Investigating High-Speed Liquid Impingement with Full-Field Measurements

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Abstract. Repeated high-speed liquid impingement on solid surfaces often results in erosion that can have undesirable consequences. At the 2018 BSSM conference, we presented the preliminary results of our investigation into the fundamentals of Water Droplet Erosion using full-field measurements. This investigation is now complete, and the results have been interpreted in detail using modelling. This has offered new insight into the process of liquid impingement. The most significant being, the assumption of a rigid solid surface (foundational to much previous analysis) is inappropriate.

Introduction

The erosion of engineering components by the repeated impingement of high-speed (50 ms^{-1} and above [1]) droplets of water is a challenge to the efficient running and function of: steam turbine blades, leading-surfaces of high-speed aircraft, wind turbine blades, gas turbine compressor blades, and aeroengine fan blades. Following nearly a century of research activity [2], the complexities of this form of erosive wear have meant a theory of Water Droplet Erosion (WDE), established from first principles, has eluded the research community thus far [3]. To advance fundamental understanding, researchers have frequently focussed on an individual high-speed droplet impingement, both in modelling and experiment. By deconstructing the material and surface evolution, which occurs over thousands of impingements, to focus on an individual event, it has then been possible to understand in greater detail how changes in relevant parameters effect the dynamic mechanical loading that drives the erosion–particularly in the early-stages. This has high industrial relevance when alternative component design strategies to minimise the effect of the dynamic loading are explored.

In recent years, the capacity of the predictions from models has outstripped the measurements made experimentally. There remains significant uncertainty surrounding the exact nature of the dynamic loading resulting from a high-speed liquid impingement and there has not been sufficiently precise and detailed experimental measurements available to fully assess the accuracy of the models. We have sought to address this uncertainty by using the Grid Method to perform full-field measurements of the solid response to a high-speed liquid impingement and then analyse the results with modelling.

Methodology

A test specimen, manufactured from polymethylmethacrylate (PMMA) with a grid (pitch 0.34 mm) printed on the surface, was subjected to a high-speed impingement of water. The rig [4] generated a high-speed curved-fronted water jet (a commonly-used experimental analogue of a high-speed droplet) with an impingement velocity of 233 ms^{-1} and equivalent radius of 2.4 mm (mean values). PMMA was selected as the material due to its low stiffness and comparatively well-understood response to high-speed liquid impingement [5]. The grid was recorded by an ultra-high-speed camera at 5 MHz. Figure 1 shows the experimental set-up used.

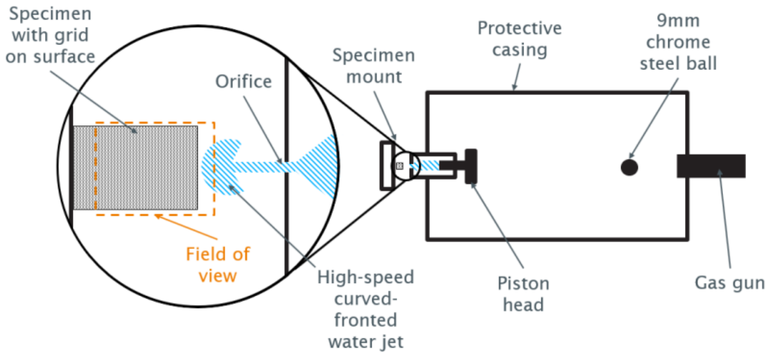

Figure 1: Experimental set-up for producing high-speed liquid impingement on specimen with grid pattern.

To better interpret the experimental results, two models were created. One model assumed the high-speed liquid was unaffected by the deformation of the solid surface, the other did not. This second model was semi-empirical, where the loading generated by the high-speed liquid was modified by previous experimental measurements of impingements on PMMA [6]. Both models used explicit Finite Elements to simulate the material response. To compare effectively with the experimental measurements, image deformation simulations [7] were performed.

Results

The results supported the current qualitative description of a high-speed impingement. However, the widespread assumption of a rigid solid surface in existing theory and modelling of high-speed liquid impingement was found to be inaccurate. Only the second model, which recognised the effect of the deformation of the solid surface, was successful in predicting the measured temporal and spatial variation in displacement and acceleration (Fig. 2). This model suggested the PMMA was experiencing strain-rates of the order 10,000 /s and the energy absorbed by the solid surface was less than 0.3% of the total kinetic energy of the equivalent droplet impingement.

