DNS of Active Control of Disturbances in a Blasius Boundary Layer

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Abstract. Three different control concepts to attenuate disturbances in different stages of the laminar-turbulent transition are presented. Active control via **FIR filter** is a linear concept based on the principles of wave superposition suitable for linear and weakly nonlinear disturbances. The concept of **v-control** originates from turbulence control where it was basically intended to suppress quasi-steady longitudinal disturbances. In our case the resonant behavior of nonlinear waves was strongly altered. As a third concept the **vorticity-control** is a novel approach, sensing the spanwise vorticity (shear stress) at the wall and prescribing v at the wall in phase. This strategy yields a direct attenuation of both linear and nonlinear waves as well as a change in their resonant behavior.

1 Introduction

Many concepts with the objective to actively delay the laminar-turbulent transition are currently under investigation. In contrast to rather mathematical approaches based on optimal control theory, we follow a more practical path here, which is based on the use of a FIR-filter as in the experiments of Baumann & Nitsche [1], the "v-control" as in the work on turbulence control of Hammond [6] and Choi et al [2] or the "vorticity-control", a novel approach in transition control (Fig. 1). Two questions are addressed: To what extent can a linear technique be used in the non-linear regime of transition and to what extent can the feedback of instantaneous signals from the flow field to the wall be used for transition control, i.e. transition delay. Moreover, the underlying control mechanisms are of major interest.

2 Numerical Method

All simulations were performed in a rectangular integration domain with the spatial DNS-code developed by Konzelmann, Rist and Kloker [7]. The flow is split into a steady 2D-part (Blasius base flow) and an unsteady 3D-part. The x-(streamwise) and y-(wall-normal) directions are discretized with finite differences of fourth-order accuracy and in the spanwise direction z a spectral Fourier representation is applied. Time integration is performed by the classical fourth order Runge-Kutta scheme. The utilized variables are

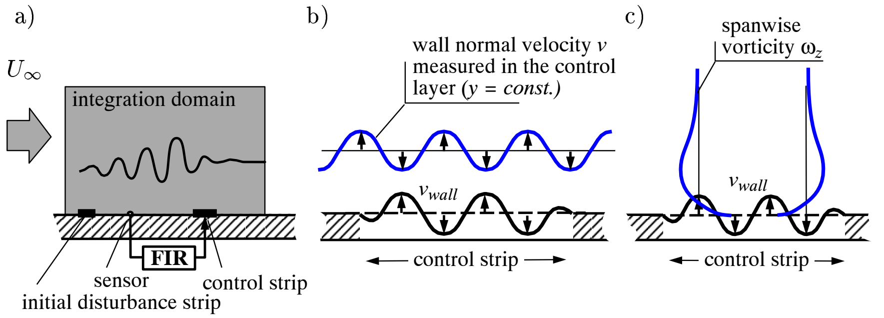


Fig. 1. Different control strategies: a): FIR filter, b): v-control, c): vorticity control

normalized with $\tilde{U}_\infty = 30\frac{m}{s}$, $\tilde{\nu} = 1.5 \cdot 10^{-5}\frac{m}{s^2}$ and $\tilde{L} = 0.05m$ ($\tilde{}$ denotes dimensional variables):

$$x = \frac{\tilde{x}}{\tilde{L}} \quad , \quad y = \frac{\tilde{x}}{\tilde{L}} \cdot \sqrt{Re} \quad , \quad z = \frac{\tilde{z}}{\tilde{L}} \quad , \quad t = \tilde{t} \cdot \frac{\tilde{U}_\infty}{\tilde{L}} \quad ,$$
$$u = \frac{\tilde{u}}{\tilde{U}_\infty} \quad , \quad v = \frac{\tilde{v}}{\tilde{U}_\infty} \cdot \sqrt{Re} \quad , \quad w = \frac{\tilde{w}}{\tilde{U}_\infty} \quad , \quad Re = \frac{\tilde{U}_\infty \tilde{L}}{\tilde{\nu}} = 10^5 \quad ,$$

where u, v and w are the components of the unsteady velocity disturbances. This leads to the dimensionless Frequency $\beta = \frac{2\pi \tilde{f} \tilde{L}}{\tilde{U}_\infty}$, where $\tilde{f}$ is the Frequency in $[Hz]$ and the dimensionless spanwise vorticity $\omega_z = \frac{\partial u}{\partial y} - \frac{1}{Re}\frac{\partial v}{\partial x}$.

