DIRECT NUMERICAL SIMULATIONS OF DRAG REDUCTION IN TURBULENT CHANNEL FLOW OVER BIO-INSPIRED HERRINGBONE RIBLET TEXTURE

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Abstract The use of drag reducing surface textures is a promising passive method to reduce fuel consumption. Probably most well-known is the utilisation of shark-skin inspired ridges or riblets parallel to the mean flow. They can reduce drag up to 10%. Recently another bio-inspired texture based on bird flight feather riblets has been proposed. It differs from the standard riblets in two ways. First, the riblets are arranged in a converging/diverging or herringbone pattern. Second, the riblet height or groove depth changes gradually. Drag reductions as high as 20% have been claimed [2]. The objective of the present work is to study the drag reducing properties and mechanisms of this texture. To that purpose Direct Numerical Simulations (DNSs) of turbulent plane channel flow have been performed. Structured roughness has been applied to both walls and several geometric parameters have been varied. Marginal drag reductions on the order of 2.5% and significant drag increases well beyond 100% were found. The latter is attributed to a strong secondary flow that mixes momentum through the whole channel. In future optimization studies we might look for conditions at which secondary motions affect the near-wall cycle of turbulence only.

INTRODUCTION

A significant part of the fuel consumption by transport vehicles originates from drag in turbulent flows. To reduce costs, emissions and fossil fuel consumption, turbulent drag reduction (DR) is highly desirable. The latter can be achieved using both passive and active methods. A well-known passive method comprises the use of shark-skin inspired ridges or riblets aligned with the mean flow. When optimally designed, blade riblets can reduce skin friction up to 10% when used in a flat plate configuration [1]. The optimal riblet size scales in wall units; the optimal spacing s is given by $s^+ \approx 17$.

A not yet thoroughly studied alternative to the standard riblets is the bio-inspired bird flight feather riblet texture (see figure 1). It differs from the standard riblet texture in two ways. First, the riblets are arranged in a converging/diverging or herringbone pattern. Second, the riblet height or groove depth changes gradually.

A recent experimental study suggests that the herringbone riblet texture may result in up to 20% DR [2], about twice the maximum DR found for conventional riblets. The objective of our numerical work is to reproduce comparable drag reductions by means of DNS and to find out what mechanisms play a role.

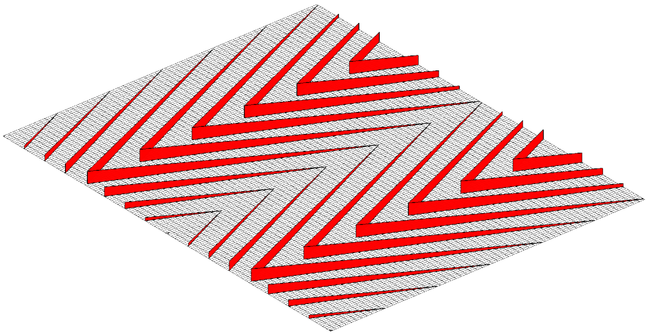

Figure 1. Part of a bio-inspired bird flight feather riblet texture.

METHODOLOGY

Direct Numerical Simulations (DNSs) of plane turbulent channel flow between two horizontal walls have been performed. Structured roughness has been applied to both walls to enforce symmetry in the mean flow [3]. A computationally efficient Immersed Boundary Method (IBM) has been used in which the texture is represented by a force distribution on a rectangular grid. The riblets have been modelled as fences with zero thickness. No-penetration and no-slip boundary conditions are applied at the walls, while periodicity is imposed in the streamwise and spanwise directions. The flow is driven by a streamwise pressure gradient that maintains a constant flow rate in the channel. The Navier-Stokes equations are solved using a standard pressure-correction method. The simulations are carried out at a bulk Reynolds number of 5500, corresponding to $Re_\tau \approx 180$ for smooth walls.

Our numerical code has been tested in several ways. First, a DNS of turbulent smooth plane channel flow has reproduced the correct skin friction. Furthermore, several DNSs of flow over straight blade riblets have been performed. The maximum DR of about 10% has been reproduced. Finally, some DNSs of flow over blade riblets under yaw have been carried out. The experimentally observed loss of DR for increasing yaw angles has been captured in our simulations.

RESULTS & DISCUSSION

The turbulent flow over the herringbone texture has been simulated using various DNSs. A small parametric study has been performed. Reductions of drag on the order of 2.5% have been found, as well as drag increases beyond 100%. Although DR has been found, at low Reynolds numbers this texture likely does not outperform the standard blade riblets. However, possibly higher values of DR might be obtained at higher Reynolds numbers.

The reason for drag increase or reduction might be attributed largely to the secondary flow that occupies the channel (see figure 2). A similar motion has been reported quite recently for a similar texture [4]. Drag reduction is obtained only for weak secondary flows. On the other hand, for cases with strong secondary motion momentum is mixed through the whole channel, contributing to significant drag increase.

Regarding the mechanisms for either drag increase or reduction, likely two effects compete. On the one hand there is a tendency to increase drag by additional pressure drag and momentum mixing. On the other hand, at favourable conditions the strong secondary flow might manipulate the near-wall cycle that sustains turbulence in such a way that drag decreases. The latter phenomenon has been observed in a DNS study of imposed counterrotating streamwise vortices and spanwise colliding wall jets [5]. In future optimization studies we might look for conditions at which secondary motions are confined to the near-wall region only.

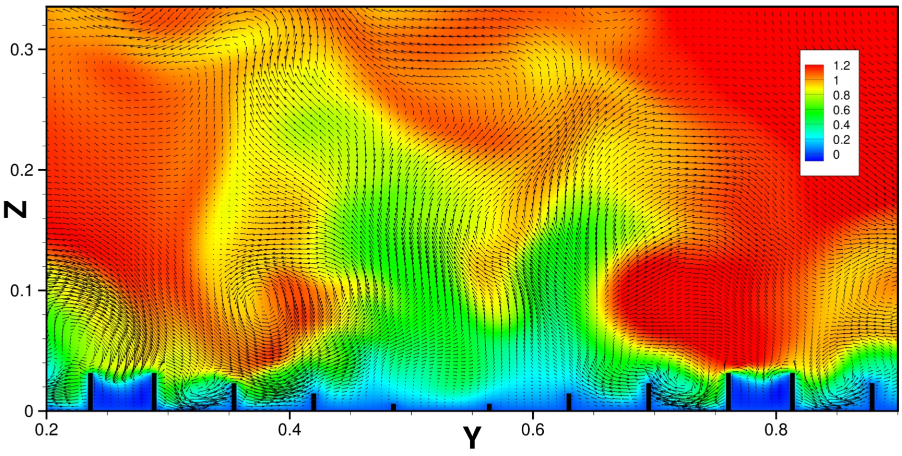

Figure 2. Instantaneous snapshot of the flow field just above the bottom wall. Colour represents the streamwise velocity normalised by the bulk velocity. Y is the spanwise, Z is the wall-normal coordinate, both normalised by the full channel height.

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