A review on high speed flow with micro ramps

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ABSTRACT

Micro vortex generators are plying an important role of being an effective form of passive flow control in supressing boundary layer in high speed flow. Shock Boundary Layer Interaction (SBLI) is an undesirable phenomenon that occurs in the high speed flows in devices like scramjet intake which has a detrimental effect on its performance. Due to adverse pressure gradient created by SBLI, the flow might be decelerated to subsonic speeds via a normal shock. This leads to undesirable phenomena such as wall pressure loading, high local wall heating, increased drag coefficient, reduced mass flow ingestion, lower-pressure recovery and inlet unstart conditions. High drag and increased localized heating will reduce the mechanical integrity of the system. To counteract these effects, Micro Ramps or Micro Vortex Generators are used which produce pairs of counter-rotating vortices thereby suppressing the SBLI and precluding flow separation. Moreover vortex generators possess the potential to reduce the dependence on boundary-layer bleed for the purpose of separation suppression. The optimum position and configuration of the Micro Ramp array in the flow path is playing an important role. The effectiveness of the Micro Ramps are reviewed from various papers and the possibility of using the micro ramps to improve the flow performance parameters are discussed.

KEY WORDS: MVGs, Micro ramps, Scramjet intake, shock wave boundary layer interaction.

1. INTRODUCTION

Several studies were conducted on SBLI to understand the dynamics of physical mechanisms driving the flow unsteadiness and the underlying causes. Recently, studies were channelized to apply flow control techniques in order to alleviate or diminish the detrimental effects of flow separation. Various aspects of transonic/ supersonic and hypersonic flows with different control strategies (e.g., vanes, micro-ramps, micro-jets, synthetic jets, energy deposition, plasma discharge, actuators, ramp cavity, etc.) were attempted. These flow control mechanisms have been developed to prevent the boundary layer separation and to keep the overall efficiency high. They can be classified as either active or passive boundary layer control mechanisms. Active methods involve boundary layer bleeding at the shock impingement location. By removing the low energy part of the boundary layer, the boundary layer thickening is reduced which inhibits the separation. This thins out the boundary layer and reduces the pressure loss. The problem is one tenth of the incoming mass flow has to be removed to make the system effective. To compensate for this loss of mass flow, the size of the inlet has to be increased which results in increase in weight and drag. Passive devices such as microramps, micro-vanes, thick-vanes and fences have emerged as a good flow control methods because of robustness, easy implementation, light weight, cost-effectiveness and simplicity. Micro-ramp is a micro vortex generator, which completely eliminates bleeding.

Micro Ramps or Micro Vortex Generators (MVG) are in general used to counteract these effects, by producing a pair of counter-rotating vortices (Fig.1). This suppresses the SBLI and precludes flow separation. The effect of micro ramps in the suppression of SBLI in hypersonic flow and the possibility of using Micro Vortex Generators in the high speed flow to improve the performance are discussed.

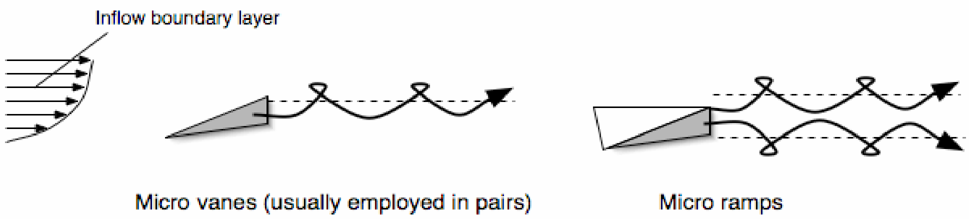

Fig.1. Streamwise vortices generated by the micro-vortex generators (Lee sang, 2011)

Babinsky in his studies reveals that micro ramps can delay shock-induced separation and improve boundary layer health as shown in figure 2. This in turn reduces the bleed requirement in intakes. He conducted experiments at Mach 2.5, to determine the nature of flow controlled by micro-ramps. He suggested that the smaller devices need to be placed closer to the expected adverse pressure gradients.

