AIAA Journal
Vol. 48, No. 8, August 2010

# Technical Notes

## Feedback Control of Boundary-Layer Bypass Transition: Comparison of Simulations with Experiments

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DOI: 10.2514/1.J050150

### Nomenclature

| | | |
|---|---|---|
| $L$ | = | integral length scale of inflow turbulence |
| $l^2$ | = | control penalty (see [6]) |
| $Re$ | = | Reynolds number |
| Tu | = | turbulence intensity |
| $u_{\mathrm{rms,max}}$ | = | wall-normal maximum of the rms value of the streamwise disturbance velocity |
| $x$ | = | distance from the leading edge |
| $\delta_0^*$ | = | displacement thickness at the inflow |
| $\Omega_{\mathrm{rms}}$ | = | disturbance attenuation due to control |

### Introduction

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. To go from computer simulations to physical experiments, it is not sufficient to reproduce a physical configuration. It is also necessary to use (and possibly model) sensors and actuators. A general review on the application of control theory to fluid dynamics is given in [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 large-eddy simulation (LES) 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, and actuator) and possible benefits.

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 freestream turbulence [7] (typically above 0.5–1% of the freestream velocity). A visualization of the process, taken from the present simulation, is shown in Fig. 1. Owing to the nonmodal 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 localized regions of chaotic swirly motion, turbulent spots. Subsequently, spots grow and merge, and a fully developed turbulent flow is observed.

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 aimed at reproducing the disturbance conditions in the experiment, as well as the control performance. A schematic of the experimental setup is shown in Fig. 2a. Freestream 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 Fig. 2b. 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 $u_{\mathrm{rms}}$ at different positions. The disturbance attenuation is quantified as

$$\Omega_{\mathrm{rms}} = 1 - \frac{u_{\mathrm{rms,max,on}}}{u_{\mathrm{rms,max,off}}} \quad (1)$$

so that $\Omega_{\mathrm{rms}}$ 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) [9] and LES. A thorough study on different LES models was performed, and the approximate-deconvolution-model–relaxation-term subgrid-scale model turned out to be particularly suited for this transitional flow [6,10]. 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 characterized 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). 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 framework, where a linear quadratic regulator (LQR) is combined with a Kalman filter [12]. The boundary-layer flow is modeled by the Orr–Sommerfeld and Squire system, governing the evolution of perturbations in parallel flows. The objective is to minimize 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 was active. The flowfield 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

Presented as Paper 2009-0612 at the 47th AIAA Aerospace Sciences Meeting, Orlando, FL, 5–8 January 2009; received 25 August 2009; revision received 4 April 2010; accepted for publication 14 April 2010. 

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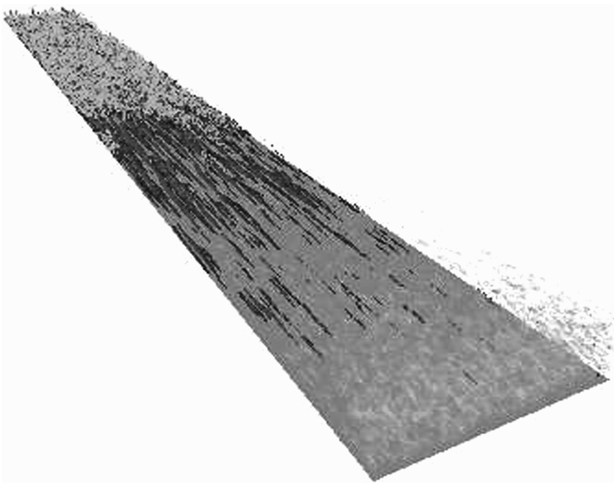
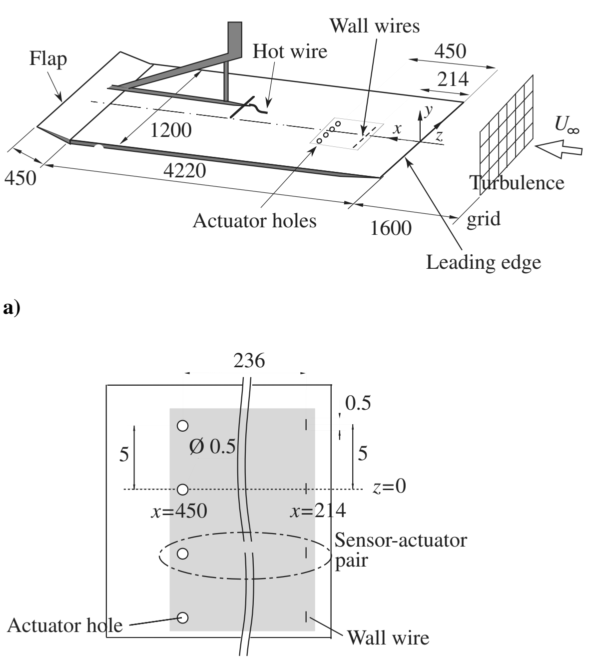


