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EXPERIMENTS AND SIMULATIONS OF WEAK SHOCK WAVE DIFFRACTION PHENOMENA

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Abstract: Shock wave diffraction is a complex process which has been studied at great length but has never been fully understood. The diffraction process creates numerous complex wave structures, a shear layer and a strong vortex. The structure of this shear layer has been the subject of numerous studies. Some simulations have shown this shear layer to be unstable and develop Kelvin-Helmholtz-style instabilities. The diffraction process is widely regarded as self-similar in time; however, these instabilities have never been seen experimentally at small time scales. The high speed and small scale of the phenomena present make them extremely challenging to visualize using any experimental method. In this study, shadowgraph, PIV, laser sheet visualization and CFD have been used in conjunction in order to give a complete picture of the flow field generated by a $M_i = 1.28$ diffracting around a 172° corner.

Key words: Shock diffraction, Shadowgraph, PIV

INTRODUCTION

When a travelling normal shock wave encounters an increase in area, it diffracts into the area increase. Skews [1] showed how the shock wave diffracts around different angles. He showed that past a critical angle of 75° , the flow remains unchanged. As the shock wave diffracts around the corner, a contact surface is created. This surface separates the gas that has passed through the normal shock from the gas that has passed through the curved shock. If induced flow cannot navigate the sharp corner, separation occurs leading to a shear layer which is swept into the strong vortex generated [2]. The structure of the shear layer has been touched on in many numerical and experimental studies and has been a source of disagreement in the research community. This study aims to put those conflicts to rest and to show the complete picture of the flow field for the first time. Previous studies by Sun & Takayama [3] showed shear layer instabilities computationally but the authors were unable to find them experimentally. Skews [4]

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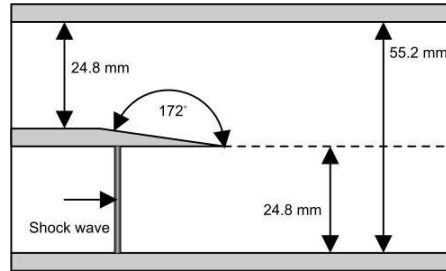


Fig. 1: Schematic of test section

used an extremely large shock tube to allow the diffracted shock wave to pass far away before returning from the wall of the test section, and found instabilities on the shear layer, albeit at much longer times than were predicted numerically. This led to the conclusion that the process is not actually self-similar in time. All previous experimental studies have used density-based techniques. This study aims to show the applicability of particle-based techniques in conjunction with density-based techniques and CFD in order to give a more complete picture of the flowfield. One incident shock Mach number will be investigated using a mixture of ultra high-speed shadowgraph, PIV, laser sheet visualization and numerical simulations.

EXPERIMENTAL SETUP

The incident shock Mach number is $M_i = 1.283 \pm 0.016$. The shocks are generated using a small 24.8mm square shock tube. The shock waves propagate up to the test section where they diffract around a sharp knife-edge. A schematic of the setup can be seen in Fig. 1.

SHADOWGRAPH

Focused shadowgraph images were recorded using the Shimadzu *HPV* – 1 at 250Kfps with an exposure time of $2\mu s$. Constant illumination comes from an in-house-constructed, 300W Xenon arc lamp. Owing to the low resolution of the images, the de-focusing does not affect the accuracy of the results as the circle of confusion of the system is relatively large. This system gives excellent temporal resolution. The full field image shows an area of 67.5 x 56.3mm, whereas the close up image shows an area of 40.8 x 34.0mm.

PARTICLE IMAGE VELOCIMETRY

Particle image velocimetry (PIV) results were gathered using the LaVision FlowMaster with an Imager pro X 2M camera and a Litron Nano-L-200-15 PIV Nd:YAG laser. This system allows a very small δt , one of the limiting factors in previous studies [5]. For this experiment, $\delta t = 1\mu s$. The laser sheet was aimed vertically down the shock tube with the camera normal to the laser sheet. Al_2O_3 nanoparticles were injected into the test section using a Scitek Consultants PS-10 powder seeder. The average particle size was estimated to be $0.3\mu m$. The relaxation time was estimated to be $1.43\mu s$ using the

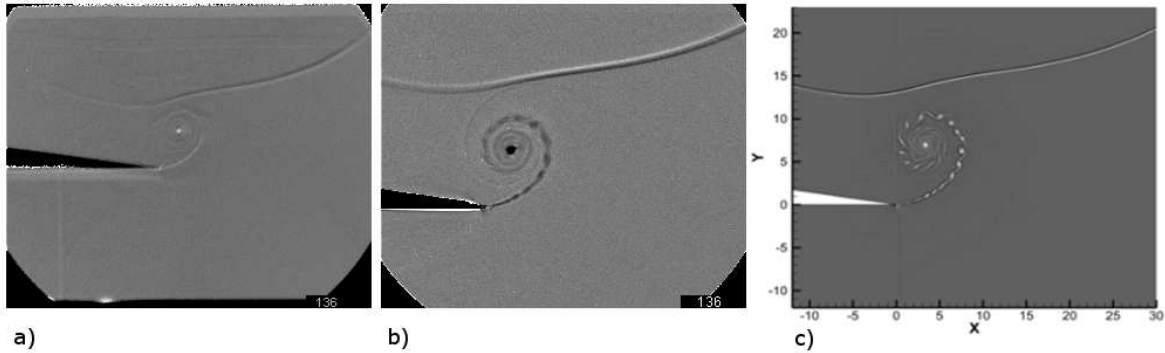


Fig. 2: Comparison of a) full field, b) close up and c) numerical shadowgraph

theory given by Melling [6] with a correction for slip factor and mean free path length. The interrogation window size was 32×32 pixels, corresponding to a size of 1×1 mm. Raw PIV images were used as laser sheet visualization, as they highlighted some flow characteristics that were ambiguous in other tests.

NUMERICAL SIMULATIONS

Numerical simulations were performed using the commercial code Fluent as part of Ansys 13. The simulations used an inviscid density based solver and was second order discretized in both space and time. The initial coarse mesh size of 0.4 mm was refined four times based on pressure gradient giving a minimum grid size of $25 \mu\text{m}$. The CFL number was kept at 0.2 throughout the simulation to avoid non-physical oscillations such as those seen by De & Thangadurai [7].

RESULTS AND DISCUSSION

Fig. 2 shows a comparison between a full-scale shadowgraph image and a close-up shadowgraph image. All three of these images are $136 \mu\text{s}$ after the shock wave has reached the apex. By this time the diffracted shock wave and the expansion wave are returning from the edges of the test section, but have not yet reached the shear layer or vortex and therefore have no impact. The instabilities on the shear layer can only be clearly distinguished using a close-up shadowgraph image and can easily be missed in the full-scale image. The ghosting artifacts seen in Fig. 2a are a known side effect of running the HPV-1 at almost its top speed. A computational shadowgraph is shown for comparison. Numerical simulations show the K-H style instabilities on the shear layer. The coarse-grid simulations did not show these instabilities at all.

Fig. 3 shows the comparison between the PIV vectors captured and the CFD simulations. The velocity magnitudes measured agree at almost every point in the flow-field, the only exception being in the core of the main vortex or other areas where seeding density is too low. These areas appear as *holes* in the vector map. This is due to the inertia of the nanoparticles causing them to be ejected from the vortex core or by seeding non-uniformity. This can be used to our advantage by looking at the raw PIV image, which shows that the particles have also been ejected from the K-H style

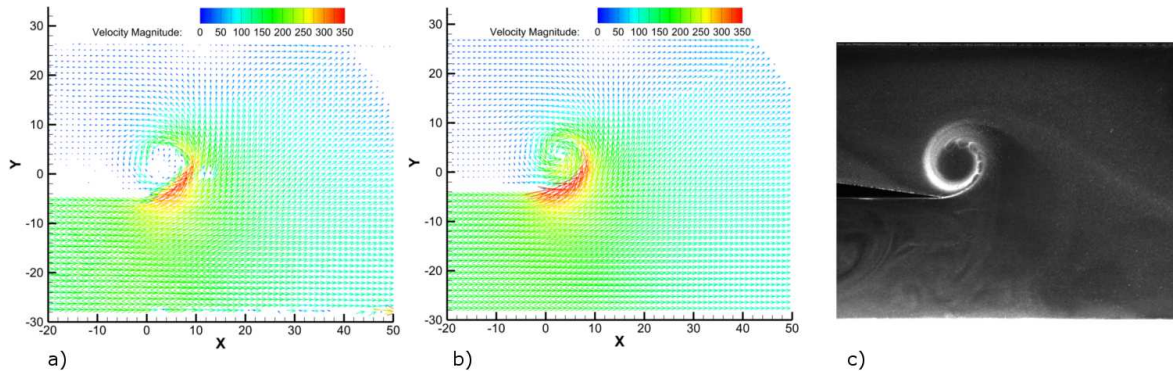


Fig. 3: comparison of a) PIV, b) CFD and c) raw PIV image (best viewed online)

instabilities found on the shear layer. The shock wave loses strength as it diffracts. This is reflected in the velocity vectors.

CONCLUSIONS

This study highlights the need to use multiple experimental techniques to investigate small-scale phenomena associated with moving shock waves. Optically zooming the images recorded using shadowgraph has uncovered flow features that had previously been missed. Focused shadowgraph is the optimal tool for measurements of this type, as it is very difficult to achieve schlieren images of such small features in a flow dominated by larger, stronger features. Raw PIV images used as laser sheet visualization show any vortices in the flow very clearly, as the particles are ejected from the vortex core, creating bright outlines around the vortices.

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