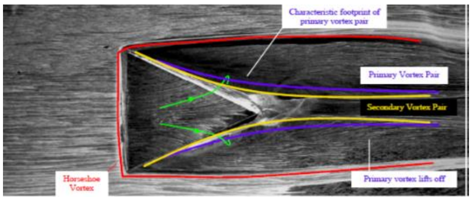

Fig. 2 . Surface flow visualization of the features of the flow field around a single microramp. Freestream Mach number was 2.5 and the height of the ramp was 80% of the undisturbed boundary layer thickness. Image from Ford and Babinsky

The experiments and the LES (Large Eddy Simulations) results by Sang Lee indicate that the micro-ramps, whose height is h≈0.5δ, can significantly reduce boundary layer thickness. When smaller ramps are placed closer to the shock Interaction, the displacement thickness and the separated area are reduced. This effect is attributed to decreased wave drag and the closer proximity of the vortex pairs to the wall.

In the review of the application of passive control in transonic flow, the passive control techniques can reduce drag, increase lift and reduce unsteady pressures on an aerofoil. Raghunathan Michael Rybalko and Eric Loth in their experiments and computations on Micro-Ramps for External Compression Low-Boom Inlets proved that the optimum upstream configuration substantially reduces the post-shock separation area but did not significantly impact recovery at the aerodynamic interface plane. But downstream device placement allowed for fuller boundary layer velocity profiles and reduced distortion. This improved pressure recovery and mass flow ratio at the aerodynamic interface plane compared to the baseline solid- wall configuration (Fig. 3)

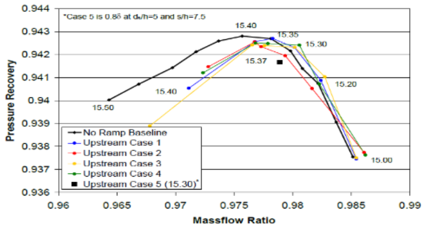

Fig.3. Cane curves for upstream micro-ramp DOE study on A4 inlet geometry

Experiments were conducted by Hirt and Anderson to study the effectiveness of micro-ramp flow control in the 15 x 15 cm supersonic wind tunnel at NASA Glenn Research Center (GRC) Fifteen numbers micro-ramp configurations of varying height, chord length, and spanwise spacing between micro-ramps were studied (Fig.4). The configurations of the micro ramps used in the experiment is shown in Figure 1. An oblique shock was created using a shock generator plate at 8.5° angle of attack. Micro-ramps were placed upstream of where the shock reflects off of the tunnel floor. Boundary layer profiles and properties and Mach number contours were examined for various micro-ramp configurations (Fig. 5)

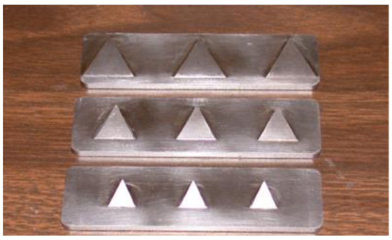

Fig.4. Picture of three micro-ramp inserts from the experiment in the 15 x 15 cm supersonic wind tunnel

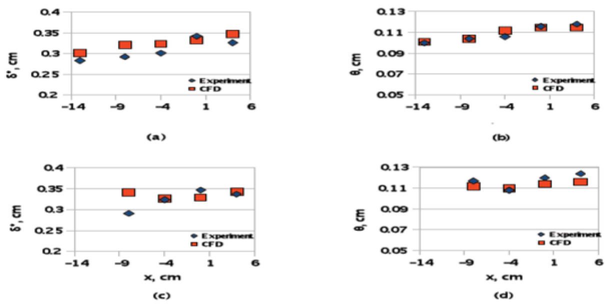

Fig.5. (a) Empty tunnel compressible displacement thickness, (b) empty tunnel compressible momentum thickness, (c) micro-ramps only compressible displacement thickness and (d) micro-ramps only compressible momentum thickness along the stream wise direction.

Frank K. Lu, Qin Li, in their Review of Micro Vortex Generators in High-Speed Flow explained the wake of the MVG of two school of thought. First, the MVG wake is thought to be trailing vortices where the higher momentum energizes the boundary layer to reduce the subsequent separation. Secondly, an instability mechanism is thought to produce a train of either hairpin vortices or vortex rings where vortex bursting is thought to cause substantial distortion of the leading shock that may cause it to actually disappear. Finally, performance metrics need to be developed to substantiate the effectiveness of MVGs like the reduction of the separation zone

