Wave Diffractions over a Cavity

S Vishnu Prasad[1], Rajesh G[1,*], Anbu Serene Raj C[1] and Vinoth P[1]
1: Dept. of Aerospace Engineering, IIT Madras, Chennai, India
* Corresponding author: grajesh@smail.iitm.ac.in

Keywords: Wave diffraction, Shock waves, Expansion waves, Shock tube

ABSTRACT The shock wave propagation, diffraction, focusing, mitigation and attenuation have been extensively studied for several decades. However, its counterpart, expansion wave diffraction over geometries/obstacles such as cavities, has not been studied adequately and is still an untouched area. The current study compares the shock and expansion wave diffractions over a cavity at one diaphragm rupture pressure ratio numerically and experimentally. The diffraction patterns and flow structures observed for a particular diaphragm rupture pressure ratio (DPR) over a rectangular cavity of aspect ratio (L/D = 2.0) are contrasted. Experiments are performed in a closed-ended shock tube, while the numerical simulations are carried out using an in-house 2D inviscid, finite volume, high-resolution TENO (Targeted Essentially Non-Oscillatory) shock capturing code.

1 INTRODUCTION

Comprehending wave propagation and diffraction principles over various geometries can be crucial to creating an effective blast wave and shock wave attenuation system. Many techniques, such as the use of solid barriers, foams, textiles, porous materials, granular filters, metallic grids, perforated plates, branched/bend ducts, and ducts with rough walls, can be used to accomplish attenuation. Another significant application pertains to public safety, specifically the susceptibility of structures to air blasts resulting from bomb explosions or industrial accidents. Blast effects travel long distances via wave propagation, resulting in complicated shock wave diffraction/reflection phenomena that influence structure loading histories. Over the past 40 years, numerous studies by Igra et al. (1996,1998,2001), Sun and Takayama (2003), Skews et al. (2012), Law et al. (2014), Chaudhuri and Jacobs (2017) have examined the diffraction of shock waves with different geometry configurations to further a comprehensive understanding in this area. Igra et al.(1996) studied the flow field resulting from the interaction between a planar shock wave and a square cavity was studied in detail, both experimentally and numerically. They also extended the study to different gas-filled cavities in 2016 to find its significant effect on the evolved flowfield.

Expansion waves are seen as commonly as compression waves. An internal combustion engine is a common example of a technology application where the repeated opening and closing of the input and outflow valves generates intricate patterns of shock and rarefaction waves. Its propagation, interaction, and diffraction find applications such as pressure vessel fracturing, flow leakage into high-pressure tanks, and rapid depressurization of quench bombs, as well as the quenching of nozzle plumes for ramjet/rocket-fired artillery shells caused by expansion fan interaction in the near-field of an artillery gun. Only a few sporadic studies have been conducted where an expansion wave diffraction is of primary focus. Whalley and Skews (2018) investigated the flow field developing due to expansion waves entering a cavity from an upstream tube and its focusing effect. Experimental and numerical results demanded further improvement to analyse the flow structures and features properly.

The present study aims to investigate the expansion wave propagation and diffraction over a rectangular cavity of aspect ratio (length (L)/depth (D)) of 2.0 at a particular diaphragm rupture pressure ratio (DPR). Furthermore, the results will be contrasted against shock diffraction over the same cavity at the same DPR.

2 METHODOLOGY

2.1 Computational Details

An in-house 2D shock-capturing finite volume code is developed to simulate the wave diffraction over the cavity. The finite volume code uses a high-order, high-resolution shock-capturing TENO scheme developed by Lin Fu (2019). The TENO reconstruction is preferred over the other types of WENO schemes due to its ENO-like property in identifying the shock and other discontinuities in the stencil, thus choosing between a low dissipative scheme or a high dissipative scheme for the final flux reconstruction. This property of the TENO scheme makes it more robust and attractive to use in the simulations of various flows that involve shockwaves and other discontinuities in the flow field. The high dissipative solver used in the present scheme to calculate the flux is an approximate Riemann solver HLLC developed by Toro et al. (2019). The time marching is carried out using a classical RK-4 method.

