Three-dimensional Supersonic Boundary Layer Separation Induced by Curved Sidewall

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1 Introduction

The swept shock wave boundary layer interactions occur widely in the internal and external flow relevant to the hypersonic aircraft. A typical example is the interaction between an oblique detonation wave and a sidewall boundary layer. In order to reduce the boundary layer separation, the planar surface is replaced by the curved surface to generate sidewall compression [1]. Despite the fact that the compression waves will finally form a strong shock wave, the curved sidewall is able to reduce the extent of bottom wall boundary layer separation. According to this idea, a three-dimensional supersonic boundary layer separation induced by a curved sidewall is studied in this paper, in which the sidewall generates a compression wave fan and focus into a planar shock wave.

2 Description of Experiment

Experiments are carried out in a Mach 2.95 continuous supersonic quiet wind tunnel. The inflow of the tunnel is atmosphere, whose pressure and temperature are 1.01×10^5 Pa and 300K respectively.

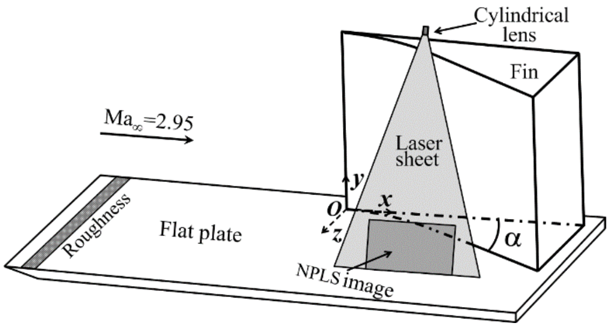

Figure 1. Experimental configuration

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Fig. 1 shows the experimental model used for present study. The generated turbulent boundary layer thickness $\delta_{0.995}$ at the fin tip is 4.6 mm through PIV measurement. The Cartesian coordinate system adopted in this study is also shown in Fig. 1.

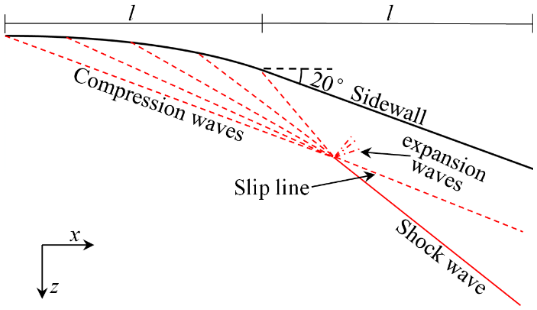

Figure 2. Profile and inviscid wave system of the curved sidewall

Fig. 2 shows the profile of the curved sidewall and its inviscid compression wave system. It has two part: one part is a curved line which generates a compression fan, and the other part is a straight line which ensures that the compression waves form a straight shock wave. The parameter *l*=60 mm is adopted as the measure of characteristic in this article.

The flowfield is visualized using Nanoparticle-based Planar Laser Scattering (NPLS) technique which is based on Rayleigh scattering and uses the nanoparticles as tracer particles [2]. The previous experimental results indicate that the nanoparticles can follow supersonic flow faithfully and reveal fine flow structures [3-4]. The oil flow visualization is also carried out on the flat plate. The current study adopts a mixture of lubricating oil and TiO_2 powder.

3 Description of Computation

The Reynolds-averaged Navier-Stokes equations with the *k*-*ω* shear stress transport (SST) model are discretized by the finite volume method. The inviscid terms are discretized by the second-order Roe scheme and the viscous terms are discretized by the second-order central-difference scheme.

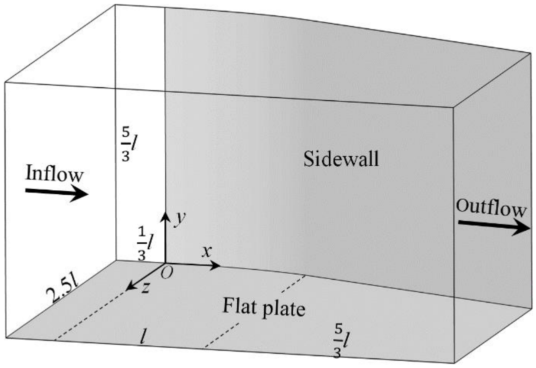

Figure 3. Computational domain

Fig. 3 shows the computational domain. The free-stream condition is applied at the inflow plane, in which the flow parameters vary only in wall-normal (y) direction and their profiles are obtained by a two-dimensional calculation. The flow quantities at the outflow plane are extrapolated from the flow in the interior. The solid walls is set to have the adiabatic non-slip condition and other boundaries are set to have the symmetry condition.