3 Control Concepts and their Application

The (linear) **FIR-filter** is an on-line concept which has to be trained for each flow condition or has to be adapted continuously. Superposition of anti-phase disturbances is used to eliminate the initial perturbations. In our case, the filter is trained once using data of simulations with successful cancellation to obtain the filter coefficients for the subsequent runs avoiding time-consuming calculations. Application of the FIR-filter to linear and weakly nonlinear disturbances show a reduction in amplitude of about 1.5 to 2.5 orders of magnitude at a fixed position downstream [3].

After obtaining excellent results in the linear case, active control via FIR-filters was applied to fundamental resonance which would lead to a K-breakdown (Fig. 2). Due to the onset of fundamental resonance the phases of the interacting modes (1,0) and (1,1) (the first index gives multiples of the frequency β, the second multiples of the basic spanwise wave number γ) are synchronized, i.e. their phase speed becomes equal (Fig. 3 (a)). With application of control to the 2D mode the phase coupling is broken up and the waves evolve independently (Fig. 2 and Fig. 3 (b)). As a result, the control based on the wave superposition principle is most effective when applied at an early stage of transition.

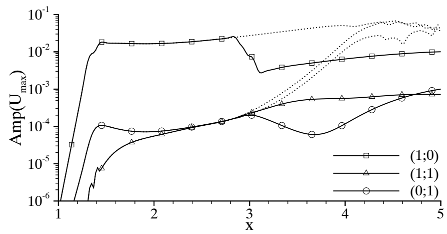


Fig. 2. Secondary instability: control of the fundamental 2D mode via FIR filter at $x = 2.96$, dotted lines: uncontrolled case. (frequency $\beta = 10$, spanwise wave number $\gamma = 20$)

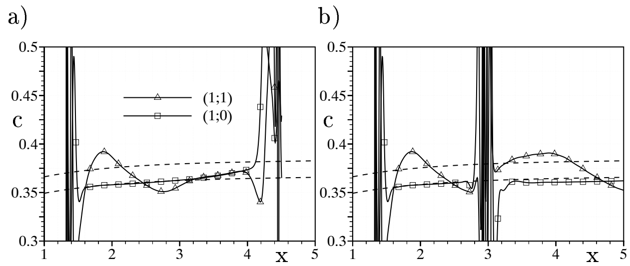
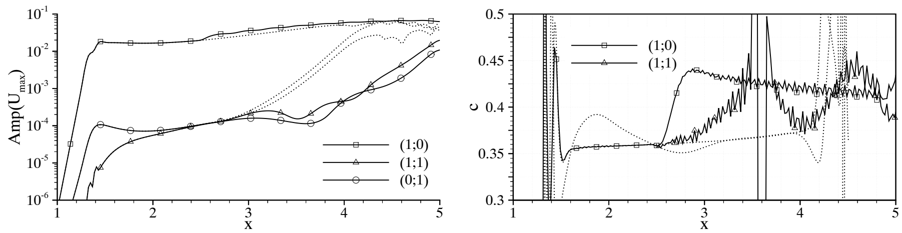


Fig. 3. Secondary instability: phase velocities **(a)** uncontrolled case, **(b)** controlled case, dashed lines: phase velocities according to the linear stability theory

Another approach, suitable for nonlinear disturbances is the **"v-control"** originally applied to turbulent flows. In this case the instantaneous wall-normal velocity at a sufficient distance from the wall ($y \approx \frac{\delta}{3}$) is prescribed with opposite sign as a boundary-condition on the wall at the next time step of the simulation.