The computational domains for the present study are shown in Figure 1. The driver (high-pressure section) and driven (low-pressure section) sections of the shock tube are 350 mm and 1000 mm long, respectively. Figure 1(a) depicts the rectangular cavity placed in the driver section at a distance of 100 mm from the diaphragm location for the expansion wave diffraction study. The length of the driven section is taken to be sufficiently long to provide enough test duration between the diaphragm rupture and the arrival of the reflected shock wave into the driver. Similarly, figure 1(b) illustrates the domain of the shock wave diffraction study, with the cavity placed in the driven section of the shock tube at a distance of 850 mm from the diaphragm location. The height of the shock tube is 100 mm.

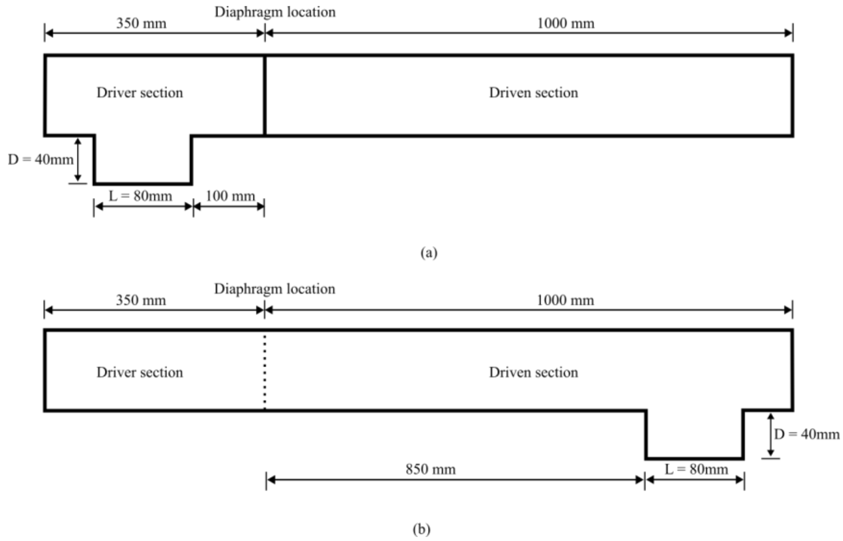

Figure 1. Schematic of the computational domain for (a) Expansion wave diffraction and (b) Shock wave diffraction study.

2.2 *Experimental Details*

A closed-ended rectangular shock tube of cross-section 100 mm × 50 mm, designed in the High-speed flow and Ballistics lab at IIT Madras, is used for the current experimental study. The same shock tube is used for the two wave diffraction studies, with the only difference being the location of the cavity: in the driver section for expansion wave diffraction and in the driven section for shock wave diffraction. In the driver section, a 20-bar piezoresistive sensor is flush-mounted to measure the absolute pressure and diaphragm rupture pressure ratio. Two piezoelectric pressure sensors are placed in the driven section, separated by 400mm from each other, to calculate the shock speed in the driven section. A time-resolved Z-type schlieren with a Cavitar Cavilux laser light source at 10 ns pulse width setting and the i-Speed-726 high-speed camera at 30000 fps is used to visualise the flow field.

3 RESULTS & DISCUSSIONS

An experiment is conducted to study the shock wave diffraction over the rectangular cavity of aspect ratio (L/D) = 2.0. An incident shock mach number (M_s) of 1.44 ± 0.1 corresponding to a diaphragm rupture pressure ratio (DPR = P_4/P_1) of 5.71 was considered. The sequence of schlieren images in figure 3 shows the instantaneous diffraction pattern of the planar shock wave as it passes over the cavity at a shock Mach number, M_s = 1.44.

