Experimental study on multiple shock waves in a rectangular duct

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Abstract

Multiple shock wave turbulent boundary layer interactions and its oscillations are present in constant or nearly constant area ducts such as scramjet inlets, supersonic ejectors, supersonic wind tunnels, etc. Under certain conditions, a series of normal shock pattern called shock train may form and can cause highly non-uniform and unsteady flow downstream of the interaction. The parameters which affect the structure of this shock pattern is well known for steady state analysis, but the possible reasons for the oscillation characteristics are not yet understood very well. The present study investigates the characteristics of multiple shock waves in a supersonic rectangular area passage for steady as well as unsteady flow conditions. The experimental results are compared with the numerical results obtained from the simulations. The variation in the mean shock position is examined through the wall static pressure distribution and shock location images. Analysis of shock structure variation and its effect on flow field is carried out to understand the mechanism of multiple shock formation and its oscillations.

1Introduction

In the supersonic air intakes, the purpose of the isolator is to separate the inlet from the combustion chamber. In the isolator, the deceleration from supersonic to subsonic velocity can either occur through a normal shock or with a more complicated and gradual transition Matsuo et al (1999). However, due to the existence of a viscous boundary layer, the shock structure is spread into a series of oblique or lambda shock waves and is explained by Sullins (1993). This shock system is known as shock train. Depending on the boundary conditions, such as Mach number, the pressure at the inlet, and outlet of passage, etc., the shock system can be of normal or oblique in nature. In a normal shock train, the first shock will be bifurcated, and the proceeding shocks will be non-bifurcated in nature. In an oblique shock train, the intersecting shock is generated from opposite walls of the duct. These shocks cross to form an X pattern. The shock train region is followed by the mixing region, where both sonic and subsonic flow fields are present with no shock condition. The static pressure is increased in the mixing region as well. The entire region from the beginning of the shock train to the end of the mixing region is known as a pseudo-shock.

In the supersonic flow fields, the shockwave will be interacting with the boundary layer, and a complex flow field is generated after this interaction region. The shockwave/boundary layer interaction creates a local thickening of the boundary layer Wiess et al (2010) and leads to the formation of a virtual nozzle throat. Immediately downstream of the mainshock, the flow is accelerated again at supersonic speeds through this virtual nozzle until the next shock recompresses the flow again. The intense adverse pressure gradient imposed on the boundary layer by the shockwave due to SBLI causes the boundary layer to thicken and possibly to separate (Carrol et al (1990)). TheseSBLIs are the reason for unsteadiness in the flow, and the boundary layer separation leads to highly unsteady flow field resulting inlet instability, aircraft buffeting, and aerostructure fatigue. Three different flow patterns were explained in the experimental investigation conducted by Sajben et al (1984), Chen et al (1979) and Bogar et al (1982), to be no separation, pressure gradient induced separation and shock-induced separation. At the stems of the throat shock, downstream propagating subsonic waves were initiated, and this makes the self-excited oscillations inside the diffuser

The present study investigates the characteristics of multiple shock waves in supersonic rectangular area passage for steady as well as unsteady flow conditions. The experimental results are compared with the numerical results obtained from the simulations. The variation in the mean shock position is examined through the wall static pressure distribution and shock location images. Analysis of shock structure variation and its effect on flow field is carried out to understand the mechanism of multiple shock formation and its oscillations.

2Experimental setup

Experimental studies are conducted in a fully transparent blowdown tunnel having a Mach number of 1.75 at the nozzle exit. The nozzle is designed by MOC and has a throat height of 10mm, and the whole geometry is having a constant width of 20mm. The details of the experimental facility are shown in figure1.

