Vortex and drag control mechanism in turbulent flows using riblets

Introduction

National fuels use is on the rise, so is its subsidies, which makes a large chunk of national annual budgets.This study concerns with drag reduction efforts which is related to vehicles efficiencies by way of aerodynamics effects. The study supports national agenda of reducing fuels use. Highly ordered and directional rough surfaces, known as riblets aligned in the flow direction are known to reduce skin friction by 8-10%. Riblets have been used on aeroplanes to reduce drags which normally accounts for 40-50% of its fuel use. Riblets have also been used as a passive flow control tool i.e. for lift and heat transfer enhancements, separation delay and etc. Decelerating flows over smooth surfaces due to the geometry of such shapes that creates an adverse pressure gradient (APG) environment also reduces the skin friction. Studies have shown that if the riblets were arranged into a diverging and a converging direction (with an angle in the direction of the flow), the boundary layer thickens in the converging areas and vice versa. The effects in the converging region is similar to one caused by APG i.e. reduction in skin friction. However it is not known if the diverging region produces the opposite effects therefore producing no net skin friction reduction. This study seeks to understand the role of riblets in a diverging and a converging direction in the presence of APG using state of the art 2-dimensional traverse and constant temperature anemometer (CTA). The experiments are to be performed in APG turbulent flows where diverging and converging riblets are applied onto wind tunnel's floors. Energy spectra from the different flows will be analyzed to observe the effects of riblets and APG independently, towards the near-wall vortices and the so-called large-scales features in the logarithmic region.

It is anticipated that the aviation, the maritime, sporting equipment & gears and automotive industries to benefit from such findings. The latter, where local universities have ready-access to conduct collaborative research directly benefit the aerodynamics sections. Lost due to aerodynamic effects accounts for approximately 20% of the energy for a typical passenger vehicle, making it more important than other methods aimed at reducing fuels such as wall oscillation, coating technology and even engine's thermal efficiency.

In the last three decades riblet surfaces have been investigated extensively on account of their ability to reduce skin friction drag [1,2,3]. Initially derived from observations of the microscopic skin topology of fast swimming sharks, riblets consist of small continuous ribs and grooves mostly aligned in the streamwise direction. These grooves scale on the viscous length-scale having a height and spacing on the order 15$\mu/U\tau$, where μ is the kinematic viscosity and U_τ is the friction velocity. Extensive research has found that these highly ordered rough surfaces can achieve skin friction reductions of up to 8−10%. Riblet surfaces are also known to constrain the growth of turbulent spots by around 14% [4]. Various mechanisms have been proposed for how these surfaces achieve such reductions, but in general it seems clear that they modify the near-wall cycle of streaks and quasi streamwise vortices [5,6] in a manner that reduces the overall velocity gradient near the wall. It is possible that many surface roughnesses can interfere with the near-wall cycle in such a manner, however riblets are unique in the sense that their streamwise continuous geometry does not generate additional form drag. Riblets are also known for their ability to generate secondary flows, which may also contribute to the drag reduction mechanism [7,8].

The study of flows with pressure gradients have started much earlier e.g. [9]. Pressure gradient studies are important because almost all flows/engineering applications have flow subjected to different geometries thereby exposing to APG and favourable pressure gradient (FPG). However, it is the zero pressure gradient (ZPG) studies that receive much attentions [10,11,12]. Recent simulations in APG flow [10] indicate that moderate pressure gradient, with APG parameter $\beta = \delta^*/\tau_o\,(\mathrm{d}P/\mathrm{d}x) \approx 2$, (here δ^* is the displacement thickness, τ_o is the wall shear stress and $\mathrm{d}P/\mathrm{d}x$ is the pressure gradient) causes the streak spacing to increase i.e. $\lambda_y^+ \approx 400$; a large increase from the nominal streak spacing in ZPG, channel or pipe flows i.e. $\lambda_y^+ \approx 100-130$ [5]. Even though the increase has not been validated by experiment, the evidence further supports that pressure gradients alter near-wall properties of flows. Other experiments in support of structural changes in the near-wall region is that of [12] who observed that the inclination angles ϕ of near-wall vortices are suppressed in FPG where $\phi < 12^o$. In contrast, $\phi > 20^o$ is observed in APG flows [13] and nominally $\phi \approx 15^o$ in ZPG flows [10]. The findings that near-wall features change with pressure gradient is in line with *commonly known properties of such flows e.g. (near-wall) turbulence intensities which increase with pressure gradients [11,12,13,14,15,16].*

When combined, flows with riblet walls subjected to APG produce improved skin friction reduction [18]. At low speeds and subjected APG, riblets are even more effective [19]. However, flows subjected to pressure gradients with riblets patterned in a diverging and a converging direction, have not been conducted. This is important because experiments and simulations have individually tested riblets effect in pressure gradients and in diverging and converging patterns in ZPG only. Furthermore, there are also some small parts of the fast swimming sharks where such patterns have been observed. Therefore, it is the objective of this study to set up an experiment and analyze the effects of riblets arranged in a diverging and a converging direction subjected to presssure gradients.

