Feedback Control of Boundary Layer Bypass Transition: Comparison of a numerical study with experiments

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Nomenclature

δ_0^* Displacement thickness at the inflow

Ω_{rms} Disturbance attenuation due to the control

L Integral length scale of inflow turbulence

l^2 Control penalty (see Ref. 6)

Re Reynolds number

Tu Turbulence intensity

$u_{rms,max}$ Wall-normal maximum of the rms value of the streamwise disturbance velocity

x Distance from the leading edge

Introduction

Objective and outline

Feedback manipulation (or control) of flows aiming to reduce the friction drag is a promising way of using the knowledge and predicting ability provided by supercomputers in the last decades. In order to go from computer simulations to physical experiments, it is not sufficient to reproduce a physical configuration. It is also necessary to use (and possible model)

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sensors and actuators. A general review on the application of control theory to fluid dynamics is given in Ref. 1. Studies on the application of model-based linear feedback control have shown possibilities to delay transition.[2] More recent efforts aim to build reduced-order models for the flow enabling fast computation of the control signal in large systems.[3,4]

Numerical studies of flow control usually show a large potential whereas the experimental results are more modest. In this paper, however, we aim at bridging the gap between experiments and simulations. The flow case under study is bypass transition in a flat-plate boundary layer. We will first briefly introduce our previous experimental[5] and numerical work.[6] A LES (large-eddy simulation) will then be matched to the experiments and control is applied in the matched simulation. This work is performed in order to identify critical technologies (sensor, controller, actuator) and possible benefits.

Bypass transition

The term boundary layer bypass transition denotes transition scenarios where the dominant instability mechanism is not the exponential growth of two-dimensional Tollmien-Schlichting waves. The most common example is probably transition induced by high levels of free-stream turbulence[7] (typically above 0.5-1% of the free-stream velocity). A visualisation of the process, taken from the present simulation, is shown in figure 1. Owing to the non-modal effect, elongated streamwise streaks are induced inside the boundary layer by streamwise vortices. This process is known as the lift-up effect.[8] These streaks grow in strength and become susceptible to high-frequency secondary instabilities. These form localised regions of chaotic swirly motion, turbulent spots. Subsequently spots grow, merge and a fully-developed turbulent flow is observed.

Experimental demonstration of feedback control

An experimental demonstration of feedback control of bypass transition has been reported earlier.[5] The data from this experiment will be used here as reference in a numerical study aiming at reproducing the disturbance conditions in the experiment as well as the control performance. A schematic of the experimental setup is shown in figure 2 (a). Free-stream turbulence was generated by a grid upstream of the plate and the velocity was measured by a hot wire traversed in the flow. One control unit is depicted in figure 2 (b). Variations of the streamwise wall shear stress were measured by the upstream wall wires. Control suction through the actuator holes was turned on (with a time delay to account for the disturbance propagation downstream) during periods when the shear was below a preset threshold. The effect of the control is measured by studying the attenuation of the maximum of u_{rms} at different positions. The disturbance attenuation is quantified as

$$\Omega_{rms} = 1 - \frac{u_{rms,max,on}}{u_{rms,max,off}}, \tag{1}$$

so that Ω_{rms} is the relative decrease of the disturbance level in the boundary layer due to the control.

Numerical simulations of feedback control

Bypass transition was simulated using direct numerical simulations (DNS)[10] and large-eddy simulations (LES). A thorough study on different LES models was performed and the ADM-RT sub-grid-scale model turned out to be particularly suited for this transitional flow.[6] The simulation code employed[11] uses Fourier representation in the streamwise and spanwise directions and Chebyshev polynomials in the wall-normal direction. Resolution and domain size are reported in table 1.

A linear feedback control scheme was employed in order to reduce the disturbance growth and consequently delay transition. The case of bypass transition represents an extension of the linear control approach[2] to flows characterised by strong nonlinearities. Control was applied by distributed blowing and suction at a portion of the wall. Initially, the control signal was based on the full knowledge of the instantaneous velocity field (i.e. full information control). In order to relax this unphysical requirement possible only in a numerical simulation, an estimator based on wall measurements was built.

Both the full information controller and the estimator are derived within the Linear Quadratic Gaussian (LQG) framework where a Linear Quadratic Regulator (LQR) is combined with a Kalman filter.[12] The boundary layer flow is modelled by the Orr-Sommerfeld and Squire system governing the evolution of perturbations in parallel flows. The objective is to minimise the kinetic energy of the perturbations.