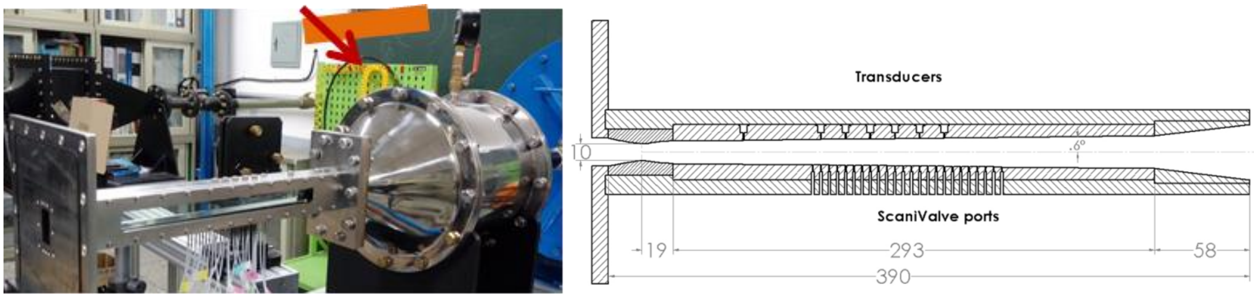

Figure 1: Details of experimental facility

The standard Z type Schlieren optical arrangement was used to visualize the flow fields shown in Figure 2. Schlieren photography was performed to qualitatively visualize the movement of shock in the test section of the wind tunnel. The instantaneousSchlieren visualization was conducted using a high intensity LED light source and a slit is positioned in front of the light source, effectively creating a point source of light. The slit is positioned at the focal point of the concave mirror M1and after reflecting from it the light beam will be collimated and allowed to pass through the test section (TS). The collimated light was aligned perpendicularly, both horizontally and vertically, to the wind tunnel test section. After reflecting from the second mirror M2, the light beam focus to the focal point of M2, where the knife edge is positioned. In no flow condition, the knife edge is adjusted to cut off half of the light, so that half of the light escaping is able to illuminate the screen uniformly. This light is collected to the high-speed camera through a lens and then recorded. The images are recorded using Phantom Miro M310 camera.

Schlieren optical technique is an extremely useful tool for making an-intrusive measurements of density gradients with high sensitivity and accuracy. The preliminary experiments were done with mirrors having a focal length of 2m and 200mmdiameter. The images were taken at a frame rate of 10000 fps and having a size of 440 x 200 pixels with an exposure time of 10 µs. The image resolution of the acquisition was measured approximately to be 0.4mm/pixel.

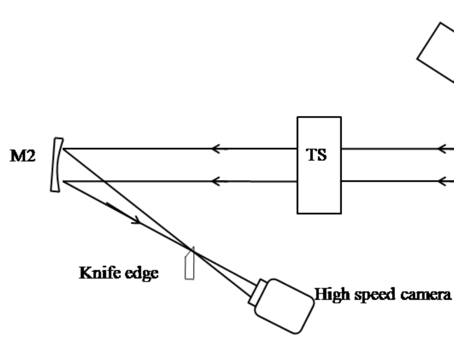

Figure 2: Schematic of the Schlieren optical arrangement.M1 and M2 are concavemirrors of 2m focal length and 200mm diameter; TS indicates the test section.

The Schlieren images were processed using Matlab code to identify the shock locations. The knife edge cut the focused light beam partially such that the high-density region of the shock is obtained as a bright line. The Matlab code takes a strip from the image in the center line where the shape of normal shock is vertical and the background image is subtracted from this. The code look for the highest gradient in intensity presents in the image and take that particular value of the pixel in flow direction as the stock location. With this shock capturing code, the shock position was determined with an estimated uncertainty of ± 1 pixel (±0.34mm).

3Results and discussions

The investigations included Schlieren visualization using high-speed camera and surface pressure2measurements using Scanivalve. During the experiments, pressure ratio is increased to position the first shock wave in the quasi-parallel test section measurements were taken at this time. The experimental images were compared with the computational results obtained from Reynolds averaged Navier Stokes computations. The obtained results are plotted in the figure3. It can be seen from the figure that the results match very well with a small variation in the shock angle which was formed primarily due to the variation of boundary layer thickness in the flow upstream of the first shock wave. The upper part of the figure represents the variation of the Mach number in the flow field and the flow is from left to right.

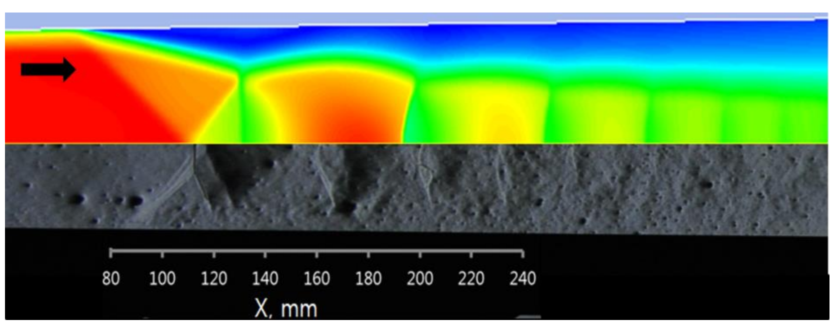

Figure 3: Comparison of experimental and computational results

The Schlieren image of multiple shock waves and comparison of surface pressure measurements between experiment and computation are shown in figure4. The nozzle throat location is taken as the reference point for measurements. Figure 4a represents the position of shock train in the rectangular duct while figure 4b is the comparison of wall static pressure for experiment and computation.