Objectives

1) *To design and fabricate a 2-dimensional traverse powered by fine-step stepper motors, and design and improved an existing wind tunnel to be a boundary layer wind tunnel with adjustable roof for all pressure gradient requirements. This facility is capable of performing boundary layer measurement using constant temperature anemometer (CTA), skin friction measurement by drag balance and measurement with riblets applied to wind tunnel walls.*

2) *To investigate the effects of riblets arranged in a diverging and a converging direction subjected to presssure gradients. Both the near-wall streaks and the large-scale features in the logarithmic region will be studied using enery spectrum analysis. The skin friction will be measured by a drag balance equipment.*

3) *To establish an empirical formulation for approximating drag reductions, which parameters include APG parameter β.*

4) *To assess the possibility of applying the diverging and a converging riblets patttern onto a car top body and perform computational fluid dynamic (CFD) simulations, based on this to make recommendations to local automotive manufacturers of aerodynamic benefits of such riblets.*

Methodology

The first step is tedious as a 2-dimensional (2D) traverse will have to be designed and built in-house. This traverse will be powered by four fine-stepper motors (800 step for 1 revolution) to move hot-wire sensors in 2D. This is required to ensure spanwise spectra is smooth. Figure 1 shows the in-house traverse to be built. The base plate is made of aluminum so that machining could be done easily. Standard ball screws will be used to ensure standard movement for all sensors. General arrangement of the traverse is shown in Figure 1.

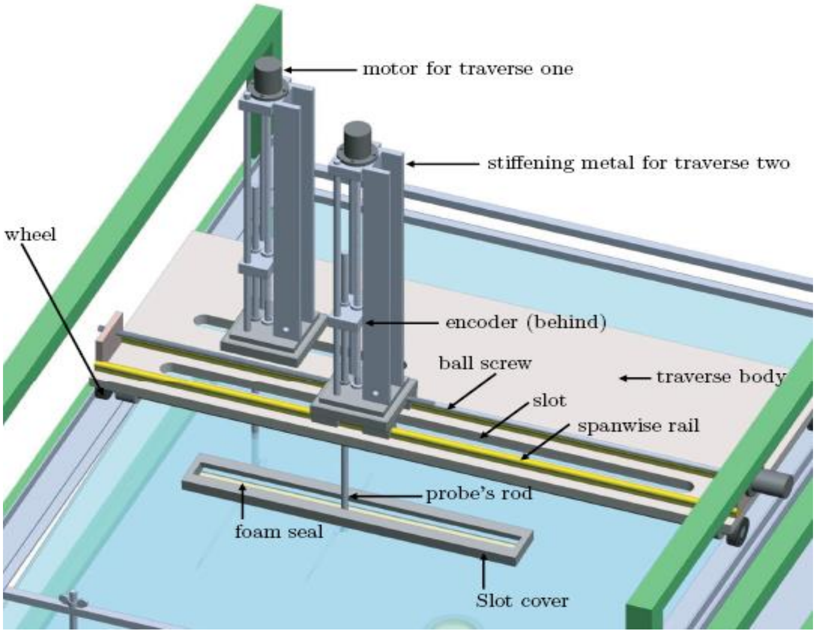

Figure 1: 2D traverse to move CTA sensor to be built

The use of CTA will have to be automated because of the expected high sensor failures. Therefore, an etching chamber to fabricate sensors and calibration method will have to be designed and put into operations. Etching chamber requires sulfuric nitric acid, therefore a proper ventilating mechanism and chemical box must be provided. Since the Dantec platinum wires will be used, and their sizes are in the order of 2.5μm, a microscope shall be available at all times. In order to avoid attenuation of signal (due to hotwire), small sensor lengths $l^+ = lU_\tau/\nu \approx 15$ shall be used [17] (here l refer to physical sensor length). Microscope will also be used for riblet fabrication purposes and setting the wall-normal position of the sensor. The steps above are expected to achieve objective 1.

Data will be collected with existing data acquisition box connected to a laptop using Matlab acquisition codes. The existing data acquisition box is capable to handle high requirements of at least 100 KHz sampling rate with at least four channels in operations. High frequency rate is required to detect the energetic near-wall features and the large-scale features using the energy spectrum method [17]. Since approximating skin friction using momentum balance method could give large errors [18], a drag balance will have to be purchased and installed flush with the riblets and wind tunnel walls. To cut costs and to add flexibility to the experiment, riblets will be fabricated in-house too.