To characterize the effects of an array of microramps on a normal shock wave/boundary-layer interaction, instantaneous schelieren photography, surface oil-flow visualization, pressure-sensitive paint, and particle image velocimetry were implemented by Thomas g. Herges The results revealed that a micro ramp produces a complex vortex structure in its wake with two primary counter rotating vortices surrounded by a train of Kelvin- Helmholtz (K-H) vortices. In the region of the primary vortices, a stream wise velocity deficit is observed in addition to an induced upwash/downwash. This persists through the normal shock with reduced strength. The span wise-averaged skin-friction coefficient is increased by the micro ramp flow control and the spanwise-averaged incompressible shape factor is reduced, thereby improving the health of the boundary layer. The velocity in the near-wall region appears to be the best indicator of micro ramp effectiveness at controlling SWBLIs.

Effect of micro ramps is capable of delaying the separation and diminishing the extent of recirculation zone on a fully developed turbulent flow over a forward facing step (FFS) in a supersonic low noise wind tunnel at Mach number 4. This was studied by Zhang Qing-Hu with the help of nano-tracer planar laser scattering (NPLS) and supersonic particle image velocimetry (PIV).

The influence on the ring-like vortex structure in MVG controlled supersonic ramp flow by different inflow conditions were studied by Yonghua Yan and Chaoqun Liu generating three turbulent inflow profiles with different boundary layer thickness as the inflow in front of the MVG. It is found that the inflow conditions give significant influences to the ring-like vortex structure including the ring-like vortex shapes, vorticity origins, momentum deficit zones, stream wise velocity profiles after MVG, vortex organizations, and, more important, the interaction between vortex rings and shocks which control the boundary layer separation.

Anne-Marie Schreyer in their study of effects of an array of microramp sub-boundary layer vortex generators on a hypersonic shock/turbulent boundary layer interactions at Mach 7.2, with Mean flow surveys and turbulence measurements using PIV, it is found that microramps strongly altered the flow field, decreasing the mean velocity at the spanwise locations downstream of the microramp vertices, and increasing it at the spanwise locations in between vertices. (Fig.6).

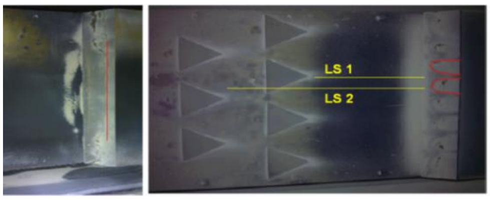

Fig.6.Surface flow visualizations using deposition of PIV seeding particles. Left: undisturbed interaction. The extent of the separated region onto the ramp surface is marked with a red line. Right: interaction disturbed by two staggered row of microramps. The yellow lines mark the positions of the laser sheets in respect to the microramps, for which PIV images were taken: LS 1 downstream of the vertex of a microramp in the _rst row, LS 2 in between the vertex of a microramp in the _rst row and the vertex of a microramp in the second row in the array

Review by Titchner and Babinsky gives a consolidated study on the research conducted by various experts by bringing out very strongly the potential of mechanical vortex generators as a possible control device for mitigation of shock-induced separation. The authors explained two main important conclusions. At first, the devices are successful flow control devices in the transonic flow regime than in purely supersonic interactions. Secondly, the detailed comparative review shows that the effectiveness of counter-rotating MVGs is better for $D/d \geq 4$ (where D is the inter-VG spacing) and h/δ between 0.2 and 0.5.

Lin et al investigated boundary layer separation control by a comparative studies between various profiles of vortex generators. The device height was varied between 10% and 50% of the boundary layer height. Comparative studies on separation control effectiveness and device induced vortex characterization were carried out. These low profile vortex generators (esp. of device heights 0.1δ and 0.2δ) were found to be effective in reducing the 2D and 3D boundary layer separation Also, their placement with respect to the baseline separation was found to be critical to their flow control efficiency so as to provide ample time to for the streamwise vortices to energize the low momentum portion of the boundary layer near the surface. Hence Micro ramps are used extensively in delaying boundary layer separation, enhancing aircraft wing lift, tailor wing-buet characteristics at transonic speeds, reducing after body drag of aircraft fuselages and delaying separation in subsonic diffusers. But conventional micro ramps tend to increase the parasitic drag on the aircraft due to their size and mostly they are used to control flow separation over a relatively short downstream distance. A non-conventional wave type VG of height to boundary layer thickness 0.27 and 0.42 was invented by Kuethe. This was effectively used the Taylor-Goertler instability to generate streamwise vortices within the boundary layer.

