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Riblet drag reduction in mild adverse pressure gradients: A numerical investigation

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A B S T R A C T

Riblet films are a passive method of turbulent boundary layer control that can reduce viscous drag. They have been studied with great detail for over 30 years. Although common riblet applications include flows with Adverse Pressure Gradients (APG), nearly all research thus far has been performed in channel flows. Recent research has provided motivation to study riblets in more complicated turbulent flows with claims that riblet drag reduction can double in mild APG common to airfoils at moderate angles of attack. Therefore, in this study, we compare drag reduction by scalloped riblet films between riblets in a zero pressure gradient and those in a mild APG using high-resolution large eddy simulations. In order to gain a fundamental understanding of the relationship between drag reduction and pressure gradient, we simulated several different riblet sizes that encompassed a broad range of s^+ (riblet width in wall units), similarly to many previously published experimental studies. We found that there was only a slight improvement in drag reduction for riblets in the mild APG. We also observed that peak values of streamwise turbulence intensity, turbulent kinetic energy, and streamwise vorticity scale with riblet width. Primary Reynolds shear stresses and turbulence kinetic energy production however scale with the ability of the riblet to reduce skin-friction.

1. Introductions

Riblets are micro-grooved structures that are aligned in the primary direction of a turbulent flow. If sized and shaped correctly, riblets can reduce skin-friction drag by as much as 10%. Riblets were first conceived in the mid 1970s during a time of increasing energy costs. According to Walsh (1990), R.L. Ash initially proposed the idea that streamwise fences could modify the boundary layer to reduce skin friction in 1976. The idea that near-wall coherent structures within the turbulent boundary layer could be modified to achieve drag reduction was likely influenced by the pioneering works of Kline et al. (1967) and Brown and Roshko (1974). Riblet drag reduction, $\%DR$ is defined as follows:

$$\%DR = 100 \times \frac{F_{riblet} - F_{baseline}}{F_{baseline}} \quad (1)$$

In the above equation, the viscous force on the riblets is denoted by F_{riblet} and the baseline skin-friction, $F_{baseline}$ is the force on a surface without riblets. Traditionally, drag reduction is plotted as a function of riblet width (plotted in wall coordinates), $s^+ = sw_{\tau,0}/\nu$, where the friction velocity, $w_{\tau,0} = \sqrt{\tau_0/\rho}$, is based on τ_0, which is the wall shear stress on the surface without riblets. Although the optimum width for drag reduction varies with shape, in general, riblets achieve maximum drag reduction at a size near $s^+ \approx 15$.

Walsh (1982) and Walsh (1983) pioneered early research concerning riblets. He completed experiments in a wind tunnel for a variety of riblets and Bechert et al. (1997) furthered riblet research with experiments using an oil channel. Riblets have three operating conditions: viscous region, optimal region, and the drag augmentation region. In the viscous region $0 < s^+ \leq 10$, riblet drag reduction varies linearly with s^+. Here, Luchini et al. (1991) clarified the concept of the riblet protrusion height, which quantifies the relative resistance riblets impose on streamwise and spanwise velocities (see Section 4.2 for a detailed description). Bechert et al. (1997) used this concept to derive a theoretical viscous region for any riblet. Recently, Garcia-Mayoral and Jimenez (2011) used Direct Numerical Simulation (DNS) to help explain why the viscous region breaks down. The authors identified a Kelvin–Helmholtz-like instability that leads to spanwise turbulent structures that

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increase turbulent mixing near the optimal region, which for most riblets is near $s^+ \approx 15$. If the break up of these structures can be delayed the drag reducing potential of the riblet in the optimal region can be increased. After reaching maximum drag reduction, riblets gradually lose their effectiveness and eventually increase skin-friction drag as s^+ increases. Riblet sizes in the drag augmentation regime exhibit k-type roughness behavior, i.e., the effective roughness height is proportional to the riblet width, see Jiménez (2004).

To understand the mechanisms of drag reduction near the optimal regime, several experimental papers (e.g. Djenidi and Antonia (1996),Park and Wallace (1994), Lee and Lee (2001),Suzuki and Kasagi (1994)) have examined the structure of turbulence very near riblets. Computational studies by Choi et al. (1993),Chu and Karniadakis (1993), and Goldstein et al. (1995) endeavored to clarify these mechanisms with DNS. Together, these works have confirmed that drag-reducing riblets decrease the root mean square (RMS) velocity fluctuations near the riblets by prohibiting larger scales of turbulence from interacting with much of the riblet surface area. This in turn isolates high shear stress regions to riblet peaks.