The results[6] showed that the control was able to delay the growth of the streaks in the region where it is active. The flow field can be estimated from wall measurements alone: the structures occurring in the “real” flow are reproduced correctly in the region where the measurements are taken. Downstream of this region the estimated field gradually diverges from the “real” flow, revealing the importance of the continuous excitation of the boundary layer by the external stochastic free-stream turbulence. Control based on estimation, termed compensator, was able to delay transition but less effectively than the full information control.

Matching of LES and experiments

In the following we will attempt to apply the control strategy described in the previous section to a numerical simulation that resembles the experimental conditions with $Tu = 2.5\%$ (based on the fluctuations of the streamwise velocity component). Once agreement in the disturbance development has been achieved, we will limit the actuation in the simulation to approach the physical characteristics of the control implemented in the experiment.

Matching of the disturbance growth without control

The first task is to set up a numerical simulation of the flow that reproduces as close as possible the actual flow of the experiment. However, there are restrictions that make a perfect matching with the experiment virtually impossible. The two main differences are that (i) the code we employ can not include the leading edge and therefore perturbations cannot penetrate the boundary layer directly furthest upstream and (ii) the size of the computational domain is smaller than the wind-tunnel test section and therefore only free-stream turbulence with shorter integral length scale can be simulated. The difference in length scales causes different decay rates of the external turbulence and thus different effects upon the underlying boundary layer. However, a wider computational domain would make the simulations too time-consuming and the extensive parameter studies reported here would not be feasible. Thus we are aiming at a simulation that reproduces the main features of the experimental data in terms of disturbance growth and subsequent transition. An exact match is not possible due to the differences detailed above.

The matching is performed by varying the turbulence intensity and the integral length scale of the inlet free-stream turbulence and compare the streamwise development of the wall-normal maximum of the streamwise velocity $u_{rms,max}$. We tried seven different integral length scales of the turbulence $L/\delta_0^* = 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, 8.5$ and three turbulence intensities at the inlet, $Tu = 3, 3.5, 4\%$. The turbulence length scale L is defined as 1.55 times the length scale defined from the longitudinal two-point correlation.[10]

From figure 3 we see that the case with $Tu = 3.5\%$ and $L = 4.5\delta_0^*$ is closest to the experiment in terms of initial growth and transition location and this is our reference case below. The parametric study confirms that transition is enhanced when increasing the turbulence intensity and the integral length scale of the turbulence (owing to slower decay). The turbulence level used to match the experimental data is therefore considerably higher than in the experiments.

Optimal control

In this study we are interested in the difference between distributed and localised actuation and in the effect of suction only; we therefore neglect the estimation problem and only consider the full-information control. The time-and-space varying control suction/blowing is applied in a stripe from $x = 350\delta_0^*$ to $x = 550\delta_0^*$. In the figures to come, the uncontrolled reference case is shown with a thick curve and the full-information, full-actuation controlled case is shown with a thinner line. The thin line can indeed be seen as the best possible performance we could achieve by tuning different control parameters (penalty in wave-number space) and is thus our control reference case. Experimental data is shown with markers (squares and asteriks).

At this point it is useful to recall the differences between the actuator in the experiment and in the simulations. These pertain to (i) the way the control signal is calculated and (ii) the area over which control is applied. In the experiment opposition control is adopted where the (preset) suction velocity, threshold for detection and the time delay between the sensor and the actuator are varied. In the LES an optimisation of the distributed and modulated control action is performed and no further tuning is required. Note however that the control signal is computed assuming linearly evolving disturbances and parallel base flow. Secondly, it should be mentioned that the control is active over a large area of the plate where relatively weak blowing/suction is applied in the case of the numerical simulations. On the contrary, small holes with strong suction velocity are used in the experiment. Further, in the LES we apply control over the full spanwise width of the domain while in the experiment the control units are positioned near the middle of the plate and have a spanwise width of about 20 mm through four discrete 0.5 mm holes (for each control unit).

We will now try to wind down these differences. The control strategy in terms of the way the control signal is calculated will not be changed. Instead, we will focus on the geometrical/functioning aspects of the actuator itself. The following restrictions will be used alone or in combination: (i) apply only suction, (ii) restrict the area of actuation to spanwise strips, (iii) decrease the streamwise extension of the area where suction is applied and increase the maximum suction amplitude. The amplitude increase is obtained by decreasing the cost of the control in the overall cost function (referred to as a "cheaper" control).

In figure 4 we see three cases where the actuation characteristics are varied. In particular, we first keep the actuation area the same but remove all the blowing while maintaining the suction unchanged (dashed curve in the figure); second we keep the blowing and suction unchanged but apply it only in spanwise areas of width $5\delta_0^*$ (dashdotted) with a centre-to-centre distance of $10\delta_0^*$; finally we combine the two cases above applying only suction and cutting the signal in the spanwise direction (dotted). We see that the performance of the control in the LES is gradually degrading, approaching the experimental results. However a certain delay in the transition location remains.