Several simulations have been performed applying v-control to the fundamental 2D modes (Fig. 4(a)) in the K-breakdown scenario already shown in Fig. 2 (dotted lines). Despite an increased amplitude of the 2D mode (1,0) they showed a delayed onset of resonance between the fundamental 2D mode and the resonant 3D modes with the same frequency. Looking at the phase speed of the interacting modes (Fig. 4(b)) a strong acceleration of the controlled 2D mode is observed. The resonant mode (1,1) is not able to attain the same phase speed as the fundamental one. Therefore, phase coupling between the waves is impossible and fundamental resonance is delayed.

A novel approach reducing the amplitude of both linear and nonlinear disturbances and simultaneously changing the resonant behavior of the interacting modes is the **vorticity-control**. The instantaneous spanwise vorticity ω_z at the wall is prescribed in phase as v-component at the wall multiplied by an amplitude factor of 7.5 (with respect to the dimensionless quantities used here). This concept requires only informations about the shear stress at the wall which are easily avaliable in practice. Applying the vorticity-control to the fundamental resonance scenario mentioned above, a strong damping effect on the controlled mode can be observed (Fig. 5(a)). Moreover, an effect similar to that obseved applying the v-control can be found. A strong decelleration of the controlled mode (in Fig. 5(b) the fundamental 2D mode $(1,0)$) is



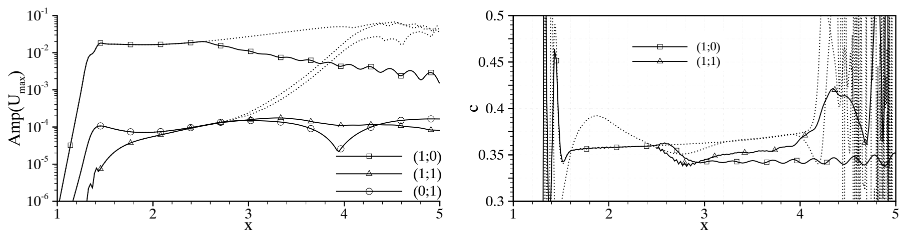
(a) u_{max} Amplitudes (b) phase velocities

Fig. 4. Secondary instability: control of the fundamental 2D mode via v-control at $x = 2.55 \ldots 5.4$, dotted lines: uncontrolled case.

initiated by application of the vorticity control. This suppresses a phase coupling between the interacting modes and reduces the secondary growth of the 3D disturbances. An explanation for the damping of the unsteady 2D modes which is not some kind of wave cancellation is obtained by the dimensionless energy balance equation (for two-dimensional, linear disturbances):

$$\frac{d}{dx}\int_0^\infty U\frac{\overline{u'^2}}{2}+\frac{\overline{v'^2}}{2Re}\,dy = \int_0^\infty \underbrace{-\overline{u'v'}\left(\frac{\partial U}{\partial y}+\frac{1}{Re}\frac{\partial V}{\partial x}\right)}_{R} dy - \nu\int_0^\infty \overline{\omega_z'^{\,2}}\,dy - \frac{1}{\rho}\frac{d}{dx}\int_0^\infty \overline{p'u'}\,dy \quad (1)$$
$$-\nu\frac{1}{Re}\frac{d}{dx}\int_0^\infty \overline{v'\omega_z'}\,dy - \int_0^\infty (\overline{u'^2}-\frac{1}{Re}\overline{v'^2})\frac{\partial U}{\partial x}\,dy + \overline{v'_{wall}p'_{wall}}$$