Most riblet research to date has been done in fully developed, turbulent channel flows. While this is an effective method to study fundamental flow physics near riblets, many practical implementations will expose riblets to varying pressure gradients specifically, Adverse Pressure Gradients (APG). An experiment focusing on the application of riblets to a practical engineering problem was carried out by Szodruch (1991). He reported that riblets attained about a 2% drag reduction when mounted on certain areas of on an Airbus A 320. More recently, Chamorro et al. (2013) measured drag reduction on a section of a wind turbine blade. The authors reported a drag reduction of 4–6% with riblets. Importantly, they determined that partially covering the airfoil with riblets actually resulted in more drag reduction than completely covering the airfoil. Sareen et al. (2014) also studied riblets mounted on a wind turbine blade, reporting a 5% drag reduction. A common feature among these three studies is that drag reduction is highly dependent upon riblet configuration (i.e., where riblets were mounted on the swept surface), which underscores the need for more fundamental research concerning riblets and APG's. Unfortunately, the few available fundamental studies disagree on how riblets perform with respect to the strength of the APG. The Clauser parameter, β quantifies the APG strength and is defined as:

$$\beta = \frac{\delta^*}{\tau_0}\frac{dp}{dz}$$

where δ^* is the displacement thickness and dp/dz is the streamwise pressure gradient. Walsh (1990) presents a brief summary of riblets in pressure gradients. Specifically, we summarize the past works of Choi (1990),Truong and Pulvin (1989), and Squire and Savill (1989). Choi (1990) tested trapezoidal riblets in a strong APG with $\beta = 5.1$. He was unable to directly measure drag, and instead used a hotwire and skin-friction hot-film sensors to measure turbulent statistics. He reported no appreciable difference in these measurements and conjectured that turbulent skin-friction (as opposed to viscous skin-friction) did not change with pressure gradient. Truong and Pulvin (1989) tested riblets mounted to a diffuser and found that as β increased, riblet drag reduction deteriorated, i.e., the riblets were not as effective. Lastly, Squire and Savill (1989) tested riblets in two mild APG conditions, $\beta = 0.2$ and $\beta = 0.5$. At $\beta = 0.5$, the drag reducing benefit of riblets was eliminated.

However, Nieuwstadt et al. (1993) noted that none of the prior studies measured drag directly, but instead used the momentum integral balance. As described by Nieuwstadt et al. (1993), the momentum balance method suffers from a great dependence upon the measured momentum thickness, θ, at upstream and downstream locations–specifically the difference of those, $\Delta\theta$. In their study, just a 2% error in momentum thickness measurement produced a 25% error in $\Delta\theta$. Using a drag balance, Nieuwstadt et al. (1993) tested trapezoidal riblets in moderate to strong APG ($\beta > 1$) and showed that riblet effectiveness *increases* with increasing β (just the opposite found by Truong and Pulvin (1989) and Squire and Savill (1989)). Debisschop and Nieuwstadt (1996) used a drag balance to test trapezoidal riblets in a wind tunnel at $\beta = 2.2$, and found that riblet drag reduction had increased from 5% in a Zero Pressure Gradient (ZPG) to 13% in an APG.

As far as computational studies, the only publication to date that considered riblets in APG is that by Klumpp et al. (2010). The authors used Large Eddy Simulations (LES) of turbulent flow around scalloped riblets to claim that even at mild APG ($\beta \approx 0.25$), riblet drag reduction can *double* that seen in a ZPG (drag reduction increased from 4.5% to 9%). Although the authors argued that their computational results mimic the experimental results by Nieuwstadt et al. (1993), there are important differences between the simulations and experiments that need to be pointed out. The main difference is that at the same Clauser parameter as that used in the simulations, $\beta = 0.25$, the experimental results from Nieuwstadt et al. (1993) showed no increase in drag reduction, while Klumpp et al. (2010) reported an increase in drag reduction from 4.5% to 9%. Only at much higher values of β did the experimental results report a significant increase in drag reduction. The reason for the discrepancy between Nieuwstadt et al. (1993) and Klumpp et al. (2010) is unknown, but one possibility could be that each study tested riblets that had different values of s^+.

It follows from the above literature that the performance of riblets in APG is still a subject of considerable debate, especially with regard to mild APG. Viswanath (2002) has experimentally shown that for a NACA0012 airfoil at an angle of attack of 4^o, the Clauser parameter corresponds to $\beta \approx 0.5$, which is a mild APG. Therefore, according to the findings of Klumpp et al. (2010), riblets could yield significant drag reducing benefits in many flows of engineering practice. This would be especially promising in terms of flow control since riblets are a passive means of drag reduction.

Therefore, the goal of this work is to contribute systematic numerical simulation results seeking to further elucidate the drag reduction capability of scalloped riblets under a mild APG, by considering a broad range of s^+ and also comparing the riblet performance in APG and ZPG turbulent boundary layers. To that end, we carry out high-resolution LES to systematically investigate riblet performance under various conditions and elucidate the fundamental physical mechanisms that govern riblet performance under APG and ZPG. This paper is organized as follows: Section 2 details our numerical methods and boundary conditions. Further details of simulation domain sizes and meshes are described in Section 3. A thorough discussion of simulation results takes place in Section 4. Lastly, we conclude in Section 5.

2. Numerical methods

2.1. Governing equations and solution method

LES of turbulent flow over riblets solves the filtered incompressible Navier–Stokes equations. The momentum and continuity equations are fully transformed into generalized curvilinear coordinates (see Kang et al. (2011)) and read as follows (repeated indices imply summation):

$$J\frac{\partial U^j}{\partial \xi_j} = 0 \quad (2)$$