**Fig. 1 Visualization of boundary-layer transition induced by freestream turbulence. Flow is from lower right to upper left. The dark structures near the wall in the boundary layer correspond to low- and high-velocity streaks, while the structures in the freestream in the boundary layer indicate vortical structures by means of the $\lambda_2$ vortex identification criterion [13].**




a)

b)

**Fig. 2 Experimental setup used in [5]: a) overview and b) close up of a control unit. Measures are in mm.**

stochastic freestream turbulence. Control based on estimation (termed compensator) was able to delay transition but less effectively than the full-information control.

## Matching of Large-Eddy Simulation 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 $\mathrm{Tu} = 2.5\%$ (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 as follows:

1) The code we employ cannot include the leading edge; therefore, perturbations cannot penetrate the boundary layer directly furthest upstream.

2) The size of the computational domain is smaller than the wind-tunnel test section; therefore, only freestream 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 previously.

The matching is performed by varying the turbulence intensity and the integral length scale of the inlet freestream turbulence and compares the streamwise development of the wall-normal maximum of the streamwise velocity $u_{\mathrm{rms,max}}$. We tried seven different integral length scales of the turbulence $L/\delta_0^* = 2.5, 3.5, 4.5, 5.5, 6.5, 7.5$, and 8.5 and three turbulence intensities at the inlet $\mathrm{Tu} = 3$, 3.5, and 4%. The turbulence length scale $L$ is defined as 1.55 times the length scale, defined from the longitudinal two-point correlation [9].

From Fig. 3, we see that the case with $\mathrm{Tu} = 3.5\%$ and $L = 4.5\delta_0^*$ is closest to the experiment in terms of initial growth and transition locations, and this is our reference case next. 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 localized actuation 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 are shown with markers (squares and asterisks).

At this point, it is useful to recall the differences between the actuator in the experiment and in the simulations. These pertain to 1) the way the control signal is calculated and 2) the area over which control is applied. In the experiment, opposition control is adopted where the (preset) suction velocity, the threshold for detection, and the time delay between the sensor and the actuator are varied. In the LES, an optimization 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. Next, 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

**Table 1 Computational box resolution and dimensions[a]**

| $L_x \times L_y \times L_z$ | $N_x \times N_y \times N_z$ |
|---|---|
| $2250 \times 60 \times 96$, $\delta_0^*$ | $576 \times 121 \times 64$ (resolution) |

[a]The box dimensions include the fringe region and are nondimensionalized with respect to the displacement thickness $\delta_0^*$ at the inflow ($Re_{\delta_0^*} = 300$).

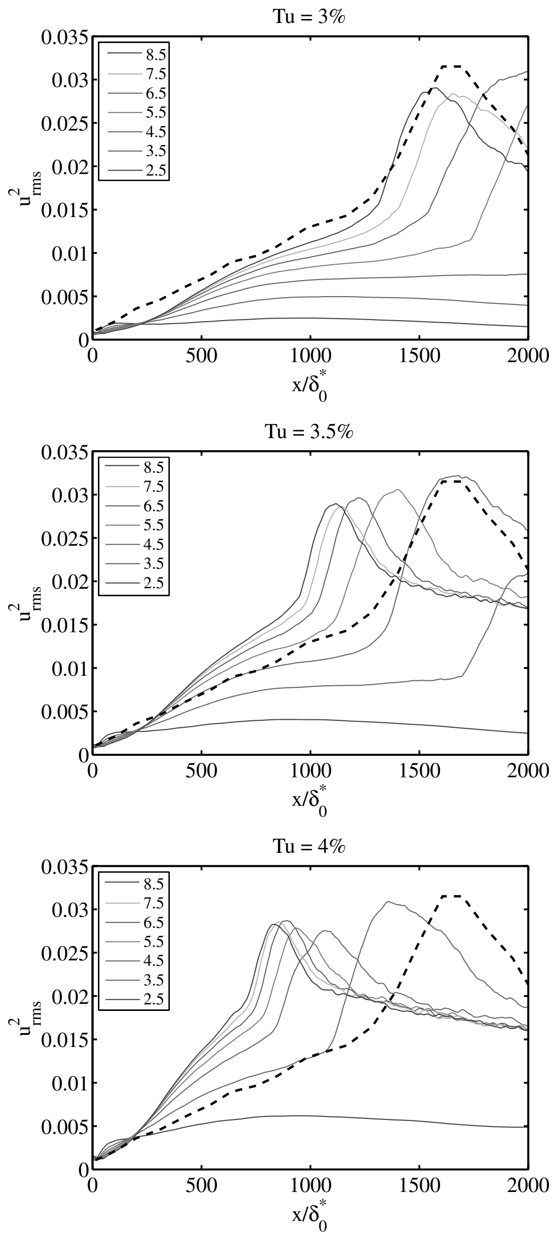



**Fig. 3 Wall-normal maximum of the streamwise velocity fluctuations $u_{rms}$. Levels of turbulence intensity from top to bottom: 3, 3.5, and 4%. Each line on the plots corresponds to a predefined integral length scale of the freestream turbulence at the inlet. The legend shows the length scale in $\delta_0^*$ units. The dashed black line indicates the experimental data.**