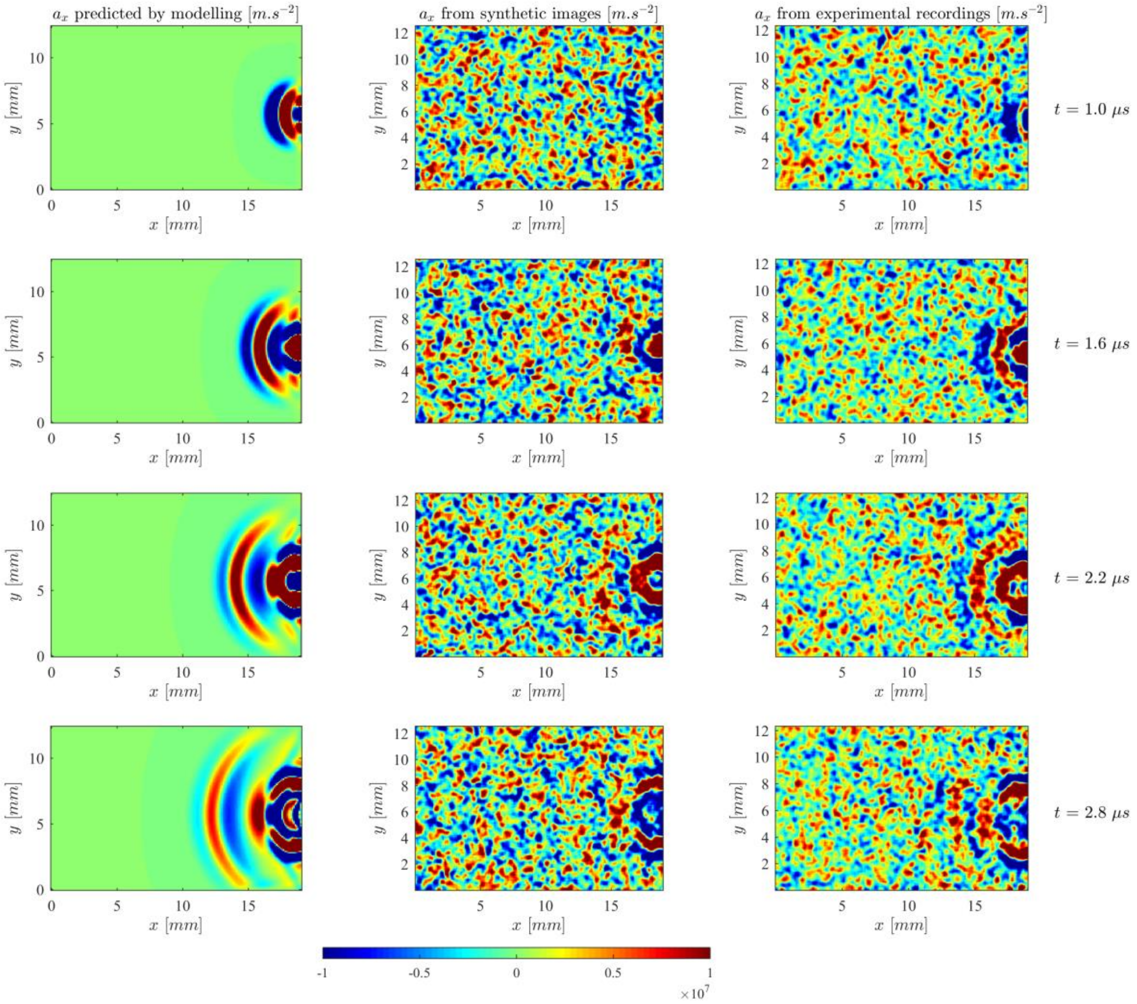

Figure 2: Acceleration in the *x*-direction (parallel to the direction of impingement), a_x, for the compliant model predictions, synthetic images, and experimental recordings. The scale of acceleration is ± one million *g*.

Conclusions

The results offer new insight for understanding the erosion that results from repeated high-speed liquid impingement. They are also of interest to a wider group of researchers developing models involving the compressibility of liquids. Finally, this work offers a case study for how full-field imagining of the material response to dynamic loading can be used to advance understanding of industrially relevant engineering challenge.

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