There are two ways to fabricate riblets a. Using epoxy and resin combination and use newly constructed mould. b. Using epoxy and resins as material again, but machine with high precision numerical control (NC) machine to produce the riblets. Both ways seems possible at the faculty because the infrastructure are available such as NC machine and areas for mixing materials. The requirement for these riblets to work are high and the precision are high too. The spacing between the riblets needs to be in the order of $s^+ = sU_\tau/\nu \approx 10 - 15$ [18], where s is the riblet spacing. The physical spacing for small wind tunnel where friction velocity is small requires $s < 500\mu m$.The repeating diverging/converging region Λ shall be greater than the boundary layer thickness δ. The height h will be dictated such that the groove area cross-section $A_g^{+1/2} \approx$ 10-15 (pocket area as seen from cross-section). The groove area cross-section A_g^+ seems to give a better characterization of riblet performance rather than the spacing s^+ [3]. Results of the latter were however obtained for riblets arranged parallel with the flow direction ($\alpha = 0^o$) and in ZPG flow. Refer to Figure 2 for most of definitions and guidelines of riblets. These steps are expected to achieve objective 2.

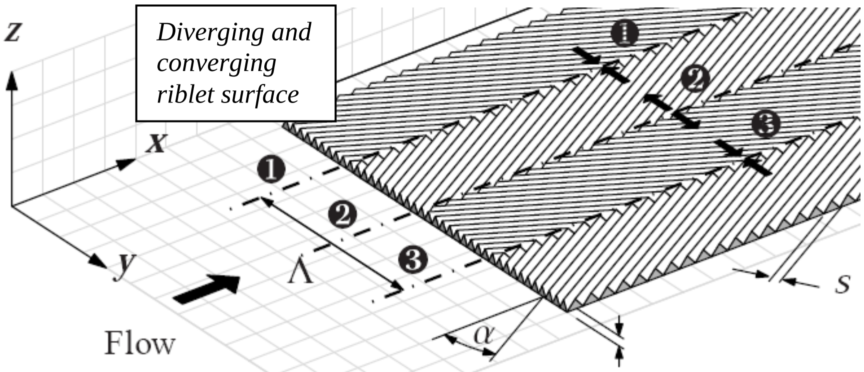

Figure 2: Riblets to be built, regions 1 and 3 are converging regions while region 2 is a diverging region. α is the angle with the direction of the flow, s is the spacing between riblet tips and h is the riblet height, Λ is the repeating diverging/converging plate.

By having a fabrication infrastructure within the faculty (Faculty of Engineering and Built Environment – FKAB, UKM), the experiment has more flexibility to have different riblet allignments (α) with the flow. This allows different settings to be performed therefore providing useful information to formulate new formulation as set in objective 3.

A comparison will have to be performed to validate the findings. Therefore, a CFD simulation using existing software will be performed. Furthermore, the riblets will be tested at UPM facility for thicker boundary layer thickness. This is expected to achieve objective 4.

Expected output

The effects of riblets in boundary layer with pressure gradient flows is of great interests because of its usefulness. A few experiments have been conducted, nevertheless, riblets arranged in diverging and converging directions in pressure gradient flows have not been recorded. Results would explain the reason for certain parts of the fast swimming sharks are ordered in such ways. An important parameter which is the APG strength β was not considered in an empirical formulation by the recently published results [3] to approximate drag reduction. Garcia-Mayoral and Jimenez, 2011 [3] also reported an energetic wavelength of $\lambda_x^+ \approx 150$ in the near-wall region ($z^+ < 30$) which is not normally observed i.e. $\lambda_x^+ \approx 1000$ [16,17]. The two last issues will be addressed sufficiently in the current proposal.

Nomenclature and symbols:

x, y *and* z : *streamwise, spanwise and wall − normal directions*
superscript $'+'$: *scaling in inner variables* U_τ *and*$_\nu$ *e.g.* $\lambda_x^+ = \lambda U_\tau / \nu$
A_g^+ : *groove area cross − section*
$h^+ = hU_\tau/\nu$: *riblet height*
$l^+ = lU_\tau/\nu$: *hotwire sensor length*
$s^+ = sU_\tau/\nu$: *riblet spacing*
U_τ : *friction velocity*
α : *angle with the flow/yaw angle*
δ : *boundary layer thickness*
δ^* : *displacement thickness*
λ : *length scale*
Λ : *repeating diverging/converging section*
ϕ : *inclination angle of near − wall vortices*
ν : *kinematic viscosity*
τ : *shear stress*
τ_o : *wall shear stress*
$\beta = \delta^*/\tau_o\,(\mathrm{d}P/\mathrm{d}x)$: *pressure gradient parameter*

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