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: 1) apply only suction, 2) restrict the area of actuation to spanwise strips, and 3) 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 Fig. 4, we see three cases where the actuation characteristics are varied. In particular, we first keep the actuation area the same but

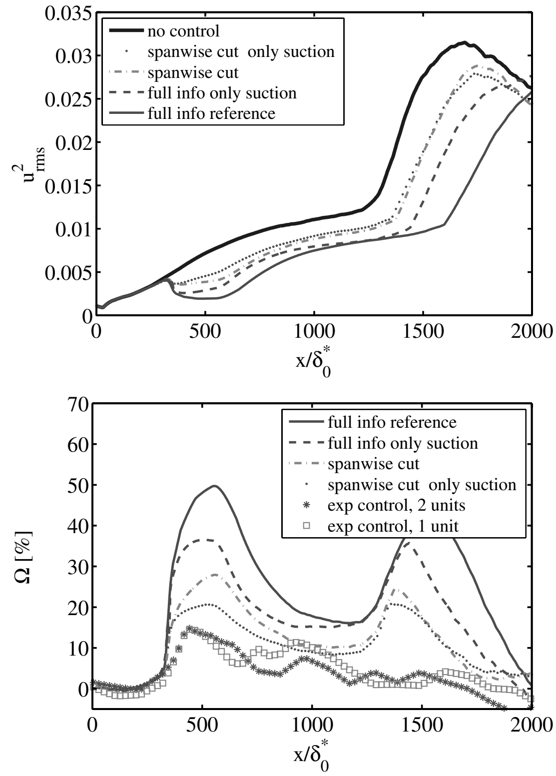



**Fig. 4 Control effect as a function of streamwise distance (curves are simulations).**

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 $5\delta_0^*$ (dashed–dotted) with a center-to-center distance of $10\delta_0^*$. Finally, we combine the two preceding cases, applying only suction and cutting

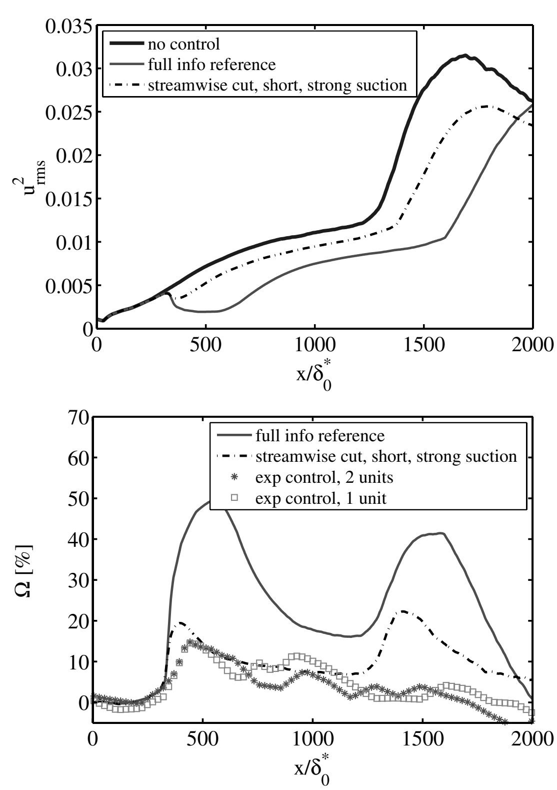



**Fig. 5 Control effect as a function of streamwise distance (solid and dashed–dotted curves are simulations).**

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 Fig. 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 [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 study [5] (suction through holes triggered by the varying wall shear stress via threshold and delay) and one numerical study [6] (LQR with and without Kalman filter estimation) 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 with 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 toward the ability of the experimental ones [by a) using only suction, b) limiting the actuation to limited spanwise positions, and c) decreasing the streamwise length of the actuation stripe].

3) Compared with 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.

## Acknowledgments

Financial support has been received from the Swedish Research Council. This work has relied on inspiration and support from D. S. Henningson and P. H. Alfredsson at the KTH Royal Institute of Technology, Department of Mechanics.

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