Scientific Journal of Impact Factor (SJIF): 5.71

e-ISSN (O): 2348-4470
p-ISSN (P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 5, Issue 04, April -2018

# A COMPREHENSIVE STUDY OF SHOCK BOUNDARY LAYER INTERACTION AND VARIOUS TECHNIQUES

Samadarshi Adhikari[1], Sonia Chalia[2]

[1,2] *Department of Aerospace Engineering, Amity University Haryana, Gurugram, India*

**Abstract-** *Shock boundary layer interaction is an undesirable event occurring in high speed aircrafts causes boundary layer separation which leads to pressure drop, undesirable heating load, vibrations, drop in aircraft performance and controlling ability. To remove these undesirable events the flow field is analyzed and diagnosed by micro vortex generators on aircraft body using flow visualization tools. Experimental techniques such as High speed Wind tunnels, Particle Image Velocimetry, Schlieren photography, oil-flow visualization are studied to analysis the changes in flow properties when shock interacts with boundary layer.*

**Keywords:** *Shock Wave, Boundary Layer, Particle Image Velocimetry, Micro Vortex Generator, High Supersonic Tunnel, Schlieren Photography*

## I. INTRODUCTION

Shock waves forms when aircraft travels with velocity more than speed of sound and characterized by an abrupt, discontinuous change in pressure, temperature, density [1]. Shock waves can occur, at air-intake compression ramps of an air-breathing propulsion system, ahead of the vehicle nose, at rounded leading-edge of wings and tails, at control surfaces, on flaperon, at rear part of an after body, etc. Shock wave boundary layer interaction (SBLI) is therefore a phenomena commonly associated with aerospace/aeronautical devices when a shock wave meets a boundary layer in high speed flows and it can affect vehicle and component geometry, structural integrity, material selection, fatigue life, weight, and cost. In addition, strong interactions with the boundary layers are the origin of severe aero-heating problems if the shock is strong enough to provoke separation [2].

The separation of the boundary layer or its disturbance by a shock wave are two phenomena, which can involve increment in losses of total pressure, high peak heat transfer rates, hence drag and can sometimes even be catastrophic if the shock is strong enough to cause separation which often results in large unsteadiness which can damage the aircraft structure or, at least, severely limit its performance. The knowledge of the boundary layer which develops on the surface of aircraft body is essential to optimize the use of aircraft, its systems and equipment and for efficient aerodynamic and propulsion design.

SBLIs which occur near deflected control surfaces that are used for controlling and maneuvering supersonic and hypersonic flights such as re-entry space plane and guided missiles. Re-entry vehicle experiences very low density flow, so high flap angles are needed to produce the required control forces on the incoming flow. Because of the high flap angles, flow separation will occur upstream of the control surface due to the high adverse pressure gradients followed by generation of complex shock-wave structures. The separation region reduces the effective area of the flap, consequently minimizing the maneuverability of the vehicle. The generated shock-waves that impinge on the vehicle's body will also increase the local heating rates. Another problem is the flow separation and unsteadiness also contributes to the rise in aerodynamic drag. When these effects combine with the fluctuating pressure loads, the result is severe enough to cause premature structural fatigue for hypersonic vehicles [3]. The effects caused by SBLI are severe therefore large portions of effort are being spent in understanding the physics of the phenomena and the methods that can be applied to overcome SBLI.

The interaction between a shock wave and a boundary layer arises in many flows and therefore continues to be the subject of considerable research. The main concern is that the interactions are caused by many oblique and normal shock waves interacting with the boundary layer of the flow consequently causing boundary layer separation and unsteady flow due to severe adverse pressure gradients so, the objective of this study is to analyzing interaction between an incident shock wave and a flat plate turbulent boundary layer using techniques such as High supersonic tunnel, Particle Image Velocimetry (PIV), Schlieren Photography, Oil-Flow visualization and experimentally investigate the performance of micro-ramps in controlling the Shock Boundary Layer Interactions induced separation utilizing micro ramp vortex generator. The results of these techniques can be further used in computational and analytical modeling purposes.

