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Active Control of Laminar-Turbulent Transition Using Instantaneous Wall Vorticity

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Many approaches with the objective to actively delay the laminar-turbulent transition are currently under investigation. Using the tools of Direct Numerical Simulation (DNS) and Linear Stability Theory (LST) we are studying active concepts to control even nonlinear stages of transition. In contrast to approaches based on optimal control theory which yield optimal results for a specific case, we follow a path which can be more or less directly implemented into application using the direct feedback of instantaneous signals from the flow field. Depending on the amplitude of the involved disturbances, an appropriate control method has to be chosen. In the case of weak disturbances in the regime where the Linear Stability Theory is valid, for instance, linear concepts using the wave superposition principle can be used [1]. However, in later stages of the transition process where strong nonlinearity takes place, the feedback of instantaneous signals seems to be the better choice [2]. Our approach, better suited for nonlinear disturbances is the "ω_z*-control*". In this case the spanwise vorticity at the wall ($\omega_{z,w}$) is multiplied by a gain A and prescribed as a wall-normal velocity (v-) boundary-condition on the wall (i.e. blowing/suction or wall displacement) with a certain phase shift Θ (Fig. 1).

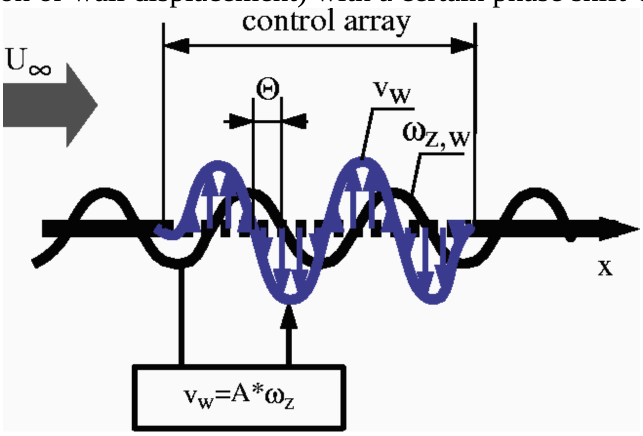

Figure 1: Control principle of "ω_z*–control*"

The concept has been implemented in linear stability theory (LST) and Direct Numerical Simulation (DNS) [3], and an analysis of the disturbance-energy equation has yielded additional insight [4]. In the first case the boundary conditions at the wall for the Orr-Sommerfeld equation (and the Squire equation) had to be changed (index '*w*' for wall properties) to

$$v_w = A \cdot \omega_{z,w}$$

$$\text{with} \quad A = |A| e^{i\Theta},$$

where $|A|$ is the amplitude factor and Θ is the phase difference between v_w and $\omega_{z,w}$. Due to the ability to express ω_z in terms of u and v the eigenvalue problem remains homogeneous and the method of solution is not altered. The resulting eigenvalues and eigenfunctions show very good agreement to the results obtained using DNS (Fig. 2).