where capitals stand for steady quantities and overbars denote the temporal average over one period in time. A detailed discussion of the energy balance equation can be found in [4] and [5]. The term on the left hand side of (1) represents the spatial increase of the fluctuation energy at a fixed x-position i.e. the amplification or attenuation of the disturbances. The major contribution to the right hand side is supplied by the first two terms. The energy production term (first term on the right hand side) indicates whether energy is transfered from base flow to disturbance ($\int R\,dy > 0$) or vice versa ($\int R\,dy < 0$) and it dominates in combination with the dissipation term $\nu\int\overline{\omega'^2}\,dy$ the energy balance. The sign of R is determined by the sign of the Reynolds stress $-\overline{u'v'}$. This implies for wave like disturbances that the phase-difference between u' and v' is the most important property of these variables for the energy balance. Figures 6(b) and (e) show besides the phases of u' and v' the phase difference between both. In the uncontrolled case $\Delta\Theta = |\Theta_u - \Theta_v| > \frac{\pi}{2}$ for $y/\sqrt{Re} < 0.02$ (Fig. 6(e)) is observed. This leads to a Reynolds stress $-\overline{u'v'} > 0$ (Fig. 6(f)) and hence to an amplification of the disturbance. On the other hand, application of vorticity control changes the phases of u' and v' in a way that the Reynolds stress $-\overline{u'v'}$ becomes negative (Fig. 6(c)) and therefore leads to a decrease in amplitude. Although the energy balance equation mentioned above has been derived for disturbances with linear amplitude we can show, that it is valid for nonlinear 2D waves, too, as long as saturation of the amplitude is not reached.



(a) u_{max} Amplitudes (b) phase velocities

Fig. 5. Secondary instability: control of the fundamental 2D mode via vorticity-control at $x = 2.55 \ldots 5.4$, dotted lines: uncontrolled case.

4 Summary

Three different unsteady control approaches to control disturbances were applied to both linear and nonlinear disturbances. Best results in the nonlinear case were obtained by using vorticity-control, a concept which follows a very simple yet effective control law. This approach is very robust in the sense that it is allmost independent of the amplitude of the controlled wave. In the cases we investigated a superposition of some kind of "anti-phase disturbance" could not be observed. Rather the changed phases of u' and v' are the reason for the weakening of the controlled modes.

Acknowledgements

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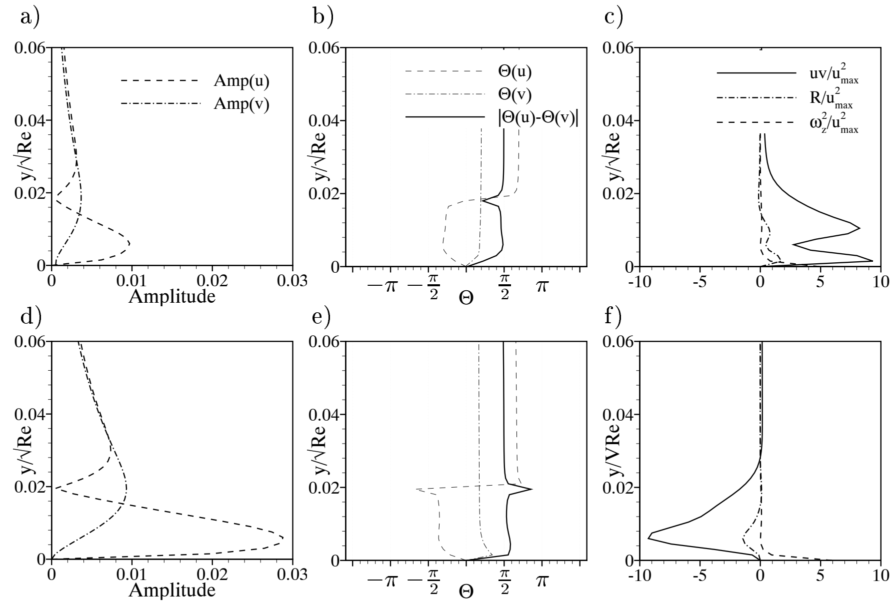

Fig. 6. Energy relevant quantities vs. y. **(a)**...**(c)** controlled case, **(d)**...**(f)** uncontrolled case. **(a), (d)** velocity profiles in wallnormal and streamwise direction; **(b), (e)** corresponding phases; **(c), (f)** energy properties

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