 

## II. SHOCK BOUNDARY LAYER INTERACTIONS

The interaction of shock wave with a boundary layer results in complex phenomena due to rapid impedance of flow in boundary layer leads to an adverse pressure gradient which can strongly disturbs flow velocity profile and consequences of this interaction are critical for the aircraft performance.

SBLI depends on the type of the boundary layer flow i.e. laminar or turbulent and the basic difference between two is represented by velocity distribution or velocity profile. Flow behavior is dictated by the resistance of the boundary layer to the pressure jump imparted by the shock, a turbulent boundary layer have more filled velocity profile than laminar layer thus more momentum will interact with shock in turbulent flow than laminar flow, keeping the same free stream Mach number [4].

The shear stresses represent a force counteracting the retardation imposed by the shock, so they also provide important contribution in shock boundary layer interaction depending on nature of boundary layer. The relative magnitude of the viscous forces decreases when the Reynolds number (Ratio of inertial force to viscous force) increases, hence the influence of the shear force will be less at high Reynolds number, therefore, This means that there is practically no influence of the Reynolds number when shock interacts with well-established turbulent flow.

The eddies in turbulent flow transfer momentum from the outer high-speed flow to the inner low-speed part of the boundary layer, hence the greater resistance to the shock and the shorter extent of the separated region when it forms. This aspect also explains the behavior of transitional interactions where the laminar-turbulent transition occurs within the interaction domain. So, it must be clear that turbulence plays a central role in the interaction.

## III. FLOW ANALYSIS AND VISUALIZATION METHODS

In last 50 years, several methods have been utilized to study and analysis shock boundary layer interaction. Some of them are as follows:

### 3.1. High Supersonic Tunnel (HSST)

HSST is a supersonic intermittent blowdown tunnel which has the capability of running analysis between Mach 4 to 6 achieved by interchangeable nozzles. The working fluid which is used in the tunnel is dry air. Gas is initially compressed and passed through an absorption dryer that acts as a drying unit before being stored in a high pressure vessel. The gas is then passed through a variable pressure reducing regulator where a power dome controller is used to regulate the gas to the necessary tunnel operating pressure. The gas is maintained at the required pressure in order to achieve the required total pressure downstream of the settling chamber by using compressed air from compressor regulated by a pressure controller. A Schematic layout of HSST is shown in Figure 1.

