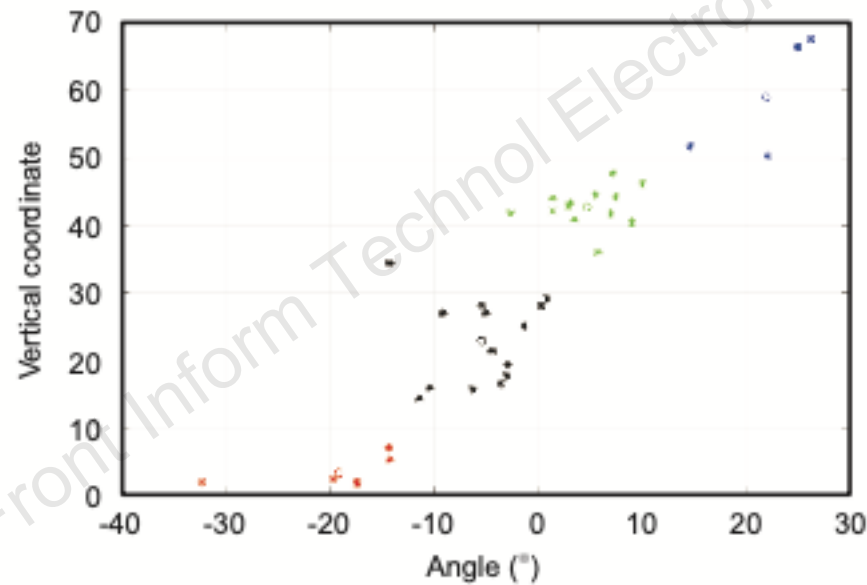


Fig. 24 Matched fragments with k -means clustering

Conclusions

By using image processing techniques, such as denoising and segmentation techniques, special fragment features are extracted from successive images. Based on the extracted information, image matching of debris is conducted and the trajectory of debris clouds is modeled according to the matched debris. A comparison of the results obtained using our method and traditional numerical methods shows that the method of obtaining hypervelocity impact experimental data through image processing will provide critical information for improving numerical simulations. Finally, an improved estimation of damage to the rear wall is presented based on the constructed model. The proposed model is validated by comparing the estimated damage to the actual damage to the rear wall.



Yan SONG received the BE degree in materials science and engineering from Jilin University, Changchun, China, in 2001, the ME degree in applied mathematics from University of Electronic Science and Technology of China, Chengdu, China, in 2005, and the PhD degree in control theory and control engineering in Shanghai Jiao Tong University, Shanghai, China, in 2013. She is currently a professor, vice dean of the Department of Control Science and Engineering, University of Shanghai for Science and Technology, Shanghai, China. From Dec. 2016 to Dec. 2017, she was a visiting scholar with the Department of Computer Science, Brunel University London, Uxbridge, UK. Her research interests include model predictive control, machine learning, and data analysis. She has published around 60 papers in refereed international journals, including around 20 IEEE Trans. journal papers. She is an active reviewer for many international journals.