4 Results and Discussion

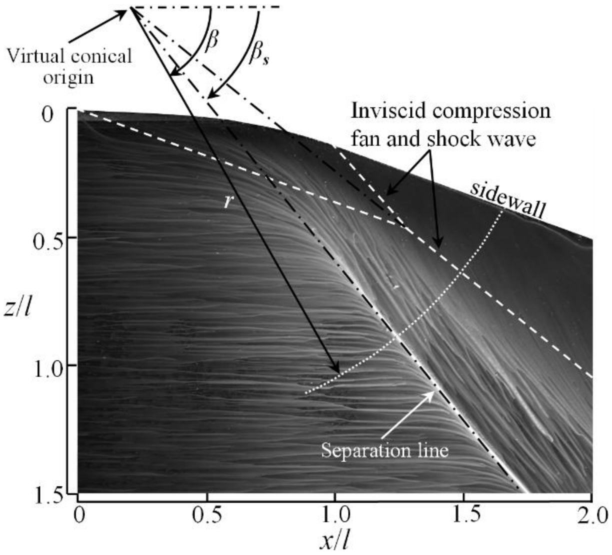

Figure 4. Oil flow visualization on the flat plate

Fig. 4 shows the oil flow picture on the flat plate. A clear convergent separation line formed upstream the inviscid shock wave can be found in the figure. This separation line does not extend to the sidewall because of the compression fan generated by the curved sidewall. The seperation line and the inviscid shock trace converge at a single point, which is often defined as the virtual conical orgin in the swept shock wave boundary layer interaction. Moreover, there is no evidence of the secondary separation found in the figure.

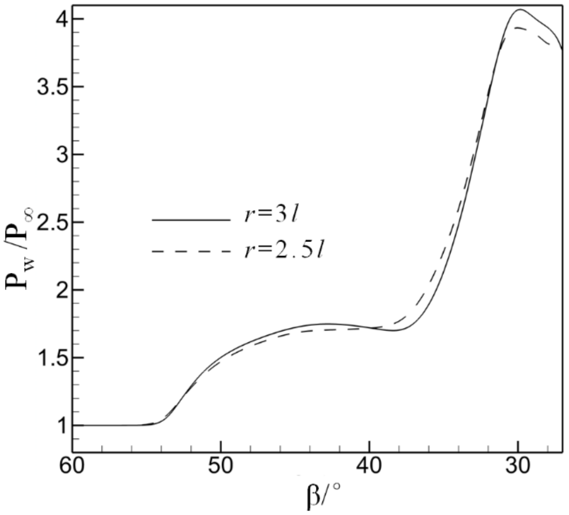

Figure 5. Pressure distribution on the flat plate

Fig. 5 shows the pressure (P_w) distribution at two radial locations (refer to figure 4 for the definition of r and β). Moreover, the pressure is normalized by the freestream pressure (P_∞). The two radial locations both lie in the region where the separation line is straight and the swept shock has been formed. The pressure distribution at two locations agree well with each other, which means that the separation flow shows conical symmetry.

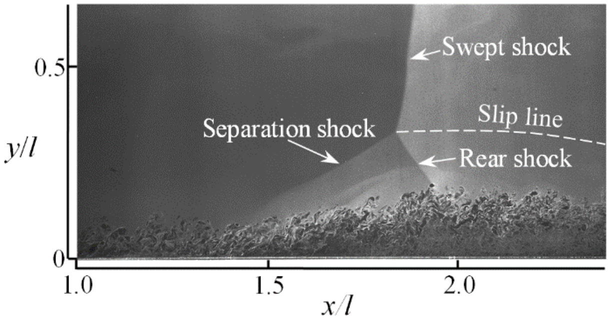

Figure 6. Instantaneous NPLS image at z=*l*

Fig. 6 shows the instantaneous streamwise (x-y) NPLS image at z=*l*. This figure clearly illustrate the structures of the separation flowfield. The swept shock wave formed by the compression fan bifurcates into two shock waves, namely the separation shock and rear shock. Moreover, the boundary layer acts as an obstacle for the main stream and generates the separation shock.

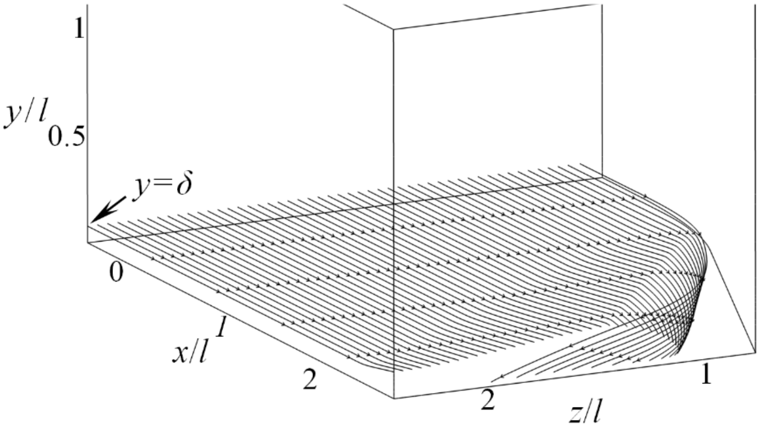

Figure 7. Distribution of streamlines emitted from $y=\delta$

The streamlines shown in Fig. 7 illustrate the development of a stream surface which emittes from a line ($y=\delta$) in the inflow plane, where δ is the boundary layer thichness of the inflow. The stream surface clearly illustrates a separation vortex which twists the streamlines in the clockwise direction (in the view of $-x$). The development of the stream surface also shows that the flow close to the sidewall gets swept sideways and is replaced by the flow originating in the outer part of the boundary layer, which means that all the flow in the inflow boundary layer is rolled into the separation vortex.

5 Conclusion

1) All the flow in the inflow boundary layer will be rolled into the separation vortex because of the swept shock wave formed by the compression fan.
2) The separation flow shows conical symmetry in the far downstream region where the swept shock wave has been formed by the compression wave fan.

References

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