In figure 5 we see the results from the simulation where all the previous restrictions on the actuator have been applied but also the streamwise extent of the control has been reduced from $200\delta_0^*$ to $20\delta_0^*$. Additionally we reduce the penalty put on the control during the design process from $l^2 = 10$ to $l^2 = 2$ (see Ref. 6 for a complete description of this parameter) resulting in stronger suction. In this last case the control effect is almost the same for both the experiment and the simulation near the actuation region but downstream there is a delay of transition only in the numerical study. This can be explained by the fact that in the experiment control is applied near the middle of the plate and where transition occurs fully developed turbulence "invades" the controlled area from the uncontrolled sides.

Conclusions

Feedback control of bypass transition has been studied. One experimental[5] (suction through holes triggered by the varying wall shear stress via threshold and delay) and one numerical[6] (LQR with and without Kalman filter estimation) study are described. A simulation giving a similar development of the disturbance amplitude as the experiment has been obtained and the LQR has been applied to this simulation.

1. The LQR with time and space varying blowing/suction gives much larger initial disturbance attenuation than the experiments (55% as compared to 15%) and a considerable transition delay.

2. The initial disturbance attenuation in the simulations approaches the one obtained in the experiments if the capability of the actuator coupled to the LQR is limited towards the ability of the experimental ones (by (i) using only suction, (ii) limiting the actuation to limited spanwise positions and (iii) decreasing the streamwise length of the actuation stripe).

3. Compared to the case with complete actuation, a smaller, but still distinct, transition delay is obtained as the actuation ability is decreased.

Based on these observations, we find it plausible that an experiment in which the full span of the wind tunnel was controlled, would produce a transition delay. The results clearly indicate the importance of a good model for the actuators. This enables us to extract relevant information on the performance of the control from numerical simulations.

Acknowledgements

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List of Table Captions

$\frac{L_x \times L_y \times L_z}{\delta_0^*}$	$N_x \times N_y \times N_z$ $(resolution)$
$2250 \times 60 \times 96$	$576 \times 121 \times 64$

TABLE 1:

List of Figure Captions

Figure 1: Visualisation of boundary layer transition induced by free-stream turbulence. Flow is from lower right to upper left. The structures near the wall in the boundary layer correspond to low and high velocity streaks while the structures in the free stream indicate vortical structures by means of the λ_2 vortex identification criterion.[9]

Figure 2: (a) Setup and (b) close up of a control unit. Measures are in mm.

Figure 3: Wall-normal maximum of the streamwise velocity fluctuations u_{rms}. Levels of turbulence intensity from top to bottom: 3%, 3.5% and 4%. Each line on the plots to corresponds to a predefined integral length scale of the free-stream turbulence at the inlet. The legend shows the length scale in δ_0^* units. The dashed black line indicates the experimental data.

Figure 4: Control effect as a function of streamwise distance. Curves are simulations: thick solid: reference case, thin solid: control reference case, dashed: control with only suction case, dashdotted: control with spanwise cut , dotted: control with only suction and spanwise cut. Squares and asterisks as before. Top: wall-normal maximum of u_{rms}. Bottom: disturbance attenuation Ω.

Figure 5: Control effect as a function of streamwise distance. Solid lines are simulations: thick solid: reference case, thin solid: control reference case, dash-dotted: control with only suction, spanwise and streamwise cut and stronger maximum suction (cheaper control). Markers: experimental data, asterisks: 1 unit and squares: 2 units. Top: wall-normal maximum of u_{rms}. Bottom: disturbance attenuation Ω.

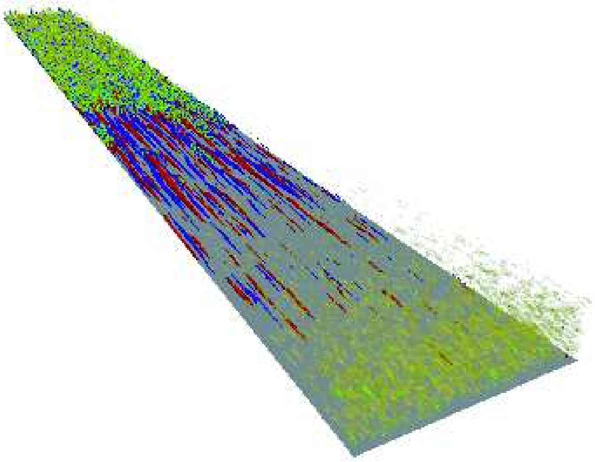


FIGURE 1:

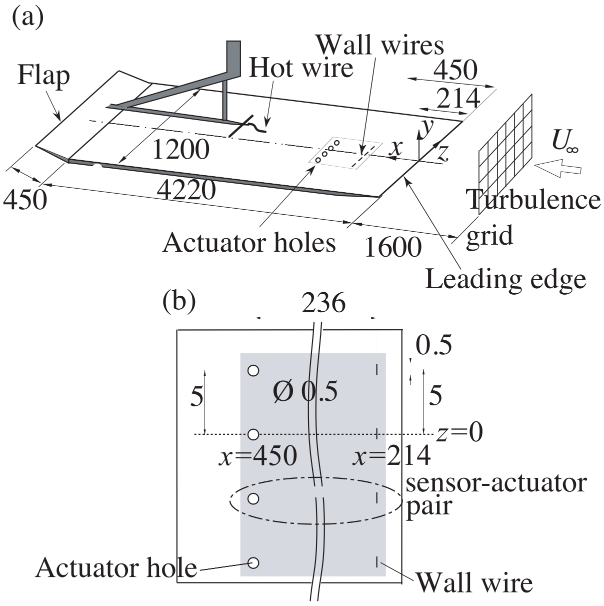

(a)
Flap
Hot wire
Wall wires
450
214
1200
y
x
z
U_∞
450
4220
Turbulence
grid
Actuator holes
1600
Leading edge
(b)
236
0.5
5
Ø 0.5
5
z=0
x=450
x=214
sensor-actuator
pair
Actuator hole
Wall wire

FIGURE 2:

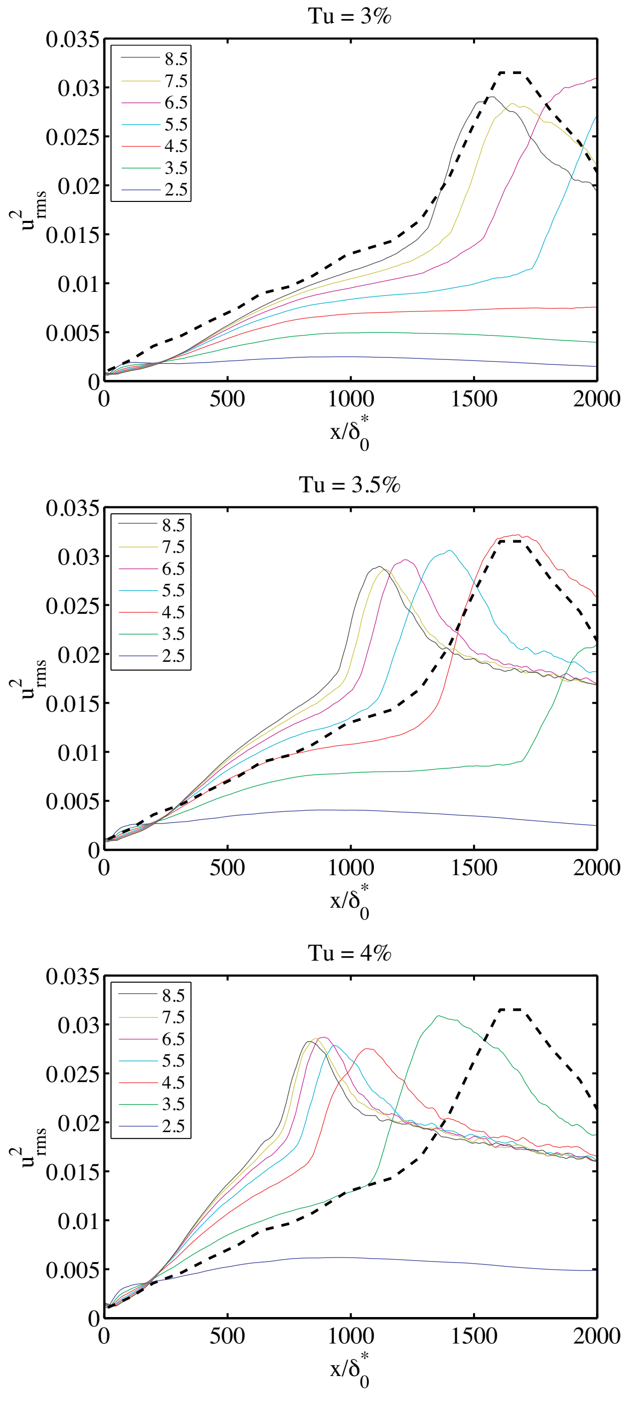
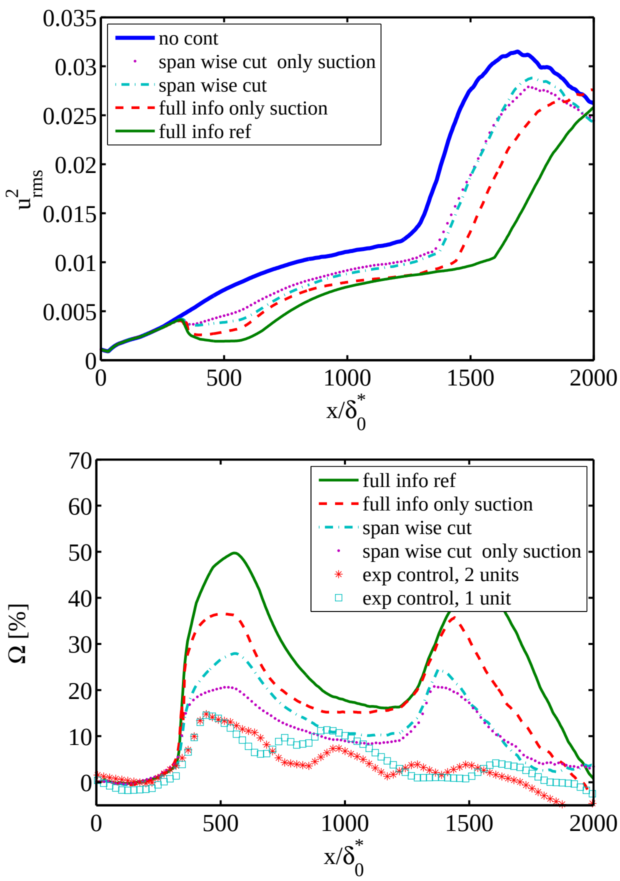
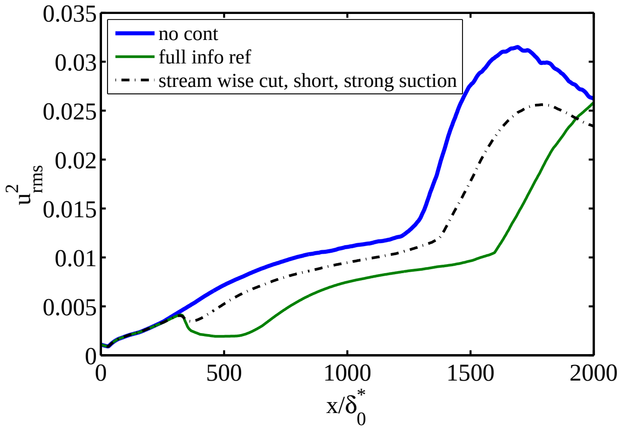