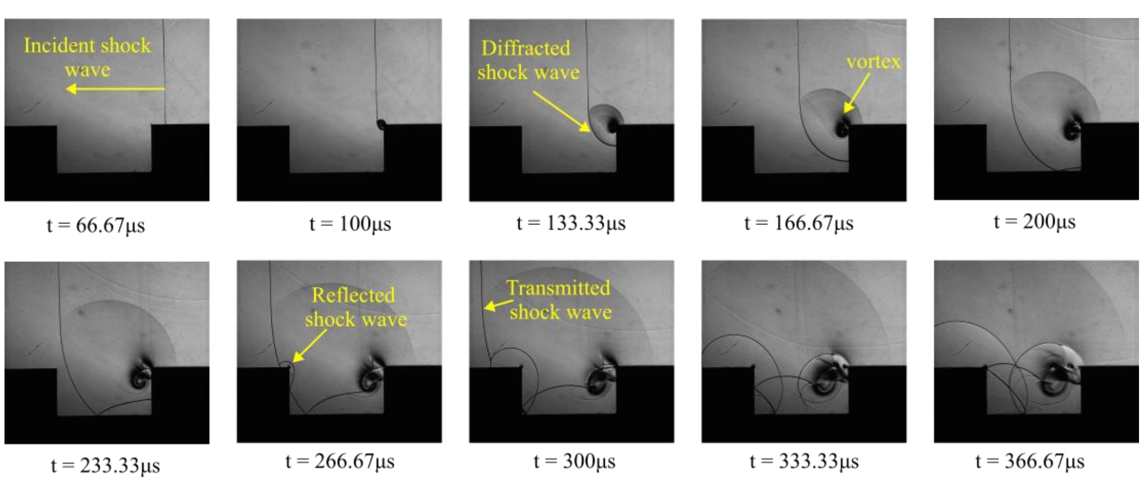

Figure 2. Schlieren images of shock wave moving over the cavity at various time instants at M_s = 1.44, captured at 30000 fps with a resolution of 700 X 700 pixels.

The frame at which the shock wave enters the schlieren visualisation window is taken to be the reference time (t = 0 µs). As seen in figure 3, the planar shock wave gets diffracted at the mouth of the cavity at t = 100 µs. The shock wave diffracts to maintain perpendicularity to the wall and travels towards the cavity rear end as time marches. The induced flow behind the shock wave separates at the backward-facing step of the cavity, creating a vortex (refer figure 3 (t = 166.67 µs)). At t = 200 µs, the diffracted shock wave hits the cavity floor and reflects back towards the top wall of the shock tube. This wave interacts with the vortex, leading to complex shock-vortex interaction patterns seen later, including embedded shocks. Later, at t = 266.67 µs, the diffracted shock reaches the end of the cavity, reflects back from the vertical wall and is also transmitted over the cavity (highlighted in figure 3 (t = 300 µs)). This diffracted wave splitting into reflected and transmitted shock waves was both experimentally and numerically visualised by Igra et al. (1996, 1998). Comparing to the work of Igra et al. (1996, 1998) which was a square cavity, the planar shock diffraction, reflection, vortex generation remains similar. But in the current study the cavity configuration is rectangular, so an extra reflection pattern from the cavity floor along with some interaction of these wave with the vortex sheding from the cavity mouth (t > 300µs) is observed, which is quite interesting and necessitates further study.

The diffraction pattern of expansion waves over the cavity has not been appropriately visualised till date. Therefore, the experiment on expansion wave diffraction will give clearer insights into this study. The full paper will comprise the experimental results of expansion wave diffraction over the cavity at the same DPR, along with numerical contours of shock and expansion diffraction.

4 CONCLUSION

Wave diffraction comparison studies are being conducted experimentally and numerically to compare the induced flow features and wave diffraction patterns of shock and expansion waves over a rectangular cavity. Experimental schlieren images on shock wave diffraction for a DPR of 5.71 reveal extraordinary reflection patterns and induced vortex-shock interactions. Expansion waves are also expected to produce interesting flow features and diffraction phenomena. The full paper will study these results against inviscid higher order accurate numerical simulations.

5 REFERENCES

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