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RECENT PROGRESS USING THE AFRODITE FLOW CONTROL STRATEGY

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Over the last decade wind tunnel experiments and numerical simulations have shown that steady spanwise mean velocity gradients are able to attenuate the growth of different types of boundary layer disturbances if introduced in a controlled way. In this paper different techniques to setup the spanwise mean velocity variations are reviewed and their stabilizing effect leading to transition delay are quantified. This control strategy has potential to lead to an unforeseen positive impact on the broad spectrum of industrial applications where reducing drag is a daily challenge.

INTRODUCTION

Recent wind tunnel experiments have shown that steady streamwise elongated streaks, produced by the lift-up mechanism, are able to reduce skin-friction drag by delaying transition to turbulence in flat plate boundary layers [5, 9]. Steady streaks may be generated by using either *active* or *passive* boundary-layer modulators, being related to whether external energy is being added or not to the control system in order to perform the control.

The underlying physical mechanism for the stabilizing effect has been shown to be associated with the extra turbulence production term, i.e. the co-variance of the streamwise and spanwise fluctuating velocity components acting on the spanwise gradient of the mean streamwise velocity component, which turns out to be of negative sign [2]. In combination with viscous dissipation it can overcome the wall-normal production term and create an overall stabilizing effect. This control method is what today is known as the method of spanwise mean velocity gradient and is used as a control strategy within the AFRODITE[1] research program. The Achilles' heel of above-described control method is that the streamwise streaks being set up by some boundary layer modulators can break down to turbulence via a secondary instability, if the streak amplitude exceeds a threshold value. This would lead to an earlier onset of transition and failure of the control would be inevitable.

A recurrent criticism of the described control method is the amount of induced drag due to the presence of the streaks and the extra drag associated with the devices themselves. Even though the control has no cost per se in terms of added energy, the devices will increase the drag, which has to be balanced against the gain. In successive studies [4, 7], where miniature vortex generators (MVGs) have been used to generate the streaky base flow, the local skin-friction coefficient has been calculated using the momentum-integral equation and the induced drag has been estimated. For the optimal streak amplitude for transition delay (around 21%) the local skin-friction drag is increased by approximately 10% just behind the MVGs compared to the Blasius boundary layer. The local skin-friction excess decays and at around 300 MVG heights downstream of the MVG array, the boundary layer has recovered and the skin-friction coefficient curve collapses onto the Blasius curve. In order to assess the total drag increase due to the MVG array a direct numerical simulation of the flow around a pair of MVGs giving a streak amplitude of approximately 25% has been performed [1]. In the simulation a flat plate length of $Re_x = xU_\infty/\nu = 4.5 \times 10^5$, expressed in terms of Reynolds number, was considered. Here x and ν denote the distance from the leading edge and the kinematic viscosity, respectively, and U_∞ is the free-stream velocity. Downstream of this position the modulated boundary layer has recovered and the contribution to the overall drag is identical to the Blasius boundary layer. The total drag increase due to the presence of the MVGs amounts to 2.5%, which is considered fairly cheap when compared with the alternative of a turbulent boundary layer over a laminar one, which can amount to an increase of the local skin-friction coefficient of up to one order of magnitude.

RESULTS

Studies of different types of boundary layer-modulators, both passive and active, have been carried out within the AFRODITE research program. A successful boundary-layer modulator for transition delay has turned out to be the minia-

