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Unsteadiness in shock and boundary layer interaction (SBLI) is a common observation and mystery of modern fluid dynamics. While many people still believe SBLI unsteadiness is a stochastic process and unpredictable, this work is focused on finding the correlation between shock oscillation and the motion of vortices. A supersonic micro vortex generation (MVG) is taken as a sample problem and the close correlation between the separation point motion, shock oscillation and vortex motion is revealed by LES observation, which shows the unsteadiness of SBLI is mainly caused by shock and vortex interaction. Continuation of this study would reveal the mystery of the physics of unsteadiness of SBLI. The detailed LES analysis will be given the final paper.

1. Introduction

Shock and turbulent boundary layer interaction, commonly called SBLI, is a major source of generation of pressure oscillation which could cost flow separation, loss of total pressure, deformation of velocity profile, acoustic noises and even structure damage (Dolling 2001; D‘enery & Dussauge 2009.) There are many people who still believe the unsteadiness of SBLI is a stochastic process and unpredictable (Anderson, 2016). On the other hand, due to the increase of computer capability and advances in numerical algorithm, large eddy simulation (LES) and direct numerical simulation (DNS) have been carried out by many authors (Garnier et al. 2002; Pirozzoli & Grasso 2006; Morgan et al. 2010, Li and Liu 2010.) DNS/LES people have apparently assumed that the SBLI is deterministic, but not random or stochastic. Some of them have noted that there is correlation between the unsteadiness of SBLI and separation bubble (Erengil & Dolling 1991; Piponniau et al. 2009; Touber & Sandham 2009.) However, the 3-D shock and vortex ring interaction has seldom reported except for the author’s group in literature. The current work is a try to find the correlation between the unsteadiness of SBLI and the vortex motion in a case of supersonic MVG. Since the vortex rings in MVG are strong, detailed study on the shock-vortex ring interaction could be a good example to help understand the unsteadiness of SBLI. In this abstract, only the correlation between the separation point location and spanwise vorticity change (large in vortex rings) is studied. Further correlation of shock oscillation and vortex ring motion must be studied and further study on small vortices and shock interaction in a fully developed turbulent boundary layer will be studied to find the correlation between the unsteadiness and motion of variety of vortices with different sizes. These LES/DNS study will be reported in details in the final version of the AIAA paper.

2. Case setup and LES observation

Flows around MVG are studied with trailing edge declining angle 70°. Figure 1 show the configuration of the ramp with MVG. The computational domain is shown in Figure 2, where h represents the height of MVG. The grid of the system is \( n_{\text{streamwise}} \times n_{\text{spanwise}} \times n_{\text{normal}} = 1600 \times 128 \times 192 \). The implicitly implemented LES method and the fifth order bandwidth-optimized WENO scheme are used to solve the unfiltered form of the Navier-Stokes equations at \( M = 2.5 \) and \( Re = 5760 \). According to Babinsky et al (2009), a pair of strong primary vorticces and a pair of secondary vortices are generated by MVG, which cause strong mixing in the boundary layer (Figure 3.) With the strong mixing, the boundary layer becomes more cable to resist shock-induced boundary layer separation. However, it is a time-averaged view given by traditional experiment, which shows the streamwise vorticity is dominant. On the other hand, Li and Liu (2010) first time reported a train of vortices produced by MVG in the wake, which could weaken the shock or even remove the shock. They believe the shock weakening and removal is due to

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the shock and vortex interaction. This is an instantaneous view which shows the spanwise vorticity is dominant to reduce the boundary layer separation.

Figure 1: The configurations of the ramp and MVG

Figure 2: The computational domain of the MVG

Figure 3: Sketch of the main flow features (one side only for clarity (Babinsky et al 2009))
3. **LES observation on the correlation of flow separation and vortex motion**

According to our LES, when the vortex generated by MVG met the separation shock, the shock is weakened and the separation point where $\frac{\partial w}{\partial y} = 0$ (the normal derivative of streamwise velocity is zero) quickly moved forward, which means the separation zone is significantly reduced by the coming vortex ring. If we record the spanwise vorticity at the separation point and record the separation location, we can clearly find that the vortex ring coming (spanwise vorticity is large) and the separation reduction happened simultaneously (Figure 5). All vortices were identified by a new Omega method (Liu et al, 2016).

![Figure 5: Correlation between separation point motion and vortex ring motion](image)

(a) Separation point location  
(b) Spanwise vorticity

(Z/h is streamwise coordinate and t/T is the time)
We further do the Fourier analysis on the two data sets to find the correlation of the separation point motion and the large spanwise vorticity (vortex ring motion) and we found the vorticity change frequency is twice high of the separation point motion frequency (Figure 6). This means vortex coming can reduce the separation with two sharp changes in spanwise vorticity, sharp increase (vortex coming) and sharp decrease (vortex leaving). This also shows the flow separation is closely related to vortex motion and they are corresponding to each other.

4. Preliminary analysis on vortex motion in supersonic boundary layer

1) Vortex structure is quite stable and shock cannot break vortex ring
2) Vortex ring with fast rotation and low pressure in the core which can break the shock
3) Supersonic flow has to change the flow direction when meeting the fast rotating vortex
4) A shock must be produced due to the flow direction change since the supersonic flow is governed by a hyperbolic governing system which does not allow downstream flow to change the upstream flow and the only solution is to generate a shock
5) The supersonic boundary layer is fully filled with shocks due to the existence of vortices which are fully filled in turbulent boundary layer
6) Turbulence boundary layer is a buildup of vortices and, therefore, shock and turbulence boundary layer interaction is a shock-vortex interaction
7) The unsteadiness in SBLI is due to the motion of vortices. The frequency of shock motion is closely related to vortex motion.

5. Conclusion

According to the above preliminary analysis, we preliminarily lead to the conclusion that the unsteadiness of shock boundary layer interaction is caused by motion of vortices because shock cannot break vortex rings, has to change flow direction and then produce a new shock. Analysis of vortex ring generation and motion in turbulent boundary layer may help understand the unsteadiness of SBLI and help reduce unsteadiness of SBLI and control the frequencies of SBLI.

Further Fourier analysis on shock oscillation is needed and a more detailed analysis will be presented in the final AIAA paper.

6. Reference