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Semi-Empirical Optimisation of the Shape of a Surface Reducing Turbulent Skin Friction

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Abstract

Your abstract goes here. The abstract is a very brief summary of the dissertation's contents. It should be about half a page long. Somebody unfamiliar with your project should have a good idea of what it's about having read the abstract alone and will know whether it will be of interest to them.

Acknowledgements

It is usual to thank those individuals who have provided particularly useful assistance, technical or otherwise, during your project.

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Chapter 1

Introduction

1.1 Motivation

Whether it be water in a pipeline, or an aircraft soaring through the skies, every fluid passing by a solid and every solid passing through a fluid will experience drag. The ever pressing need to reduce our impact on the environment requires us to reduce our energy used to combat unwanted drag, which also has the added benefit of reducing costs via increased efficiency. This is especially true in the transportation sector, which accounts for 24% of total global emissions in 2019 according to the IEA, although growth has been limited to only 0.5% per year compared to an average increase of 1.9% annually since 2000 owing to efficiency improvements [**iea2021**].

The search for these efficiency improvements includes research towards drag reduction (DR) via flow control – that is manipulating the flow characteristics in such a way that somehow produces less overall drag. In fact, Ludwig Prandtl, who revolutionised the study of fluid mechanics with the introduction of the turbulent boundary layer (TBL), pioneered modern flow control as early as 1904, where he demonstrated that suction at the surface of a cylinder delays boundary layer (BL) separation and therefore decreases drag [**gad-el-hak2001**, **prandtl1904**]. Indeed, DR is a major focus of research in commercial aviation. In the context of aviation, a 1% reduction in drag corresponds to a 0.75% reduction in fuel and as a result CO_2 emissions [**leschziner2011**]. In fact, [**leschziner2011**] states that based on estimates on travel demand in 2030, a 1% reduction will constitute a 9 million tonnes reduction in CO_2 emissions.

In transport applications, and in particular aviation, the flows are at high Reynolds numbers Re, this means the regimes we are dealing with are often turbulent. Moreover, especially in aviation (with the exception of cases where supersonic effects dominate), viscous drag generated in the near-wall BL region constitutes a major component of total drag [**abbas2017**]. These two factors combined mean that "flow control methodology targeting the TBL is the most obvious option to achieve a significant skin-friction-drag reduction and ultimately to reduce emissions" [**abbas2017**].

Flow control is separated into two distinct groups, active and passive control. Active flow control requires an input in energy to affect the flow via the use of actuators, whereas passive flow control does not. Examples of active control include opposition control [**choi1994**, **luhar2014**], spanwise-wall oscillation [**jung1992**, **choi1998**, **viotti2009**], and the aforementioned BL separation control [**prandtl1904**]; the former is closed-loop and reacts to sensor inputs from the environment, whereas the latter two can be either open-loop with predetermined control patterns or reactive (feedback/feed-forward systems). The actuators used to perform active flow control can range from zero-net-mass-flux jets [**zhang2008**], to dielectric-barrier-discharge plasma actuators [**wang2013**], to fluid injection (blowing) and sucking [**chng2009**], to the ingenious moving surface using "pneumatically actuated compliant structure based on the kagome lattice geometry" [**bird2018**]. Whereas, examples of passive control include vortex generators [**chang1970**], discontinuities/notches/fences in the leading/rear edges of a wing [**chang1970**], compliant surfaces [**choi1997**], porous coatings [**klausmann2017**], superhydrophobic surfaces [**truesdell2006**], and a very well studied control technique known as riblets [**walsh1983**, **choi1993**, **garcia-mayoral2011**].

As aforementioned, active flow control allows for reactive responses which can increase the effectiveness of control techniques. Moreover, even open-loop flow control can achieve higher viscous drag reduction than passive control techniques without the need for sensors required for reactive flow control. However, this comes at a cost of the extra energy expended to modify the flow and the difficulty and innovation needed to design actuators. This can clearly be seen in the case of spanwise-wall oscillation where the wall moves as prescribed by a streamwise travelling wave, which, after accounting for the power spent to oscillate the fluid, has a net power saving of around 26% despite a drag reduction of $> 35\%$ for those conditions [**quadrio2009**]. Moreover, in order to emulate a in-plane wall motion in real life, the aforementioned compliant structure from [**bird2018**] had to be created and trialled in laboratory conditions, and then made at scale and maintained if it were to be used on real-world flows.

On the other hand, passive flow control in necessarily open-loop, and may have decreased performance in comparison to active flow control. However, it does not require actuators and the maintenance thereof. Riblets, for example, "are small surface protrusions aligned with the direction of the flow, which confer an anisotropic roughness to a surface" [**garcia-mayoral2011**] and can be seen in Figure **??**. Experiments show that under moderate adverse pressure gradient (i.e. where the pressure increases along the direction of the flow) a 13% skin friction reduction is achievable, compared to 6% reduction in a zero-pressure-gradient BL [**debisschop1996**]. Although less efficient compared to active control, due to its relatively simple design, its technology readiness level (TRL) is higher than most other flow control techniques. In fact it has been trialled in scale model aircraft tests in transonic Mach numbers [**coustols1990**], real aircraft tests, and even in commercial service for several years by Cathay Pacific on an Airbus A340 where 30% of the wetted surface was covered with riblets [**bechert2006**]. Based on a flight test on an Airbus A320, in transonic Mach number ranges, an A320 with 70% of the wetted surface covered by riblets could have a drag reduction of about 2% [**szodruch1991**]. However, the optimal grove cross section was found to have an optimum at $\left(A_g^+\right)^{1/2} \approx 11$, where the + superscript denotes non-dimensionalisation by wall units (see

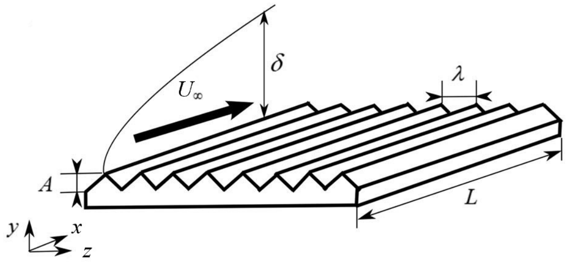

Figure 1.1: A schematic of triangular riblets the most commonly researched riblets. Figure modified from [**raayai-ardakani2019**].

Therefore, researchers have begun to explore other ways to use passive flow control for turbulent DR. The oblique wavy wall (WW) was first proposed by **chernyshenko2013** in 2013 to emulate the motions of in-plane spanwise wall oscillations in hopes that there will be a net energy decrease. We will devote the rest of this report discussing the merits of this curious passive flow control method.

1.2 Literature Review

1.2.1 The Spatial Stokes Layer (SSL)

The Stokes layer is one of a few exact solutiosn to the Navier-Stokes equation describing the motion of a viscous fluid as a function of the wall normal coordinate y, whereby the infinitely long wall is located at the bottom at $y = 0$ and oscillating harmonically in its own plane [**schlichting2017**]. It turns out that the resulting oscillation in the fluid is only of significant magnitude very close to the wall in a so-called "Stokes layer" and is significantly damped outside of the said-layer.

Chapter 2

Conclusion

Code is broken

τ_w/τ_0 problem Ycross is enough to find Pnet Subject to (1) the closed system has been obtained

Wave height versus pressure