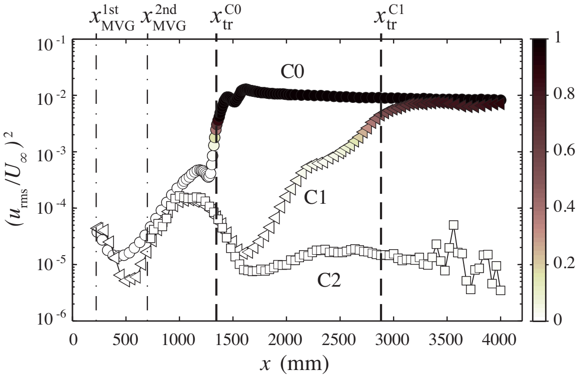

Figure 1: (Figure published in [6]). Boundary-layer disturbance energy evolution in the streamwise direction for the cases C0–C2. C0: reference configuration without control. C1: control configuration with one MVG array located at $x_{\rm MVG}^{\rm 1st} = 222$ mm. C2: control configuration with two MVG arrays located at $x_{\rm MVG}^{\rm 1st}$ and $x_{\rm MVG}^{\rm 2nd} = 700$ mm. The color bar applied to the symbols correspond to the intermittency (γ) of the velocity signal. The figure is published in [6].

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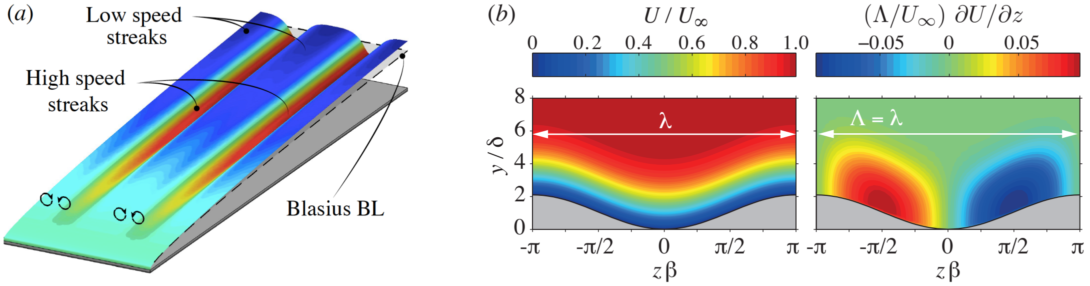

Figure 2: Different techniques to set up spanwise mean velocity gradients as a passive flow control strategy leading to transition delay. (*a*) A sketch of free-stream vortices modulating the boundary layer in the spanwise direction. The sketch is published in Siconolfi et al. [10]. (*b*) Wavy surface in the spanwise direction in order to accomplish spanwise mean velocity gradients.

ture vortex generator [9]. This passive device is typically placed in an array orthogonal to the direction of the base flow in a flat plate boundary, which creates a streaky boundary layer with alternating high and low speed streaks in the spanwise direction. Depending on the configuration with respect to both boundary layer and geometrical parameters of the devices the streaks evolve differently in the streamwise direction. A scaling relation based on empiricism has been proposed [7] and the control method has been tested for different types of disturbances [8]. Unfortunately, the natural recovery of the modulated laminar base flow in the streamwise direction is of exponential space scale and hence the passive laminar control fades away fairly rapidly. In a recent study we have shown that by placing a second array of MVGs downstream of the first one it is possible to nourish the counter-rotating streamwise vortices responsible for the modulation, which results in a prolonged streamwise extent of the control (see figure 1). With this control strategy it is possible to delay the transition to turbulence, consecutively, by reinforcing the control effect and with the ultimate implication of obtaining a net skin-friction drag reduction of at least 65% [6].

Further wind tunnel experiments in the Minimum-Turbulence-Level wind tunnel at KTH are being performed with new passive and active control method approaches. A new passive control approach is directed towards direct surface modulations, in line with the work described in [3], a necessary step in being able to delay transition to turbulence originating from free-stream turbulence according to our current knowledge. A sketch of a wavy surface is shown in figure 2(*b*). Another, control approach reported in [10] is to generate free-stream vortices, which penetrate through the boundary layer edge and modulate the boundary layer from the top (see the sketch in figure 2*a*). This work is numerical so far, but existing ideas on how to setup free-stream vortices experimentally will be tested in the near future. The conference contribution will include the latest results performed within the AFRODITE program, with focus on the presently ongoing measurements.

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