Effects of ridge-type spanwise heterogeneous roughness on shock-wave/turbulent boundary layer interactions

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1 Introduction

Shock-wave/turbulent boundary layer interactions (STBLI) may lead to detrimental effects such as increased drag, unsteady pressure loads, and engine inlet instability. Délery (1985) summarized both active and passive control strategies to alleviate these undesirable effects of STBLI. Passive control methods, such as bumps (Ogawa *et al.*, 2008), micro-vortex generators (MVG) (Rybalko *et al.*, 2012), and secondary recirculation jets (Pasquariello *et al.*, 2014), are particularly attractive because they are inexpensive and robust. However, traditional passive control methods still suffer from two significant drawbacks: they may cause a substantial increase in drag (especially when there is no flow separation), and their control efficacy is highly sensitive to the installation location. Therefore, novel passive control methods that bring less added drag and are more flexible in their installation location are needed for high-speed applications.

A promising research direction is the utilization of spanwise heterogeneous roughness, which can induce large-scale secondary flows within the turbulent boundary layer, namely streamwise vortices. They are expected to act similar as MVGs, that is, they can transport high-momentum fluid closer to the wall, thus energizing the boundary layer. Ridge-type rough surfaces that are homogeneous along the streamwise direction do not increase pressure drag therefore can be applied over large areas, such that the control effectiveness on STBLI is less sensitive to the installation location.

Wu et al. (2024) demonstrated that ridge-type roughness with relatively small ridge spacing reduces the wall pressure fluctuation peak near the separation line despite the enlarged separation bubble. The reduced pressure fluctuation peak is related to a more smeared separation shock foot. The height of the ridges has not been varied in previous studies. However, it is reasonable to assume that the ridge height directly affects the size of the subsonic part of the turbulent boundary layer, and thus the formation of isentropic compression waves at the separation and their coalescence into the separation shock.

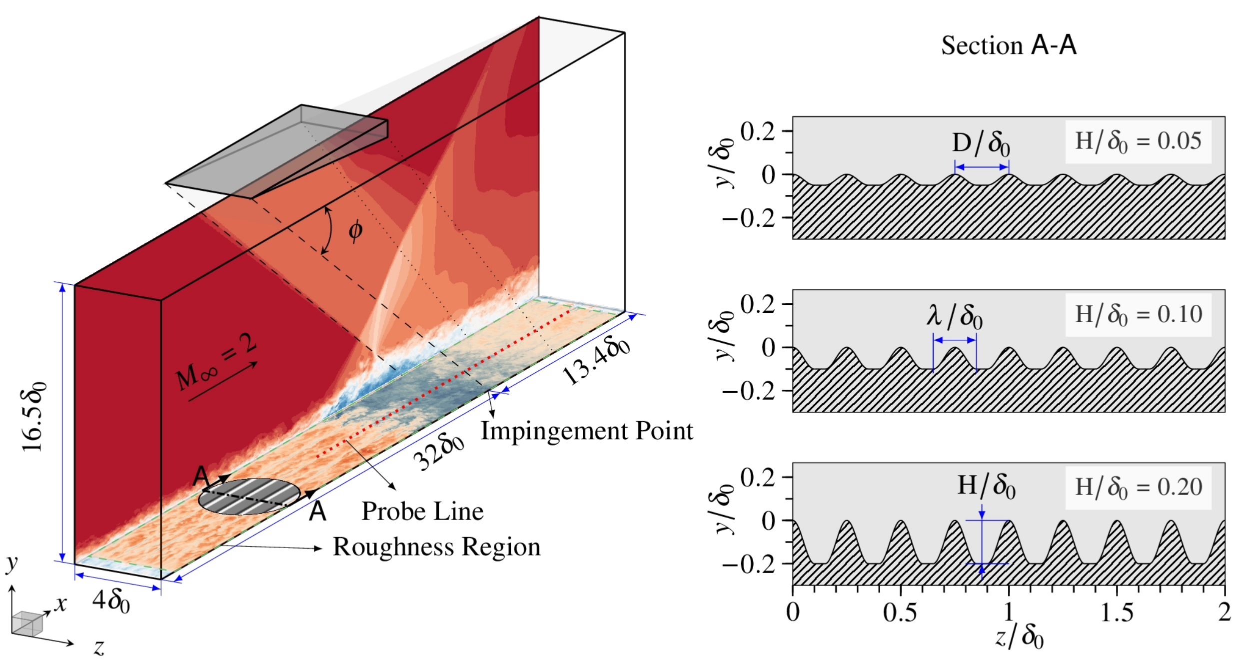

Figure 1. (a) Schematics of the computational domain (including streamwise velocity contours), and (b) schematic view of the investigated ridge-type rough walls with relevant definitions.