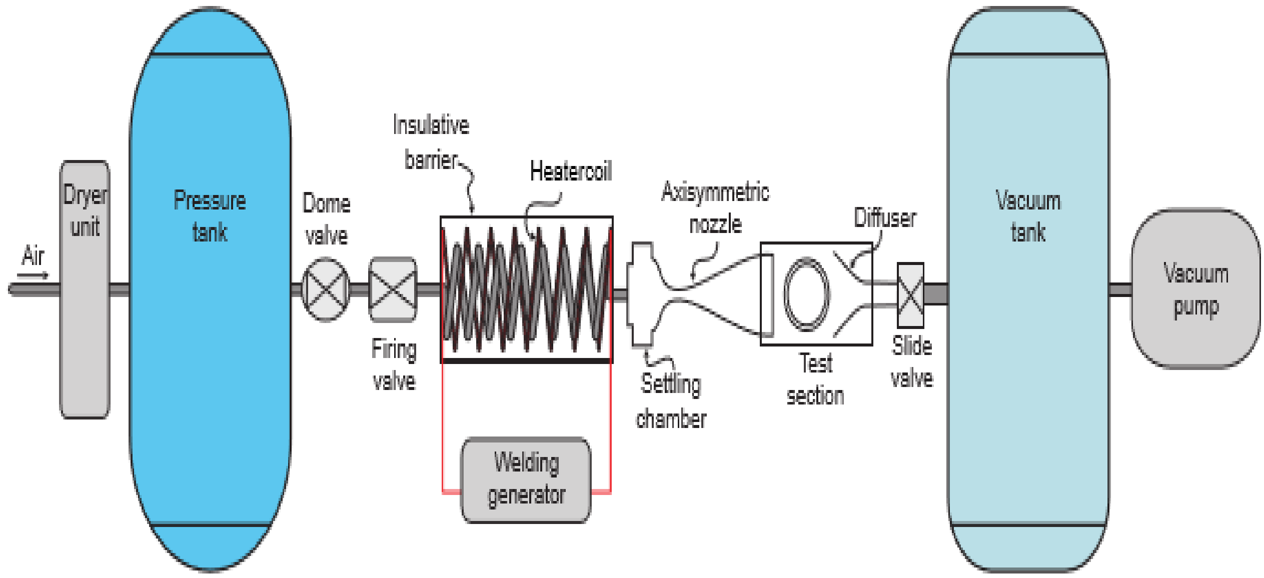


*Figure 1 Schematic layout of HSST*

The gas is passed through a pneumatically operated quick-acting ball valve, before entering the electric resistive heater that consists of a preheated heater tube. The heater tube is formed into a coil, thermally and electrically insulated from the rest of the tunnel. The heater coil is also placed in a container filled with granules of vermiculite to reduce the heat loss to the surroundings. The heater acts in raising the temperature of the gas flow that are sufficient to avoid liquefaction during the expansion through the nozzle. Air is passed into a contoured axisymmetric nozzle through the settling chamber consist a flow straightener matrix that gives a uniform distribution of flow. The test section of the tunnel is an enclosed free-jet design with two interchangeable hinged access doors on either sides of the test section wall. The doors are mounted with Quartz window for optical access to the flow visualizations. Downstream of the test section is a diffuser that has an entrance for the evacuation of the test gas from the test section to a vacuum tank. In order for the working section to be accessed during the depressurized process of the vacuum tank between the runs, a motorized slide valve is positioned between the working section and the vacuum tank. This allows access to the vacuum tank without pressuring it so that it can be maintained at a pressure. The air is evacuated from the vacuum tanks by two rotary piston vacuum pumps. The running time of the tunnel is dependent and limited by the amount of heat that is able to be supplied by the heater and the evacuated mass flow rate by the vacuum pumps. The useful steady run times typically range between 7 to 10 seconds [5 and 6].

### 3.2. Schlieren Photography

The Schlieren technique [7] consists of continuous light source with a focusing lens and a wide slit two parabolic silver coating mirrors with focal length, a knife-edge and a set of close-up lenses. To capture the images, a camera and a Photron APX-RS High Speed Video System is being used. The parallel beam of light from the continuous light source travels through the test section windows before focusing on the knife edge plane which is positioned perpendicular to the flow direction. Later on, the focused beam is captured by the cameras. The Camera is capable of shooting in continuous mode which can record 3.5fps at full resolution. The shutter speed can be adjusted to maximum value of 1/4000sec to capture clear and enough detail images. The high speed Photron camera is used to record time-resolved Schlieren images up to 5000fps at a number of pixel resolutions and shutter speeds.

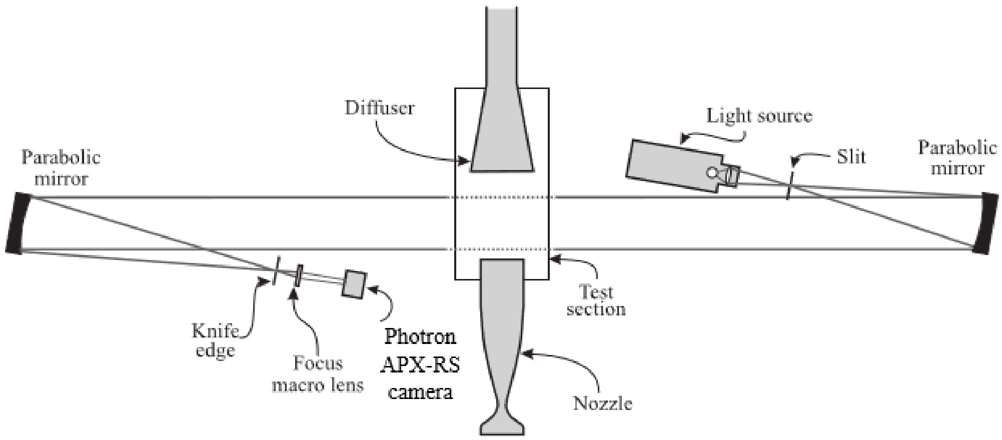


*Figure 2 Schematic setup of high-speed Schlieren photography*

Schlieren technique is considered to be a qualitative measurement technique as it does not reveal any values of the flow characteristics including density. Schlieren play a vital role in giving an initial overview of the flow structures. Since Schlieren integrate the density of the whole volume of the flow, the density change can only be detected in two-dimension. This means that unsteady flows that involves three-dimensionality will not able to be captured intensively. However for two-dimensional flow structures, Schlieren would be a very helpful tool in flow diagnostics. If this is not taken care of, instead of thin lines, thick lines will be recorded as shock waves.