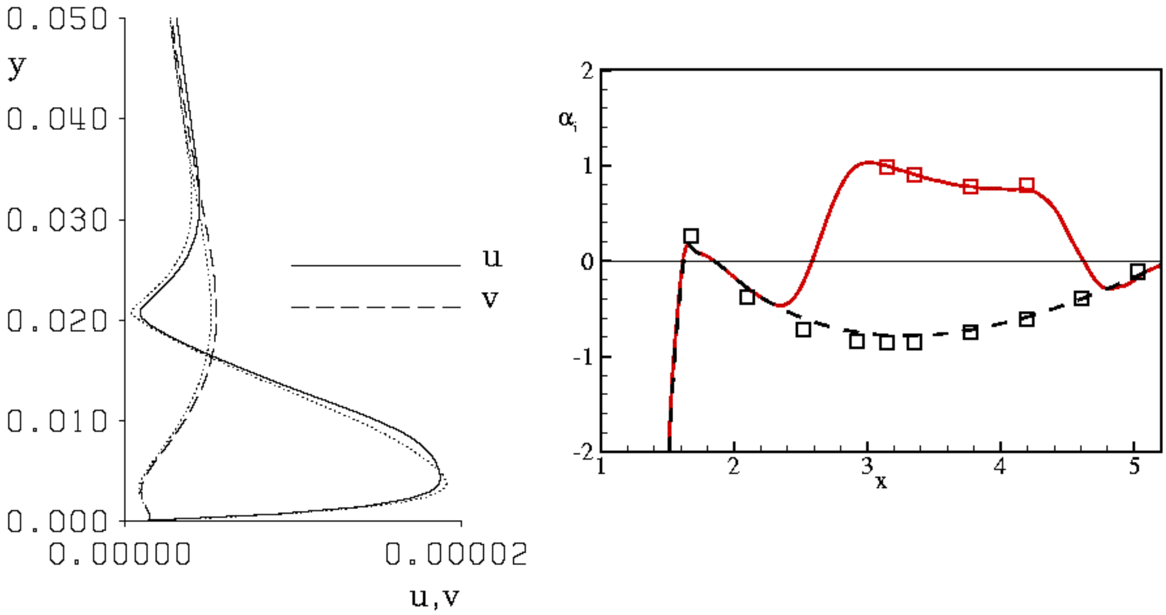

Figure 2: Comparison of eigenfunctions (left) and amplification rates (right) of LST (dotted lines, resp. symbols) with DNS. Linear case with $|A| = 0.0001$ and $\Theta = \pi/2$ at $x = 3.46$. The red curve is for ω_z–*control* between $x \approx 2.5$ and $x \approx 4.5$. All quantities are normalized with $U_\infty = 30$ *m/s* and $L = 0.05$ *m*.

Fig. 3 indicates the influence of active control on the unstable region of the *Blasius* boundary layer flow. Small amplitudes already are sufficient for a strong damping effect. If the amplitude factor $|A|$ is larger than approximately $5 \cdot 10^{-5}$ for a phase angle of $\Theta = 0$, the boundary layer is stable for all considered frequencies and downstream positions. Detailed investigations of the dependence of the eigenvalues on the phase angle (Fig. 4) show that best attenuation can be reached adjusting the phase shift Θ to approximately 90^o.

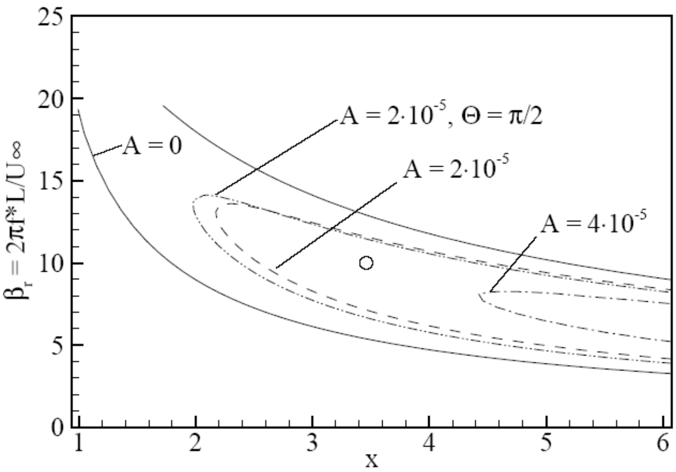

Figure 3: Curves of zero amplification for the *Blasius* boundary layer flow with different gains *A* and phase angles $\Theta = 0$, except where marked. The small circle marks the position in the x/β-diagram (β_r = dimensionless frequency) of the calculations shown in Fig. 4.

To investigate the behaviour of *nonlinear* waves in the *Blasius* boundary layer and to verify the LST results in the linear case, a number of DNS calculations have been performed in a rectangular integration domain with the spatial DNS-code [3] already used for other investigations of laminar-turbulent transition. 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 discretised with finite differences of fourth-order accuracy and in the spanwise direction z a spectral Fourier representation is applied. Time integration is performed by a classical fourth-order Runge-Kutta scheme. The ω_z*-control* is implemented as a time delay in the numerical simulations.

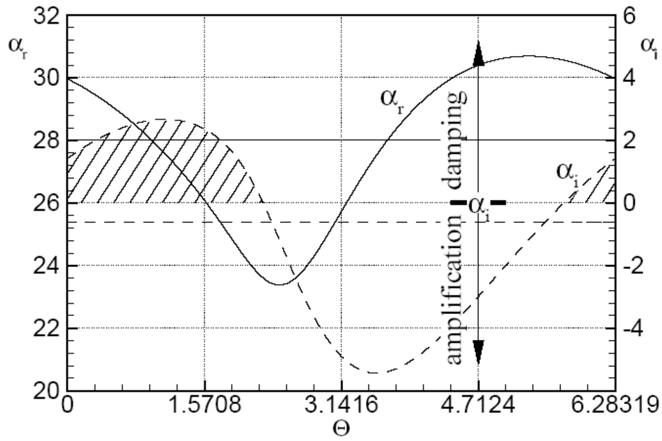

Figure 4: Variation of the eigenvalues with respect to the phase angle Θ between $\omega_{z,w}$ and v_w for $|A| = 10^{-4}$ at the position marked in Fig. 3. In the hatched areas Tollmien-Schlichting waves are damped. The horizontal lines (solid and dashed) show the uncontrolled values of α_r and α_i. Non-dimensional frequency is $\beta = 10$.

