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DOWNSTREAM DEVELOPMENT OF LOCALLY CONTROLLED TURBULENT BOUNDARY LAYER

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INTRODUCTION

A broad variety of control methods aimed at the reduction of skin friction drag in turbulent boundary layers was introduced over the past few decades. Since the majority of these control methods are proposed for a configuration of a periodic fully developed turbulent channel flow controlling the entire wall area, the knowledge about local control application is still limited. However, localized control is more realistic from the engineering point of view. In this case the flow alteration outside of the control region also has to be taken into account for the overall control performance estimation. In the present work two locally applied drag reducing control methods with entirely different control mechanisms are investigated in the framework of a spatially developing turbulent boundary layer (TBL) in order to analyse the flow behaviour downstream of the control region. In addition, the global performance of these flow control techniques is evaluated.

PROCEDURE

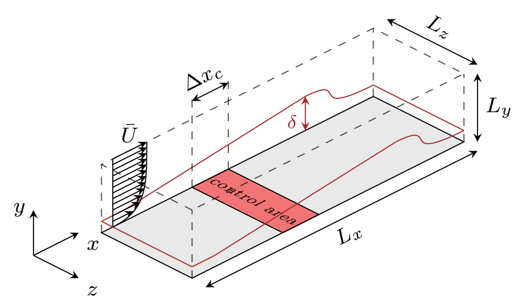

Figure 1: Sketch of numerical domain and control placement.

A direct numerical simulation of a zero pressure gradient TBL is carried out using a pseudo-spectral solver for incompressible boundary layer flows. The setup of the simulation is similar to the one used by Schlatter *et al.* [3] in terms of size and resolution (Table 1). All quantities are non-dimensionalized using initial displacement thickness, δ_0^*, and free-stream velocity, U_∞.

grid size $N_x \times N_y \times N_z$	domain dimension $L_x \times L_y \times L_z$	Re_θ
$3072 \times 301 \times 256$	$3000 \times 100 \times 120$	$250 - 2400$

Table 1: Domain properties.

Two control types are investigated in the present work: an active scheme of uniform blowing and a reactive scheme of body force damping. Both control schemes are applied to the entire spanwise extent of the simulation domain, while the local control placement in streamwise direction is defined by

$$f(x) = \begin{cases} 1, & \text{within control region,} \\ 0, & \text{otherwise,} \end{cases} \quad (1)$$

with a smooth transition between the uncontrolled and controlled region. Figure 1 demonstrates the control placement in the considered simulation domain.

Local uniform blowing [2] is given as

$$v_w = v\left(x, y=0, z, t\right) = \alpha \cdot f\left(x\right), \quad (2)$$

where α represents the blowing intensity, which is fixed to 0.5% of U_∞. Body force damping [1] introduces a wall-normal body force distribution,

$$b_y(x,y,z,t) = -\frac{f\left(x\right)}{\Phi} \cdot v(x,y,z,t), \quad (3)$$

which is opposed to the actual velocity $v(x,y,z)$ at this position. The forcing time scale Φ is chosen to be 5/3 in order to achieve a similar local drag reduction rate to the uniform blowing case. The control is applied in the near wall region up to $y^+ < 40$.

The control performance is estimated using the local drag reduction rate

$$R\left(x\right) = 1 - \frac{c_f\left(x\right)}{c_{f,0}\left(x\right)}, \quad (4)$$

and the integral drag reduction rate which represents the overall drag reduction at a certain position x,

$$R_{int}\left(x\right) = 1 - \frac{\bar{c}_f\left(x\right)}{\bar{c}_{f,0}\left(x\right)} \quad \text{with} \quad \bar{c}_f\left(x\right) = \frac{1}{x}\int_0^x c_f\left(x\right)\mathrm{d}x, \quad (5)$$

where the subscript "0" denotes the uncontrolled values.

RESULTS & DISCUSSION

Within the control region, about 63% and 57% drag reduction can be achieved locally for body force damping and uniform blowing (Figure 2). In the case of uniform blowing the flow field response is fast and a slight reduction of c_f is already observed upstream of the control region. For body force damping the flow field response is rather slow and the

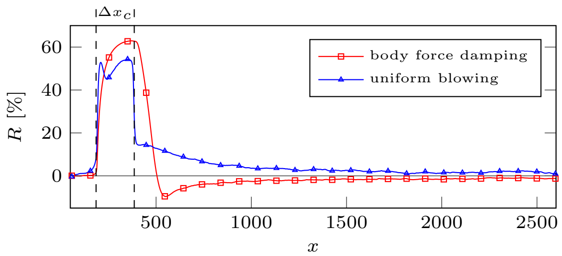

Figure 2: Local drag reduction rate.

