Numerical Simulation of Roughness Effect on the Stability of a Hypersonic Boundary Layer

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Abstract: Besides the roughness induced by-pass transition, finite roughness can also affect the stability of hypersonic boundary-layer flows. Previous study showed that the roughness location plays an important role in the spatial development of unstable boundary-layer wave. In this paper, we further investigate the effects of roughness height and location on the stability of a Mach 5.92 flat-plate boundary layer. The preliminary results show that mode S is amplified in the region upstream of the surface roughness. However, both waves are damped along the roughness. The overall wave amplification depends on the roughness height. More computations are ongoing and will be reported in the final paper.

Keywords: Roughness, High-Order Cut-cell Method, Boundary Layer Stability.

1 Introduction

Direct numerical simulation has become an effective research tool for studying hypersonic boundary layer receptivity, stability, and transition by numerically solving the time-dependent 3-D Navier–Stokes equations for the temporally or spatially evolving instability waves. Malik et al. [1] investigated the responses of a Mach 8 flow over a sharp wedge of a half-angle of 5.3^{o} to three types of external forcing: a planar freestream acoustic wave, a narrow acoustic beam enforced on the bow shock near the leading edge, and a blowing-suction slot on the wedge surface. They concluded that these three types of forcing eventually resulted in the same type of instability waves in the boundary layer. Recently, Wang et al. [2] further studied the response of the same hypersonic boundary layer to wall blowing–suction. The results showed that mode S is strongly excited only when the actuator is located upstream of the corresponding synchronization point. Marxen et al. [3] studied the effects of a localized two-dimensional roughness element on the disturbance amplification in a hypersonic boundary layer. Their numerical experiments showed that in the vicinity of the separation regions, near the leading and trailing edges of the roughness, an increased amplification of a second-mode disturbance occurs for a certain frequency.

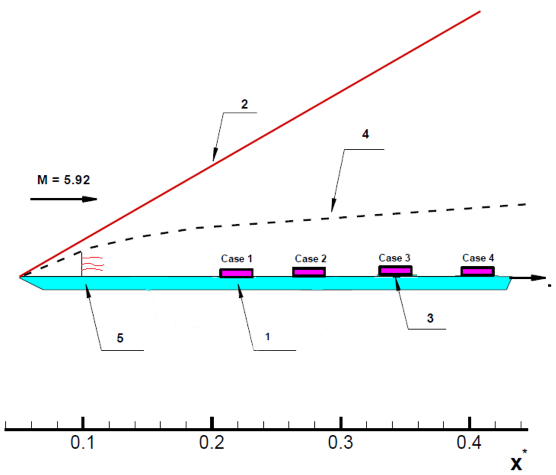

Figure 1. A schematic of the problem: 1. Roughness 2. Bow Shock 3. Synchronization point 4. Boundary layer 5. Imposed disturbances

Previous study showed that the roughness location plays an important role in the spatial development of unstable boundary-layer wave [4]. In this paper, we further investigate the effects of roughness height and location on the stability of a Mach 5.92 flat-plate boundary layer. The steady base flow is simulated by solving compressible Navier-Stokes equations. Stability characteristics of boundary-layer waves are analyzed by linear stability theory (LST). In stability simulations, two-dimensional disturbances corresponding to mode S or mode F at a frequency of 100 kHz are introduced near the leading edge. Finite roughness with adjustable height is put downstream of the disturbances, as shown in Fig. 1. The roughness is treated using the high order cut-cell method developed by Duan et al. [5].

2 Problem Statement

A high-order cut-cell method is applied to treat the finite roughness on a Mach 5.92 flat-plate hypersonic boundary layer. Imposed disturbances corresponding to mode S and mode F at 100 Hz are calculated by linear stability theory. In order to get a full physical picture of how different roughness height and location affect the spatial development of imposed wave, sixteen different cases of stability simulations will be carried out. They include 4 roughness locations, and 4 roughness heights in each location,

Location 1: Far upstream of the synchronization point, x_r=0.1101m; Local boundary layer thickness δ= 1.448x10-3 m; Roughness height 0.25δ, 0.375δ, 0.5δ, 0.625δ
Location 2: Upstream of the synchronization point, x_r=0.185m; Local boundary layer thickness δ= 1.61x10-3 m; Roughness height 0.25δ, 0.375δ, 0.5δ, 0.625δ
Location 3: At the synchronization point, x_r=0.331m; Local boundary layer thickness δ= 2.82x10-3 m; Roughness height 0.25δ, 0.375δ, 0.5δ, 0.625δ
Location 4: Downstream of the synchronization point, x_r=0.410m; Local boundary layer thickness δ= 3.42x10-3 m; Roughness height 0.25δ, 0.375δ, 0.5δ, 0.625δ

3 Conclusion and Future Work

In this paper, we further investigate the effects of roughness height and location on the stability of a Mach 5.92 flat-plate boundary layer. The preliminary results show that mode S is amplified in the region upstream of the surface roughness. However, both waves are damped along the roughness. The overall wave amplification depends on the roughness height. More computations are ongoing and will be reported in the final paper. In addition to mode S and F, we are also planning to impose a signal with a wide range of frequency.

References

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