2 Simulation setup

A Mach 2.0 turbulent boundary layer that interacts with an oblique impinging shock wave with an angle of 40° is investigated in the present study, as shown in figure 1(a). The friction Reynolds number Re_τ of the incoming boundary layer is 250 at the inlet and 355 at the inviscid impingement point. The spanwise heterogeneous roughness consisting of sinusoidal ridges with non-dimensional spacing D/δ_0=0.25, width λ/δ_0=0.2, and three different heights of H/δ_0={0.05,0.10,0.20}, see figure 1(b).
The three-dimensional, compressible Navier-Stokes equations are solved using our in-house finite volume solver INCA (www.inca-cfd.com). We perform wall-resolved large eddy simulations (LES) using the adaptive local deconvolution method (ALDM) of Hickel *et al.* (2014). Smooth and rough walls are modeled with adiabatic non-slip boundary conditions. A cut-cell based immersed boundary method is utilized to represent the rough wall (Meyer *et al.* 2010).

3 Results and discussions

Velocity vectors and vertical velocity contours visualize the roughness-induced streamwise vortices in figure 2(a). Upwash occurs at the ridges while downwash happens in the valleys. It can be observed that the sonic line stays around 0.1δ_0 above the roughness ridge. The increase of the subsonic area in the upstream turbulent boundary layer can be represented by the spanwise-averaged height of the sonic lines in the shifted wall normal coordinate, as shown in figure 2(b).
Spanwise averaged friction coefficient, wall pressure, and wall pressure fluctuation for all cases are presented in figure 3. Friction coefficient distribution before the interaction region shows that friction increases when the ridge height increases. Furthermore, it also indicates that the mean separation region expands with the ridge height. The maximum value of wall pressure decreases and the interaction onset location moves more upstream with increasing ridge height, which results in a more gradual compression. More interestingly, the peak value of pressure fluctuations near the separation point drops as the ridge height increases but the pressure fluctuations upstream of the interaction region increase.
The streamwise distribution of the wall pressure fluctuation indicates that the investigated rough wall may be effective in attenuating the low-frequency motion of the separation shock. To further support this claim, we analyse the pressure signals from 282 numerical probes placed at y=0 in the mid-plane, as indicated by the dotted line in figure 1(a). From the pre-multiplied power spectra density map of the smooth wall case, an evident low-frequency content is observed at the separation line near St=0.05, which is a typical frequency of low-frequency unsteadiness of STBLI. However, this low-frequency content reduces with large ridge height and disappears for the case H/δ_0=0.2.

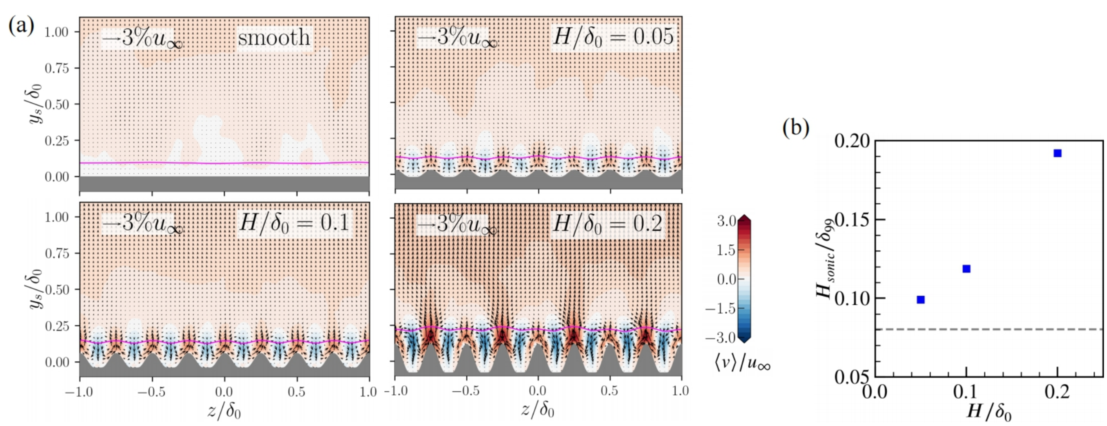

Figure 2. (a) Vertical velocity in a cross-stream plane with superposed cross-stream velocity vectors. The solid line shows the sonic line. (b) Spanwise-averaged height of the mean sonic line.

