An experimental study to investigate the effect of dynamic variation of the shock strength on shock boundary layer interaction.

Rahul R. Kapse[1,*] and T. M. Muruganandam[1]

1: Department of Aerospace Engineering, Indian Institute of Technology Madras, Tamil Nadu, India.
*rkapse1998@gmail.com

Keywords: Shockwave boundary layer interaction, Separated flows, Supersonic aircraft, Flow control

Abstract

Shockwave boundary layer interaction results from the interaction of a shockwave on the boundary layer that forms over the aircraft's surface. SBLI can occur in various aerodynamical situations, including on the aircraft's control surfaces, transonic airfoils, nozzles in over-expanded conditions, supersonic inlets, and others (Green, 1970). The shockwave produces an adverse pressure gradient, and when it interacts with the boundary layer, it thickens the boundary layer (Délery & Dussauge, 2009). When the incident shockwave is stronger, it can create a situation where the adverse pressure gradient imposed on the boundary layer becomes greater than that required for incipient separation. Under such conditions, the boundary layer will separate from the surface (Chapman et al., 1943). Boundary layer separation leads to undesired consequences on the flow, such as turbulence amplification, blockage/deflection of the flow, production of vortex structures, and low-frequency oscillation of the reflected shock (Dupont et al., 2006). This research investigates the effects of dynamic variation of the shock strength on shockwave boundary layer interaction. The experiments were conducted using a Mach 2 supersonic wind tunnel of intermittent blowdown type at Gas Dynamics Lab, NCCRD, IIT Madras. The wind tunnel's settling chamber is linked to a 4-inch pipeline leading to the central storage tank, which has a volume of 30 m^3. Connected to the settling chamber is a convergent-divergent nozzle, designed using the method of characteristics with correction for boundary layer displacement thickness. Within the convergent-divergent nozzle, the flow expands, achieving a freestream velocity of 517 m/s at the test section corresponding to Mach 2. Following the test section is a diffuser equipped with a silencer for exhaust. The test section measures 400 mm in length with a cross-section of 151 mm (height) × 100 mm (width). Stagnation pressure (P_0) in the settling chamber is maintained at 2 bar. At this stagnation pressure, the wind tunnel's mass flow rate is 4.06 kg/s, with a run time of 11.65 s. The stagnation temperature (T_0) is 303 K. A two-dimensional shock generator is mounted to the top wall of the test section and has a wedge-shaped geometry. The shock generator is connected via mechanical linkages housed in the diffuser. These linkages are further connected to an induction motor with a cam assembly. The shock generator undergoes pitching motions, which change the net flow deflection angle from 4° to 18° and modify the shock strength while maintaining a constant incoming flow Mach number. Experiments are performed at three different pitching frequencies: 6 Hz, 8 Hz, and 10 Hz.

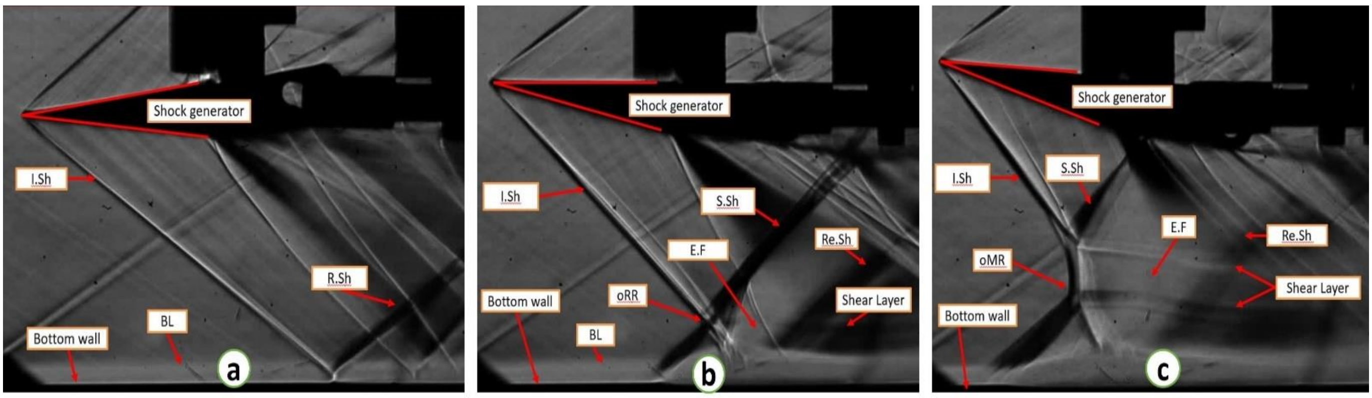

Figure 1. Schlieren flow visualization: a) Unseparated SBLI, b) SBLI with oRR configuration, c) SBLI with oMR configuration

The adverse pressure gradient imposed on the boundary layer by the incident shock varies with the flow deflection angle, which affects the shape and structure of the shockwave boundary layer interaction at the wind tunnel floor. High-speed Z-type schlieren is used as a diagnostic technique for flow visualization. Three different configurations of SBLI structures were observed. An unseparated SBLI structure is observed at lower flow deflection angles. As the flow deflection angle increases, the boundary layer separates, and a separation shock is formed upstream of the incident shock impingement location, which causes shock-shock interaction between the incident shock and the separation shock. Hence, SBLI with overall regular reflection (oRR) and overall Mach reflection (oMR) is observed at higher flow deflection angles. The transition criteria and the transition angles of the different SBLI configurations are also studied. From the data, hysteresis seems to occur for the SBLI transitions, which are discussed in detail with the supporting evidence from the Schlieren images. Also, the hysteresis in separation shock foot position for the varying strength of incident shock by pitching motion of the shock generator is observed. It is observed that the gap in the hysteresis curves widens with the increase in the pitching frequency, confirming the presence of rate-dependent behaviour in the hysteresis.

References:

- Chapman, D. R., Kuehn, D. M., Larson, H. K., Ult, R. E., In, R. E., Region, S., Importance, F. O. R., Tra, O. F., Location, S., & To, R. (1943). National advisory committee for aeronautics. Journal of Applied Physics, 14(8), 399–405. https://doi.org/10.1063/1.1715007
- Délery, J., & Dussauge, J.-P. (2009). Some physical aspects of shock wave/boundary layer interactions. Shock Waves, 19(6), 453–468. https://doi.org/10.1007/s00193- 009-0220-z
- Dupont, P., HADDAD, C., & Debiève, J. F. (2006). Space and time organization in a shock-induced separated boundary layer. Journal of Fluid Mechanics, 559, 255– 277. https://doi.org/10.1017/S0022112006000267
- Green, J. E. E. (1970). Interactions between shock waves and turbulent boundary layers. Progress in Aerospace Sciences, 11(C), 235–340. https://doi.org/10.1016/0376- 0421(70)90018-7