### 3.3. Oil-flow Visualization

Oil-flow visualization seems to be the best method to be applied for flow visualization due to its ability to reveal the footprints of the flow which later are useful to deduce the flow characteristics and has the ability to reveal the complex flow features on the surface of a model [8]. The viscosity of the paint used in oil-flow plays the most important role. Paint having a high viscosity will take longer time to move and show the desired pattern, especially for the HSST facility that has 7-8 seconds of run time, which is a critical factor. On the other hand, if the viscosity is too low, the paint would be blown downstream straight after the tunnel started and no pattern can be visualized. Apart from the viscosity, the ability of the paint to be illuminated and produce reflections that are able to be captured by the recording devices is another important criterion. The process of determining the right viscosity for a specific wind tunnel is always trial and error. For the visualization, normally one color is sufficient. However, by using multiple colors, complicated flow features such as separations and mixing can be detected. Mounting the lights on both sides of the test section provided maximum illumination with minimum direct exposure to the cameras. It also prevented shadows from occurring as a direct result from the model that would otherwise occur from using light on one side only. A Digital SLR camera can be used to record High-Definition videos of the run. Two cameras were mounted on top of the test section one at a time at an angle of 20.8◦ from the vertical plane. Due to the design of the test section, it was impossible to position the camera normal to the model surface. This creates a perspective distortion to the images recorded. The flat plate and the micro-ramps are both painted matte-black to increase the contrast. Paint is applied onto the model carefully so that the paint does not spill and flow outside the dedicated boundary with the help of syringe. After the paint was deposited, the valve that connects the test section and the vacuum tank was opened and this created a vacuum condition inside the test section. Hence, it is of utmost importance to make sure that the paint applied upstream has constant thickness and uniformly distributed otherwise when the test section starts to vacuum, the paint will start to smear and this is an undesirable condition prior to the testing. After the run, the model was taken out from the test section and pictures of the dried paint (due to evaporation during the run) were recorded. The time between two runs can be estimated to be less than 20 minutes. Multi-color paints were used for micro-ramp configurations.

### 3.4. Particle Image Velocimetry

Particle Image Velocimetry (PIV) is an optical non-intrusive method of measuring the velocity of the fluid particle in just a single test. With the use of PIV, complex flow structures and instantaneous flow organization that were not able to be visualized using the traditional point methods such as turbulence and shock wave interactions are now able to be captured. It is an indirect method in measuring the flow velocity because it measures the velocity of the seeding particles which are assumed to be following the flow accurately instead of the flow directly like other conventional methods [9]. The basic theory behind PIV is calculating the velocity based on the displacement of the seeder particles for a known period. By comparing two consecutive images of the same particles but with slight displacements, the velocity of each particle can be computed. The seeder particles or also called tracer particles play a vital role in the PIV system because they enable the visualization of the fluid flow field and information on the velocity are extracted through their behavior and motion and are sufficiently small so that they can follow the fluid motion accurately. To trace and visualize their motion, they are illuminated by a thin light sheet produced by the PIV laser. The light scattering images produced are recorded and analyzed. Basically, there are two functions of the seeder particles in PIV experiments, to follow the path of the flow as faithfully as possible and to scatter the light to the PIV recording devices.