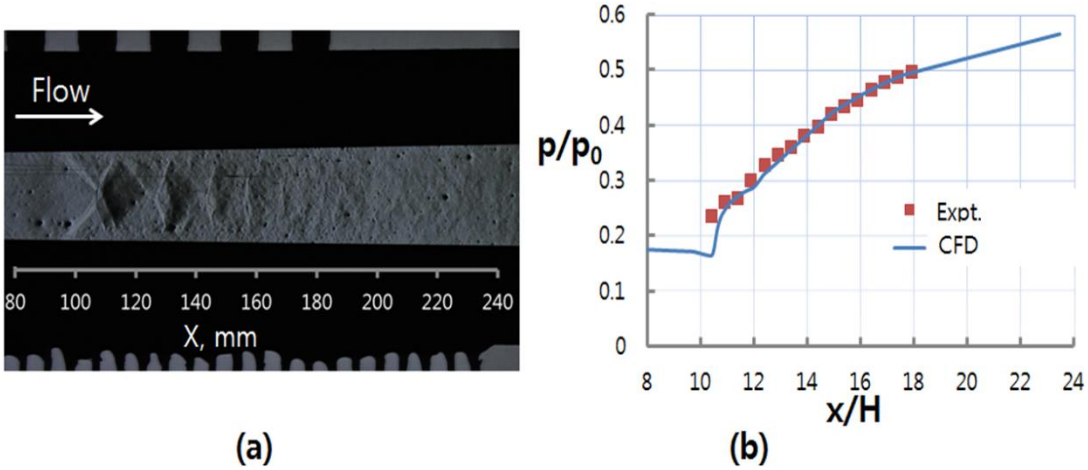

Figure 4: (a) Schlieren image from experiment and; (b) comparison of wall static pressure between experiment and computation.

The pressure on the wall is normalized with inlet stagnation pressure, and shock location is normalized with the throat height of the nozzle. There is a difference in pressure ratio between computation and experiment to maintain same shock location. In the real case, the shock will not be stationary, but oscillating. The theshock train will be oscillatory in nature even if we maintained a constant pressure ratio across the geometry. There are several parameters which influence the oscillation characteristics such as upstream disturbance, downstream disturbance, shockwave boundary layer interaction etc. The images obtained fromSchlieren visualizations were used for image processing to obtain the shock location values.
The maximum upstream and maximum downstream locations of the shock wave are represented in figure5. The images are taken arbitrarily from the set of images when the shock wave was at its extreme locations. During the experiment, the shock wave will be oscillating within these limits.