Tu = 3%
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
u2rms
8.5
7.5
6.5
5.5
4.5
3.5
2.5
0
500
1000
1500
2000
x/δ*0
Tu = 3.5%
Tu = 4%

FIGURE 3:

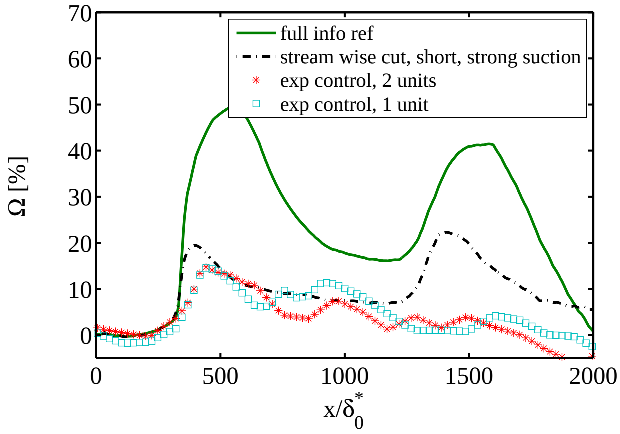


no cont
span wise cut only suction
span wise cut
full info only suction
full info ref
u^2_{rms}
x/δ_0^*
full info ref
full info only suction
span wise cut
span wise cut only suction
exp control, 2 units
exp control, 1 unit
Ω [%]
x/δ_0^*

FIGURE 4:



0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
u^2_{rms}
no cont
full info ref
stream wise cut, short, strong suction
0
500
1000
1500
2000
x/δ^*_0



70
60
50
40
30
20
10
0
Ω [%]
full info ref
stream wise cut, short, strong suction
exp control, 2 units
exp control, 1 unit
0
500
1000
1500
2000
x/δ^*_0

Figure 5: