Drag reduction strategies

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1. Motivation and objectives

In last year's Annual Research Briefs (Hill 1993) a description was given of an active control scheme using wall transpiration that leads to a 15% reduction in surface skin friction beneath a turbulent boundary layer, according to direct numerical simulation. In this research brief further details of that scheme and its variants are given together with some suggestions as to how sensor/actuator arrays could be configured to reduce surface drag. The research which is summarized here was performed during the first half of 1994.

This research is motivated by the need to understand better how the dynamics of near-wall turbulent flow can be modified so that skin friction is reduced. The reduction of turbulent skin friction is highly desirable in many engineering applications. Experiments and direct numerical simulations have led to an increased understanding of the cycle of turbulence production and transport in the boundary layer (Robinson 1991) and raised awareness of the possibility of disrupting the process with a subsequent reduction in turbulent skin friction (Bushnell & McGinley 1989, Blackwelder 1989). The implementation of active feedback control in a computational setting is a viable approach for the investigation of the modifications to the flow physics that can be achieved (Choi *et al.* 1994).

Bewley *et al.* (1993) and Hill (1993) describe how ideas from optimal control theory are employed to give "sub-optimal" drag reduction schemes. The objectives of the work reported here is to investigate in greater detail the assumptions implicit within such schemes and their limitations. It is also our objective to describe how an array of sensors and actuators could be arranged and interconnected to form a "smart" surface which has low skin friction.

2. Accomplishments

As before, the various schemes are aimed at reducing the mean drag upon a plane wall by the application of distributed or localized blowing and suction. There is no net mass flux through the wall, and an expense is associated with the control action. The simulations are performed for a channel flow with a constant mass flux through the channel. The Reynolds number based on friction velocity is of the order 100 for the tests.

2.1 Assumptions

The sub-optimal drag reduction scheme of Hill (1993) is based upon minimizing the drag by considering how the flow is most favorably influenced during consecutive short time intervals. In order to arrive at the relatively simple control law, several assumptions must be made about the flow field.

Only flow structures in a layer close to the wall are significant in deciding how control will modify the flow evolution. The characteristic thickness of this *layer of influence* is

$$L_T = \frac{4}{3}\sqrt{\frac{T}{\pi}} \text{ wall units,} \tag{1}$$

where T is the *control time interval* in wall units over which the local optimization is made. The layer of fluid between the wall and $y^+ = L_T$ will be referred to as the layer of influence. The dynamics of the flow within this layer guides the control force distribution.

One concern about the original derivation of the result reported last year was the assumption that there is no mean shear at the wall. The flow was taken to be uniform, and the effects of mean shear were assumed to be negligible. Following a considerable analytical effort, that assumption has been shown to be valid. A re-derivation of the scheme with mean shear effects included leads to the same result as that presented by Hill (1993).

Other assumptions made during the derivation have been clarified:

1. *Events far from the surface are not modified significantly by the effect of the surface control velocities.*

2. *On the control time interval, mixing within the layer of influence is sufficiently weak that it plays a negligible role in the transport of control signals.* There is an unsteady component in the near-wall flow field. The effect of unsteadiness in transporting the control signals has been neglected. Note that this does not mean that unsteadiness has been neglected.

3. *Those flow structures which govern the sensitivity of the immediate drag to changes in the control distribution do not evolve significantly on the control time interval.*

4. *The layer of influence is sufficiently thin that the mean and unsteady flow components within the layer are represented well by a low order Taylor expansion at the wall.* It is assumed that the differential scale in the wall-normal direction of the velocity fluctuations is much larger than the thickness of the layer of influence.

It is important to recognize that the present control theory deals only with efficient changes to the behavior of the viscous sub-layer region. The physics of the sweep events and turbulence production involves events further from the wall which have a much longer time scale than that of the optimization. Consequently, these flow characteristics are not necessarily modified in an optimal manner. They are influenced indirectly by the modifications which are applied in the viscous sub-layer.

2.2 Variants of the original scheme

Using the sensitivity function, two classes of scheme have been devised and tested by direct numerical simulation. The wall-normal velocity component at the nth time step is represented by its Fourier transform, $\hat{\Phi}^{(n)}(\alpha, \beta)$, where α and β are streamwise and spanwise wave numbers ($\gamma = \sqrt{\alpha^2 + \beta^2}$). The Fourier transform of the streamwise velocity fluctuations is denoted by $\hat{u}^{(n)}(\alpha, \beta; y)$.

1. In the spirit of Choi *et al.* (1994), we considered the scheme

$$\hat{\Phi}^{(n+1)}(\alpha, \beta) = \frac{\hat{u}^{(n)}(\alpha, \beta; L_T)}{\left(\ell - \frac{i\alpha}{2\gamma}(1 - \gamma L_T)\right)}. \tag{2}$$

This scheme uses information within the flow domain at $y^+ = L_T$. With $\ell = 1$ and $L_T = 10$, a drag reduction of 19% is achieved. The similar scheme of Choi *et al.*, which applies wall transpiration equal and opposite to the wall-normal velocity component at $y^+ = 10$, gives a reduction of about 23%.

2. The following relaxation scheme has been tried:

$$\hat{\Phi}^{(n+1)}(\alpha, \beta) = \frac{1}{1 + \mu\left(\ell - \frac{i\alpha}{2\gamma}(1 - \gamma L_T)\right)} \left\{ \hat{\Phi}^{(n)}(\alpha, \beta) + \mu L_T \left(\frac{\partial \hat{u}^{(n)}}{\partial y}\right)_{y=0} \right\}, \tag{3}$$

where μ is a relaxation parameter. This scheme uses wall information only and leads to a drag reduction of about 14% ($\mu = 0.05, \ell = 1, L_T = 5$).

2.3 Implications for sensor and actuator arrays

In practice an active drag reduction system is likely to consist of an array of wall-mounted sensors and actuators. For the present scheme, the sensors must measure the streamwise component of wall shear, while the "actuators" are orifices through which fluid is injected and removed. The control velocity at a particular actuator is updated on the basis of information from the sensors in its neighborhood. The prior control velocities at neighboring actuators are also required.

Consider a rectangular array of locations on the wall at which the control velocity is specified. Variable $\Phi_{i,j}^{(n)}$ denotes the control velocity at the ith streamwise and jth spanwise position. Let h_x^a and h_z^a be the streamwise and spanwise spacing, respectively, between actuators. Suppose that the unsteady component of wall shear in the streamwise direction, $\sigma_{i,j}^{(n)}$, is measured at a similar array of sensor positions, which is offset from the actuator array. Let h_x^s and h_z^s be the streamwise and spanwise spacing of the sensors. In order to define the control update at the (i, j)th actuator, data from a number of neighboring actuators and sensors is employed. Let there be N_x^a streamwise and N_z^a spanwise actuators and N_x^s streamwise and N_z^s spanwise sensors.

The following scheme is proposed:

$$\Phi_{i,j}^{(n+1)} = \sum_{k=1}^{N_x^a} \sum_{l=1}^{N_z^a} W_{k,l}^a \Phi_{i+k,j+l}^{(n)} + \mu L_T \sum_{k=1}^{N_x^s} \sum_{l=1}^{N_z^s} W_{k,l}^s \sigma_{i+k,j+l}^{(n)}. \tag{4}$$

The weights are

$$\begin{aligned} W_{k,l}^a &= c(k, N_x^a) c(l, N_z^a)\ h_x^a h_z^a\ K(-x_{k,l}^a, -z_{k,l}^a), \\ W_{k,l}^s &= c(k, N_x^s) c(l, N_z^s)\ h_x^s h_z^s\ K(-x_{k,l}^s, -z_{k,l}^s), \\ c(k, N) &= 1/2, \text{ if } k = 1, N, \\ &= 1 \text{ otherwise}, \end{aligned} \tag{5}$$

where $(x^a_{k,l}, z^a_{k,l})$ and $(x^s_{k,l}, z^s_{k,l})$ are the locations of the actuators and sensors, respectively, measured relative to the location of the actuator for which the control velocity is being computed.

The function $K(x,z)$ is defined by

$$K(x,z) = \frac{1}{4\pi^2} \int_{-\alpha_0}^{\alpha_0} \int_{-\beta_0}^{\beta_0} \frac{e^{i(\alpha x + \beta z)}}{\left(1 + \mu\left(\ell - \frac{i\alpha}{2\gamma}(1 - \gamma L_T)\right)\right)} d\beta d\alpha. \tag{6}$$

The wave number cutoffs α_0 and β_0 are introduced since the derivation for the analytical control law is not defined as α and β become very large. Preliminary experience suggests that the application of this cutoff does not have a detrimental effect.

It has been found that only a few neighboring points offer a significant contribution to the summation; the weight factors $W^{a,s}_{i,j}$ diminish rapidly in magnitude as $|i|$ and $|j|$ are increased. This is very encouraging since it suggests that a control stencil that employs information from nearby sensors and actuators alone may be quite effective. Experience with the spectral version of the control scheme suggests that the streamwise spacing between actuators/sensors should not exceed 12 wall units if the scheme is to be effective. The spanwise spacing should not exceed 4 wall units.

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