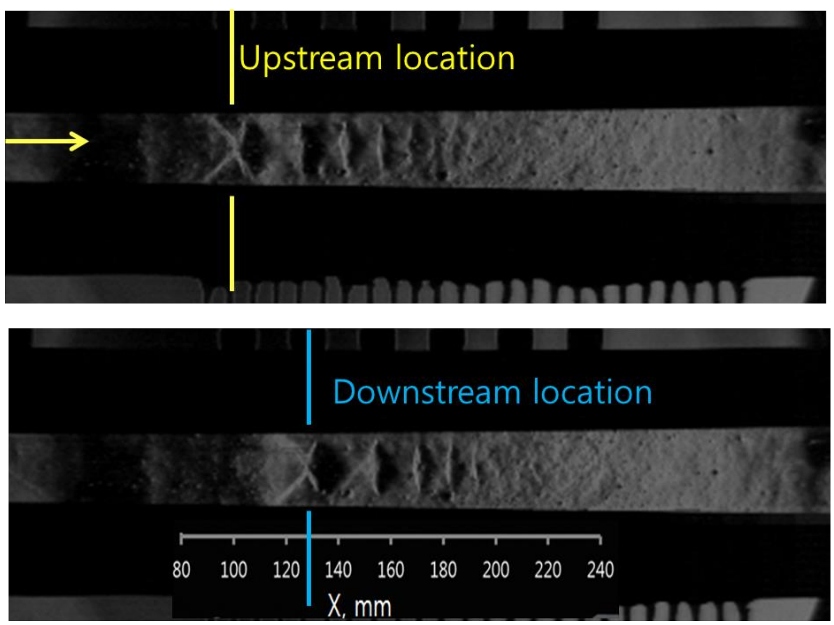

Figure 5: Maximum and minimum limit of shock train oscillation

The Matlab program computes the stock location based on the intensity of each image for each shock of the shock train. The location of the first shock wave is analyzed and the time variation is plotted in figure6, and issue-plotted along with the variation of stagnation pressure upstream of the nozzle. The red line indicates the variation of stagnation pressure upstream of the nozzle. The pressure ratio is defined as the ratio of upstream stagnation pressure to the back pressure.

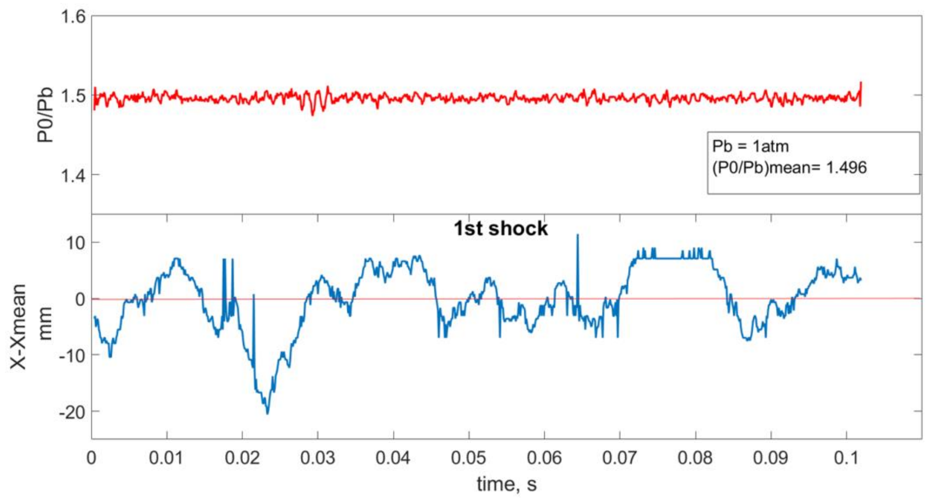

Figure 6: Temporal variation of first shock location and the upstream stagnation pressure

The probability distribution function of the first shock location is presented in figure 7. It is observed that the shock oscillates about its mean position, while it is more probable in the upstream location from the mean. The amplitude of oscillation is much larger in the upstream direction compared to the downstream direction.

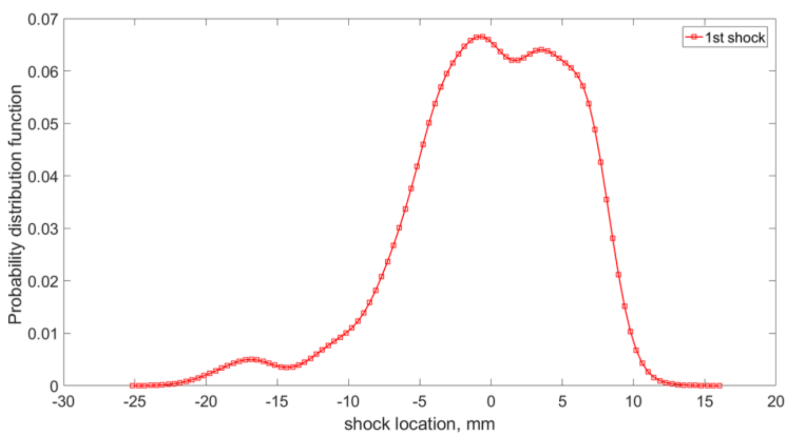

Figure 7: Probability distribution function of the first shock wave

4Conclusions

The characteristic of multiple shock waves in a rectangular channel is investigated computationally and compared with the experimental results. Unsteady experiments were conducted to investigate the shock oscillation phenomenon. A gradient-based algorithm was used to locate the shock from Schlieren images and it predicts the shock location very well. It could be noted that there exist an unsteady oscillation of the shock waves even if the pressure ratio is constant. The correlation between fluctuating pressure along the shock train region and the variation in the mean shock position is also examined through the wall static pressure distribution and shock location images.

Acknowledgments

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