On the Shock Wave Propagation Dynamics Following Sudden Area Expansion

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ABSTRACT We use both experimental and numerical techniques to study the diffraction process and downstream evolution of a normal shock wave as it moves through a back-facing step expansion. Our study follows the evolution of shock waves entering the expansion at Mach numbers ranging from 1.1 to 1.8 and expanding through area ratios of up to 5, as they propagate away from the expansion region, until their eventual transformation back into a uniform normal shock (see figure 1). As the shock wave enters the expanded region, it undergoes rapid deceleration, forming a highly non-uniform shock front. As the shock front progresses further downstream, the expanding part of the shock wave reflects to form a laterally moving shock wave that intersects the shock front at a triple point which reverberates laterally between the walls. We have identified this process as the main mechanism that disperses the flow properties behind the incident shock front and evens out variations as the shock propagates downstream. During this process, the multiple reflections created by the reverberation of the triple points between the walls of the test section generate significant pressure fluctuations behind the shock front. Additionally, we have found that the evolution of the shock front can be conveniently scaled using the height of the expanded region and the velocity of the shock wave far downstream from the expansion.

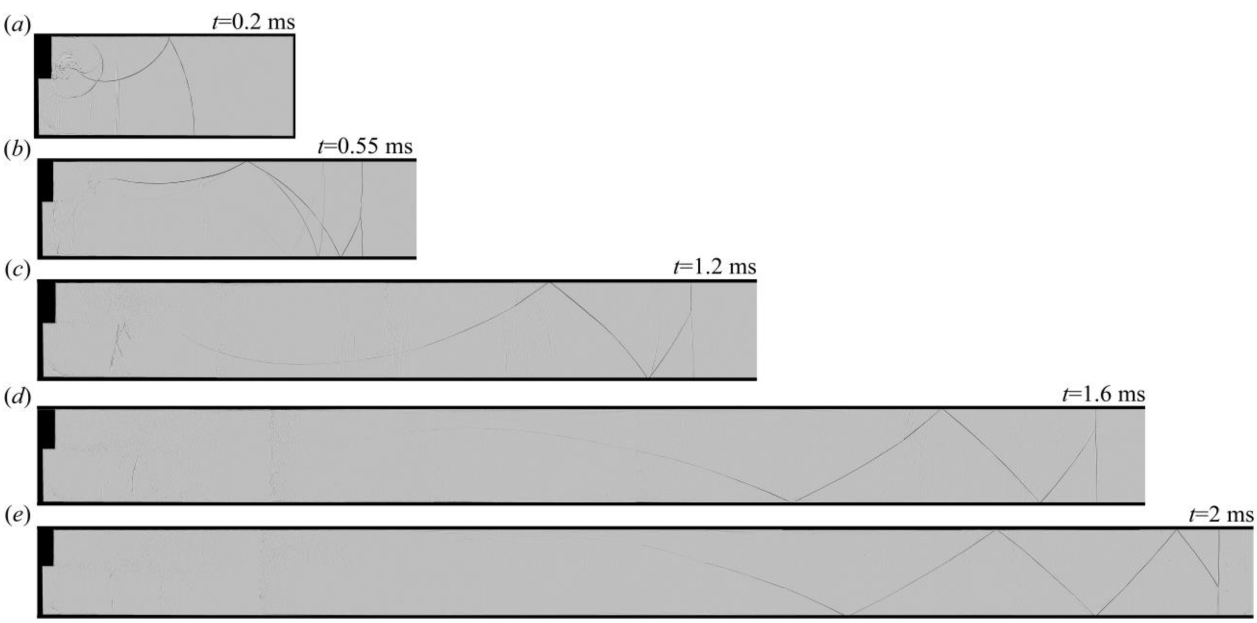

Figure 1: A series of schlieren images recorded in experiments performed with H=70mm, M=1.7, showing the shock wave propagation downstream along the test section. (x = 0mm to x = 960mm).

METHODS This research employs high-speed imaging, pressure measurements, and high-fidelity numerical simulations to explore the flow field and shock reflection patterns as a shock wave propagates downstream after a sudden area expansion. The experiments were conducted at the Transient Fluid Mechanics Laboratory shock tube located at the Technion-Israel Institute of Technology. The shock waves were generated by a pneumatic fast-opening valve, producing consistent shock waves with Mach numbers ranging from 1.1 to 1.8. The 40mm square shock tube is attached to a two meters long test section with a sudden change in area with the variable back-facing steps of 30-90mm, allowing us to observe the shock evolution for a length of 20-60 step heights. The test section has transparent walls, which provide clear optical access to perform schlieren imaging of the flow field and shock wave evolution. Pressure in the shock tube is recorded by up to 22 flush-mounted PCB 113B26 pressure transducers. High-speed imaging at 80-140 kHz frame rates is employed to track the shock wave motion over 25-80 frames in each experiment. The achievable frame rate and resolution depend on the specific experiment height and on the Mach number in the specific experiment. Experiments were conducted at different downstream locations in the test section by moving the shock tube from x=0mm to x=1860mm in 220mm steps. Three experiments were repeated for each location with varied timing to improve the temporal resolution. Experiments were performed with an incident Mach number of 1.4 and 1.7 and steps of 30 mm, 60 mm and 90 mm. The end of the test section was left open to avoid a reflected shock return from the test section end, thereby extending the experiment's duration. To enhance the experimental findings and provide further understanding, a series of numerical simulations that solve the unsteady three-dimensional compressible Navier-Stokes equations were performed at the Technion's CFD Lab using an in-house fully compressible Large Eddy Simulations (LES) solver. The solver performs inviscid flux discretization using a low dispersion sixth order Optimized Upwind Reconstruction Scheme (OURS6) as illustrated in Chandravamsi & Frankel (2023).