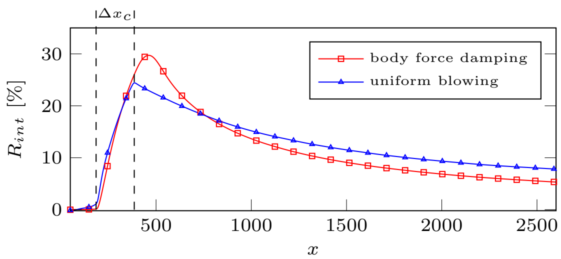

Figure 3: Integral drag reduction rate

maximum drag reduction is reached only towards the end of the control region. The integral drag reduction rate as given in Eq. 5 is similar for both control types and yields $R_{int} \approx 25\%$ at the end of the control region (Figure 3). Downstream of the controlled section body force damping remains the more efficient technique up to $x = 700$, while it is outperformed by uniform blowing further downstream. In spite of the similar drag reduction achieved within the control region, the flow development downstream significantly differs for considered control types. While body force damping exhibits a permanent negative R after a certain relaxation length, R for uniform blowing remains always positive (see Figure 2).

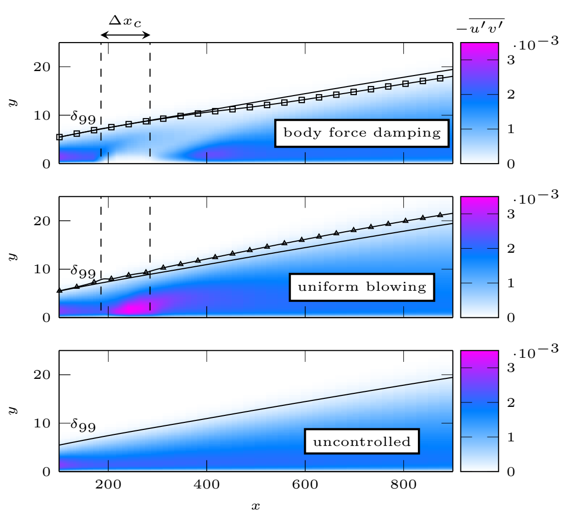

Figure 4: Reynolds shear stress.

The variation of integral drag reduction rates are linked to control-specific differences. As can be seen in Figure 4, body force damping attenuates turbulent activity in the control region and renders the TBL thinner. Conversely, uniform blowing naturally causes a thickening of the TBL as well as an increase of turbulent activity in the control region.

Since the simulation domain size is always limited, the need arises for an estimation of the flow behaviour far downstream

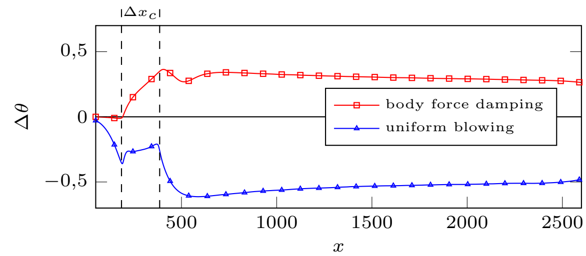

Figure 5: Alteration of momentum thickness.

of the control region. Such estimation can be performed using the simplified form of the von Kármán integral momentum equation:

$$\frac{\mathrm{d}\theta}{\mathrm{d}x} = \frac{c_f}{2} + \frac{v_w}{U_\infty}. \qquad (6)$$

The integration of the equation in streamwise direction yields a relation between R_{int} and the change of momentum thickness, $\Delta\theta$:

$$R_{int}\,(x) = \frac{\Delta\theta\,(x)}{\theta_0\,(x)} + \frac{v_w \Delta x_c}{\theta_0\,(x)\,U_\infty}. \qquad (7)$$

Since $\Delta\theta$ changes with the downstream development of the TBL (Figure 5), it is more straightforward to capture the control influence by a virtual shift of the leading edge, Δx_s. For the two discussed control techniques Δx_s is found to be either positive or negative. Once this spatial shift of the leading edge is known, the development of R and R_{int} downstream of the control can be directly estimated from empirical correlations.

OUTLOOK

In the presentation we will report various methods for estimation of the leading edge shift and show a comparison of the numerical data with the proposed estimation of the downstream TBL behaviour based on empirical correlations. Additionally, the influence of control placement on the globally achievable drag reduction rate will be discussed.

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