HYDRODYNAMIC STABILITY AND BREAKDOWN OF THE VISCOUS REGIME FOR RIBLET SURFACES

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INTRODUCTION

Riblets are small surface protrusions aligned with the direction of the flow that confer an anisotropic roughness to the surface. Within a certain $Re_{\tau}$ range, which corresponds to a riblet tip spacing $s^+$ of 0–25 wall units, the implementation of riblets reduces turbulent skin friction up to a 10–15%. In the limit of very small riblets, which we call the ‘viscous’ regime, the reduction in drag is proportional to the riblet size, and its mechanism is fairly well understood [8]. However, as the riblets get larger the effect saturates, and a minimum drag is reached when the viscous regime ‘breaks down’. This phenomenon limits the optimum performance of a given riblet geometry, and has been the subject of several studies [4, 7], but its precise mechanism has remained unclear.

SCALING OF RIBLET DRAG-REDUCTION CURVES

Early riblet literature established the use of $s^+$ as the parameter controlling drag reduction, and the criterion for optimum performance was given as $s^+\text{opt} \approx 15$. However, $s^+\text{opt}$ depends heavily on the particular riblet geometry so, for example, blade riblets with high height-to-spacing ratios $h/s$ experience the breakdown for $s^+$ much smaller than their shallow counterparts [1]. We have investigated whether some other choice of riblet dimensions describes experimental evidence better, and the best results were obtained for the square root of the groove cross-section, $l^+_g = (A^+_g)^{1/2}$ [3]. The optimum values of $s^+$ or $h^+$ have scatters of the order of 40%, while the optimum $l^+_g$ only varies by approximately 10% around $l^+_g\text{opt} \approx 10.7$, as portrayed in figure 1. For the diverse geometries reviewed, $DR_{\text{max}}$ is roughly 83% of the value that would result from extrapolating the linear viscous regime, with slope $m_l$, up to $l^+_g\text{opt}$. The approximation $DR_{\text{max}} = 0.83 m_l l^+_g\text{opt} \approx 8.9 m_l$, using a fixed $l^+_g\text{opt} = 10.7$, is quite accurate for conventional riblets. Together with cheap, two-dimensional, Stokes computations for $m_l$ [3], the above approximation can be used as a tool for riblet design, avoiding the strong dependence on costly DNSes or experiments.

THE BREAKDOWN OF THE VISCOUS REGIME

The breakdown of the viscous regime is a key issue in riblet performance, as the optimum drag reduction is proportional to the riblet size at breakdown, and understanding its mechanism could lead to larger optimal riblets and better optimum performance. The theories proposed in the literature for what causes the breakdown fall into two broad groups. The first one is that the effect of the riblets on the cross-flow loses effectiveness once they move beyond the Stokes regime. For example, [4] suggested that the deterioration is due to the generation of secondary streamwise vorticity over the riblets, as the unsteady cross-flow separates and sheds small-scale vortices that create extra dissipation. However, the presence of extra vorticity near the wall has also been reported to contribute to drag reduction in other scenarios [6]. The second group of theories assumes that the observed optimum wavelength, $s^+ \approx 10–20$, is related to the scale of the turbulent structures in the wall region, such as in the observations that the increase in drag coincides with the...
lodging of the quasi-streamwise vortices within the riblet grooves [7]. However, those observations are for $s^+ = 30–40$, well past the optimum size. In any case, all previous hypotheses fail to explain why deeper grooves experience earlier breakdowns.

We have recently documented a different scenario [3], in which near-wall spanwise rollers begin to form for riblet sizes near the optimum, and their intensity grows rapidly with the riblet size, although their dimensions in wall units for different riblet sizes remain essentially constant. They have streamwise wavelengths $\lambda_x^+ \approx 150$, and only exist for wall-normal coordinates below $y^+ \approx 30$, measured with respect to the riblet tips. In the spanwise direction, they extend from $\lambda_z^+ \approx 50$ to the full channel span. An example can be seen in figure 2, which shows instantaneous spanwise-averaged streamlines in the $x$–$y$ plane. For the corresponding simulation, the aspect ratio of the surviving rollers is at least 10 with respect to $x$ and 30 with respect to $y$, implying a quasi-two-dimensional phenomenon in an $x$–$y$ plane. The degradation of riblet performance with size obeys to an increase in the Reynolds stress for $y^+ \leq 35$, of which most is produced at the wall-paralel wavelengths of the new structures. Thus, they can clearly be identified as the source of the drag degradation.

The formation of structures perpendicular, rather than parallel, to the riblets, may seem surprising, but it is not completely unexpected. Similar spanwise rollers have been reported over vegetable canopies [2], and over porous walls [5]. The length scale of the structures varies depending on the particular problem, but, although few quantitative analyses exist in the literature, the phenomenon has always been attributed to a Kelvin–Helmholtz-like instability. In essence, the mean profile of a boundary layer almost has an inflection point at the wall, and the reason that it remains inviscidly stable is that the impermeability condition, $v = 0$, precludes the antisymmetric unstable eigenfunctions characteristic of Kelvin-Helmholtz. Once any modification of the wall allows local transpiration, the inflection-point instability reappears.

HYDRODYNAMIC STABILITY MODEL

We propose a simplified model for the hydrodynamic stability of turbulent flows over riblets. The basic hypothesis is that the longitudinal Stokes flow along the grooves is driven by the pressure variation of the overlying turbulent flow, and that the resulting longitudinal variations of the velocity within the grooves create a wall-normal transpiration. This transpiration acts as a boundary condition for an inviscid Rayleigh equation for linearised perturbations around the mean velocity profile in $y > 0$. The resulting boundary condition introduces a parameter, $L_w$, which only depends on the riblet geometry and can be interpreted as a length scale for the groove cross-section. The flow becomes unstable for all $L_w > 0$, but the instability only becomes significant for $L_w^+ \geq 4$, essentially independently of the flow Reynolds number. For the conventional riblets in [1], $L_w$ shows a good correlation with $l_g$, with $L_w \approx 0.35l_g$ for aspect ratios $h/s \geq 0.4$. If that proportionality is used in the stability threshold just mentioned, it suggests that the flow should become unstable above $l_g^+ \approx 11$, giving some theoretical support to the empirical scaling of the drag curves with $l_g^+$.

REFERENCES