RESULTS As the incident shock travels downstream of the back-facing step, the highly transient shock reflections occurring near the entrance region subside, and the multitude of shock reflections formed during the initial shock diffraction process merge (see figure 1) to form an incident shock wave which propagates downstream that continues to reflect off the walls. Figure 1(a) shows the incident shock wave as it reaches x=128mm, illustrating the complex shock reflection pattern that forms shortly after the shock impinges on the walls of the expanded region. At this stage, the reflected shock had already gone through a transition from regular to Mach reflection. The Triple Point of the Mach reflection propagates towards the bottom wall, forcing the Mach stem size to expand until it impinges the bottom wall and reflects back toward the top wall. At the same time, the size of the incident shock wave steadily reduces until it vanishes completely as the triple point reaches the bottom wall. When the triple point reflects, a new Mach stem forms, which begins to grow in size as the triple point ascends, and the previous Mach stem effectively starts acting as the incident shock wave. This Incident Shock to Mach Stem (IS↔MS) reversal process repeats each time the triple point impinges on a wall. The process repeats many times as the shock front propagates downstream. The shock front, which began as a highly curved expanding shock at the entrance to the expanded region, gets more and more normal as the shock front propagates downstream, but in fact, remains slightly curved for an extended duration. The triple point path is present in figure 2(a) for an experiment performed with an incident Mach number of 1.7 and a step height of 30 mm (full height of H=70 mm). The figure shows that as the triple point moves along the incident shock wave, it initially follows the highly curved shape of the expanding shock near the entrance point until it reaches the bottom wall. After the first reflection, the triple point moves along what was the Mach stem of the previous Mach reflection, which is relatively straight; however, as seen in figure 2(b), its velocity, u_{TP}, changes since, in fact, the shock front has not become fully uniform. In fact, it takes several reflections of the triple point to reach a uniform propagation velocity and for the incident shock front to become normal. To fully grasp the effect, figure 2(b) also presents the streamwise velocity of the shock front close to the top wall, $V_{s,t}$, and close to the bottom wall, $V_{s,b}$. Both the top and bottom velocities significantly fluctuate as the shock moves downstream; however, the fluctuation amplitude decreases. Every reflection of the triple point on one of the walls leads to an acceleration, but as it travels back along the curved incident shock wave its velocity decreases. However, as the triple point passes along the incident shock wave, it compresses the flow, thus facilitating a local shock velocity increase. This effect is notably captured as the triple point impinges on the walls, where it merges with the incident shock waves. Eventually, all three velocities converge, achieving a pseudo-steady-velocity, $u_{TP_{ss}}$.

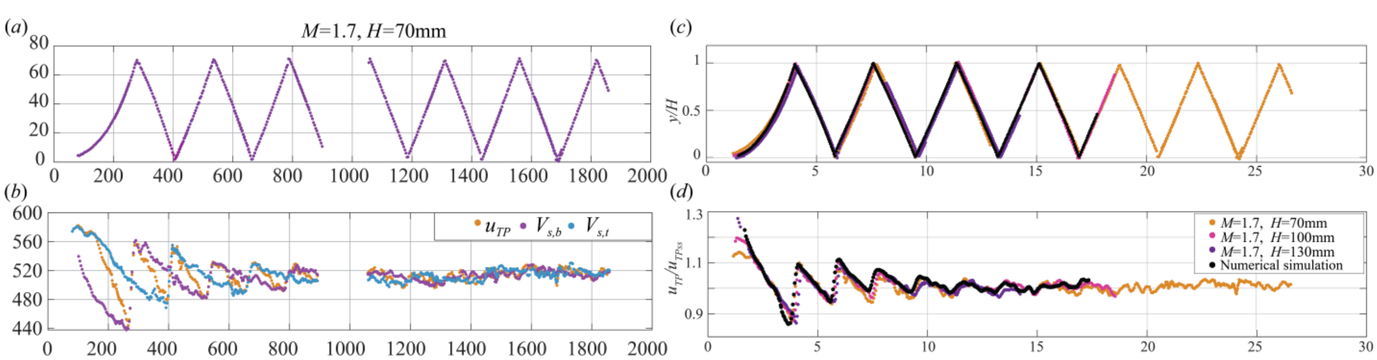

Figure 2: Experimental and numerical results obtained by tracking the TP trajectory and the top and bottom intersections of the shock front and the walls showing their stream-wise velocities plotted vs x; (a) and (b) Step hight of 40mm and M=1.7; (c) and (d) normalized experimental results combined with numerical results.

We conducted several experiments with varying step heights and incident Mach numbers and observed that the shock propagation trends are fairly consistent. By examining the differences between the experiments, we were able to scale the results and plot the triple point trajectories and stream-wise velocities, $u_{TP_{ss}}$, in a non-dimensional form, as shown in figures 2(c) and 2(d). We have found that the test section height H can be used to normalize triple point spatial positions in both x and y directions and that $u_{TP_{ss}}$ can be used to normalize the triple point stream-wise velocity. Note that $u_{TP_{ss}}$ is also the downstream normal shock wave velocity far downstream of the expansion. The numerical simulations were validated against the results and were used to expand the parameter space to Mach numbers ranging from 1.1 to 1.8 and for additional step heights up to 200mm, which will be presented in our talk.

REFERENCES

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