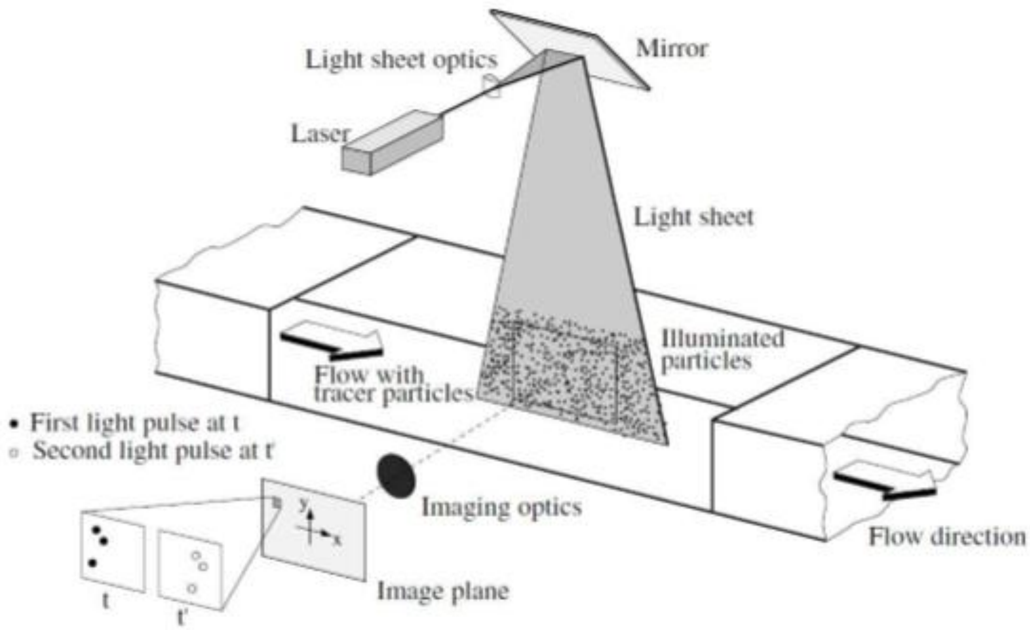


***Figure 3 Experimental Setup for PIV testing***

## IV. MICRO VORTEX GENERATORS

Conventional Vortex Generators (VGs) which have the height of the boundary layer thickness (δ) are used massively to delay boundary-layer separation, enhance aircraft wing lift, reduce drag of aircraft and avoid or delay separation in subsonic diffusers but increases parasitic drag due to their size and furthermore they are used to control a localized flow separation over a relatively short downstream distance [10]. Recent works have been focused on a specific design of micro VGs known as micro-ramps which produce pairs of counter-rotating streamwise vortices which help to suppress SBLI and reduce the chances of flow separation.

With mVGs, the mean and the instantaneous flow can be visualized by different flow diagnostics tools such as Schlieren photography, oil flow visualization, PIV etc.

 

## V. RESULTS

**a)** The boundary layer forming on top of the mVGs surface can be seen in Figure 4. Micro ramp successfully delayed the pressure rise significantly and decreased the stream wise length of the separation region. The most affected region due to SBLI is at the centerline and a small region of steady flow is at immediate downstream area from the mVGs apex

**REFERENCES**

[1] Anderson, “Fundamental of Aerodynamics, McGraw-Hill Science/Engineering/Math, 1984
[2] William F Hilton, “High Speed Aerodynamics”, Longmans Green, 1951
[3] A.J. Smits and J.P. Dussauge, “Turbulent Shear Layers in Supersonic Flow” Springer, 2006
[4] Jean M. Delery, “Shock Wave/Boundary Layer Interactions” chapter 8.3, pp. 205-264
[5] Mohd R. Saad, "Experimental studies on Shock Boundary Layer Interactions" University of Manchester, 2013
[6] A. Pope, “High-Speed Wind Tunnel Testing” John Wiley & Sons, 1978.
[7] E. Erdem, “Active Flow Control Studies in Hypersonic Flows” PhD Report, University of Manchester, 2009.
[8] A.J. Pierce, F.K. Lu, D.S. Bryant, and Y. Shih, “New developments in surface oil flow visualization” AIAA,2010.
[9] M. Raffel, C.E. Willert, and K. Kompenhans, “Particle Image Velocimetry: A Practical Guide” Springer, 2007.
[10] H. Babinsky, Y. Li, and C.W. Pitt Ford, “Micro ramp Control of Supersonic Oblique Shock-Wave/Boundary-Layer Interactions” AIAA, pp. 668–675, 2009

 