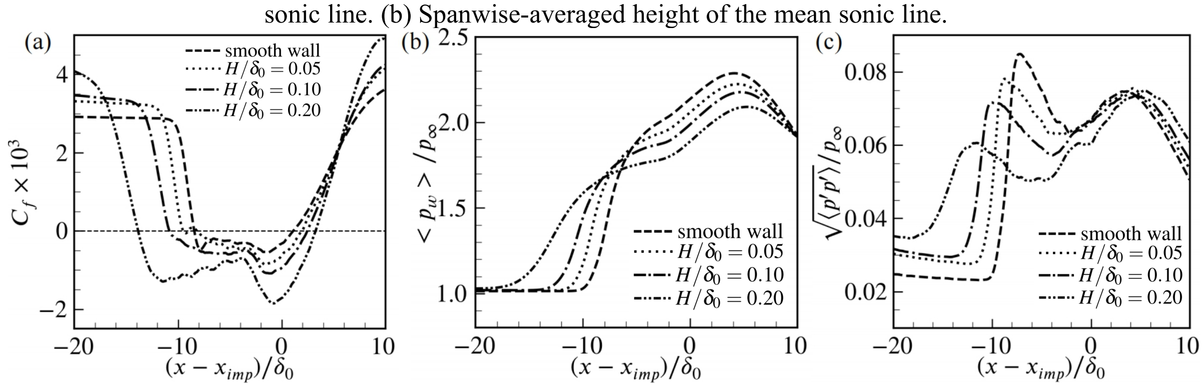

Figure 3. Spanwise averaged (a) wall pressure and (b) wall pressure fluctuations (c) friction coefficient for smooth wall.

4 Conclusions

The effect of spanwise heterogeneous roughness on the interaction between an impinging shock wave and a turbulent boundary layer at Mach 2.0 and Re_τ=355 at the impingement point has been investigated.
Spanwise heterogeneous roughness consisting of streamwise ridges with a constant ridge spacing (D/δ_0=0.25) but different ridge heights (H/δ_0=0.05,0.10,0.20) was found to increase the friction coefficient upstream of the interaction region. The roughness induces streamwise vortices in the upstream turbulent boundary layer with upwash over the ridges and downwash in the valleys. The separation and interaction length both increase when the ridge height increases, however, the pressure-fluctuation peak value drops significantly. A modal analysis shows that this is a result of the strongly reduced low-frequency unsteadiness.

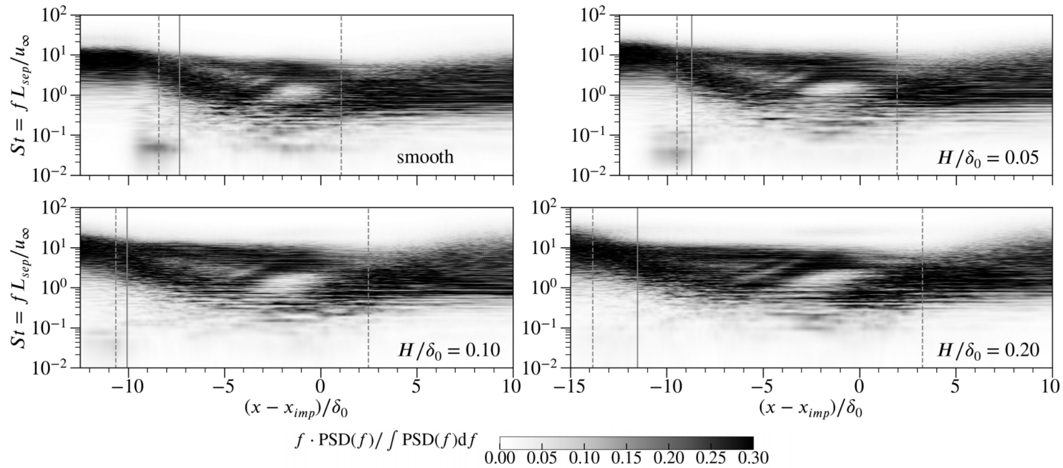

Figure 4. Pre-multiplied power spectra density maps of wall pressure signals at the mid-plane. The dotted lines denote C_f=0; the solid lines denote the location of maximum pressure fluctuation.

5 References

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