Sivakumar performed numerical simulations for a 3D inlet section using commercial coding package ANSYS Fluent. The SST k-ω turbulence model was used with y+ value of 105. The results were validated by simulating flow through a 2D mixed compression hypersonic inlet as well as comparing with experimental data. From the characteristic curves obtained, the value critical angle of attack was determined to be 8^0 with higher values of flow distortion for other values of angle of attack.

Anderson used Response Surface Methodology (RSM) to determine the optimal configuration of micro vortex arrays for controlling the shock wave turbulent boundary layer interactions effectively. The devices used consisted of standard micro ramps, tapered micro vanes and standard micro vanes. They were tested at a free stream Mach number of 2. The effectiveness of the devices was determined by inducing a shock pressure rise using a 10^0 shock generator.

Valdivia conducted an experiment by combining active (vortex generator jets-VGJ) and passive control (Wheeler Doublets-WD) techniques and its effect was studied on controlling unstarting of the engine. He concluded that combination of VGJ and WD proved more effective than VGJ's alone in preventing the unstarting of the inlet as the presence of WD's aided the performance of VGJ's by reducing to flow blockage created by the jets

Lee studied the effect of Mach number on the flow past micro ramps and concluded that micro ramps have strong local influence for flows with lower Mach numbers but yielded a higher decay rate for streamwise vorticity strength. Flows with high Mach numbers possessed a longer length of the turbulent structure and thus had a lower decay rate.

Blinde postulated a model for a flow field behind a micro ramp. He carried out studies effect of micro ramps with device height 20% of the boundary layer at Mach 1.84 with Stereo-PIV 7 measurements. He propounded that the wall normal vortices were the counter-rotating hairpin vortices with no apparent streamwise vortices with presence of high speed regions at intermediate positions. But unfortunately PIV was unable to resolve the extremely small vortex filaments.

Lu confirmed the flow field proposed by Lin by carrying out detailed Schlieren and laser sheet visualisations of wake structure near a micro vortex generator. Babinsky investigated the efficiency of different vortex generators geometries in presence of a normal shock via oil flow visualisations and determination of separation regions for different upstream positions. He concluded that micro ramps do not entirely eliminate boundary layer separation but reduce it to a certain extent. Also, the corner vortices were found to be enlarged for all cases with boundary layer control – the reason for which is yet to be determined. Boundary layer separation caused due to SBLI hampers the pressure recovery in the isolator and in case of high combustor back pressure, leads to unstarting of the inlet. In his book, "Shock wave Boundary layer interactions" he has explained the phenomenon of SBLI and its flow physics in great detail.

Saad carried out experimental to test the effect micro ramps on supressing the shock boundary layer interactions (SBLI). The freestream Mach number was maintained at 5 and three different configurations of micro ramps – MR40, MR60 and MR80 were tested. Detailed flow field behind the micro ramp was investigated using Schlieren imaging and Infrared thermography. The micro ramp configuration MR80 was found mitigate SBLI better than the former two (Fig. 7).

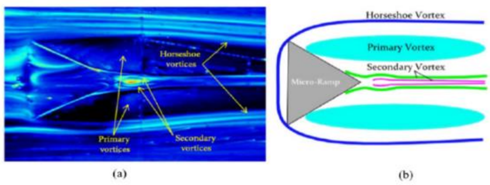

Fig. 7. Surface flow visualization image and the vortex model given by Saad (2012)

Sun carried out an experimental study to investigate the three dimensional flow field behind a single micro ramp in a Mach 2 supersonic flow. A pair of streamwise vortices originating from the trailing edge of the ramp enveloped by an arc shaped external shear layer was captured in the time averaged organization. On instantaneous analysis, the enveloping vortices were found to be the Kelvin-Helmholtz (K-H) instability that bounded the wake region. A net lift force is experienced by both type of vortices.

CONCLUSION

From the available literature, it is evident that micro ramps can effectively be used in high speed flows to control shock boundary layer interactions. This in turn will reduce the loss in stagnation pressure and improve flow distortion. Micro ramps can also be used in scram jet intakes to supress shock wave boundary layer interaction and used to start in intake effectively. For various flow conditions and applications, design of micro ramps, arrays and their locations on the flow surface needs detailed experimental and numerical studies.

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