As a test case for the effect of the ω_z*-control* on disturbances with large amplitude, a typical *K-breakdown* scenario (Fig. 5) is investigated where a fundamental 2D mode (1,0) with large amplitude and a steady disturbance (0,1) (the first index denotes multiples of the disturbance frequency β, the second multiples of the basic spanwise wave number $\gamma = 20$) are excited initially. Because of nonlinear interactions the 3D-mode (1,1) is generated and falls in resonance with the fundamental 2D-mode. The other 3D modes arise due to nonlinear combinations. When the strongly amplified 3D-waves have reached the amplitude level of the fundamental mode, saturation sets in and transition to turbulence takes place downstream of $x = 4.3$ (dotted lines).

Applying ω_z*-control* to the K-breakdown scenario in a very late, nonlinear stage (Fig. 5) two main control effects can be distinguished: first, the direct damping of nonlinear disturbances and secondly, the disruption of the resonant behaviour. The first effect is comparable to a linear ω_z*-control* case where it is possible to directly damp TS-disturbances, the second effect results from the altered wave speed of the resonant modes which are 'detuned' under the influence of control. Unsteady modes are damped very efficiently but steady disturbances ((0,1), (0,2)) are hardly influenced by the control. From Fig. 6 it can be seen that after approximately ten disturbance cycles of control the unsteady parts of the disturbances have already vanished, whereas the remaining streak-like structures are convected downstream very slowly. In the uncontrolled case the formation of Λ-vortices is followed by a rapid collapse which is absent in the controlled case. The remaining structures resemble longitudinal vortices or streaks according to the fact that the ω_z–*control* is only affecting unsteady disturbances deviating from the undisturbed base flow vorticity. Former investigations using the wave superposition principle at a comparable stage of transition [3] showed a negligible damping effect due to nonlinear interactions between the occurring modes which could not be affected by a linear method.

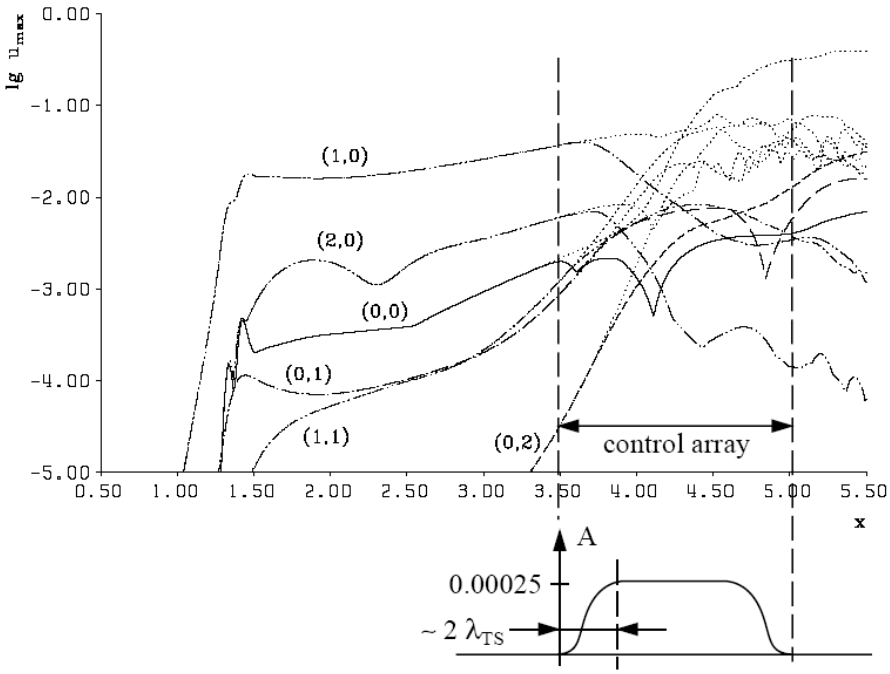

Figure 5: K-breakdown, u_{max}-amplitudes vs. x. Modes (h,0) and (h,1) controlled ($|A| = 2.5 \cdot 10^{-4}$, $\Theta \approx \pi/2$). Dotted lines: uncontrolled case. Only the most important modes are shown here. Small picture: Spatial distribution of the control gain $|A|$ with a sine-like ramp function on both sides.

References

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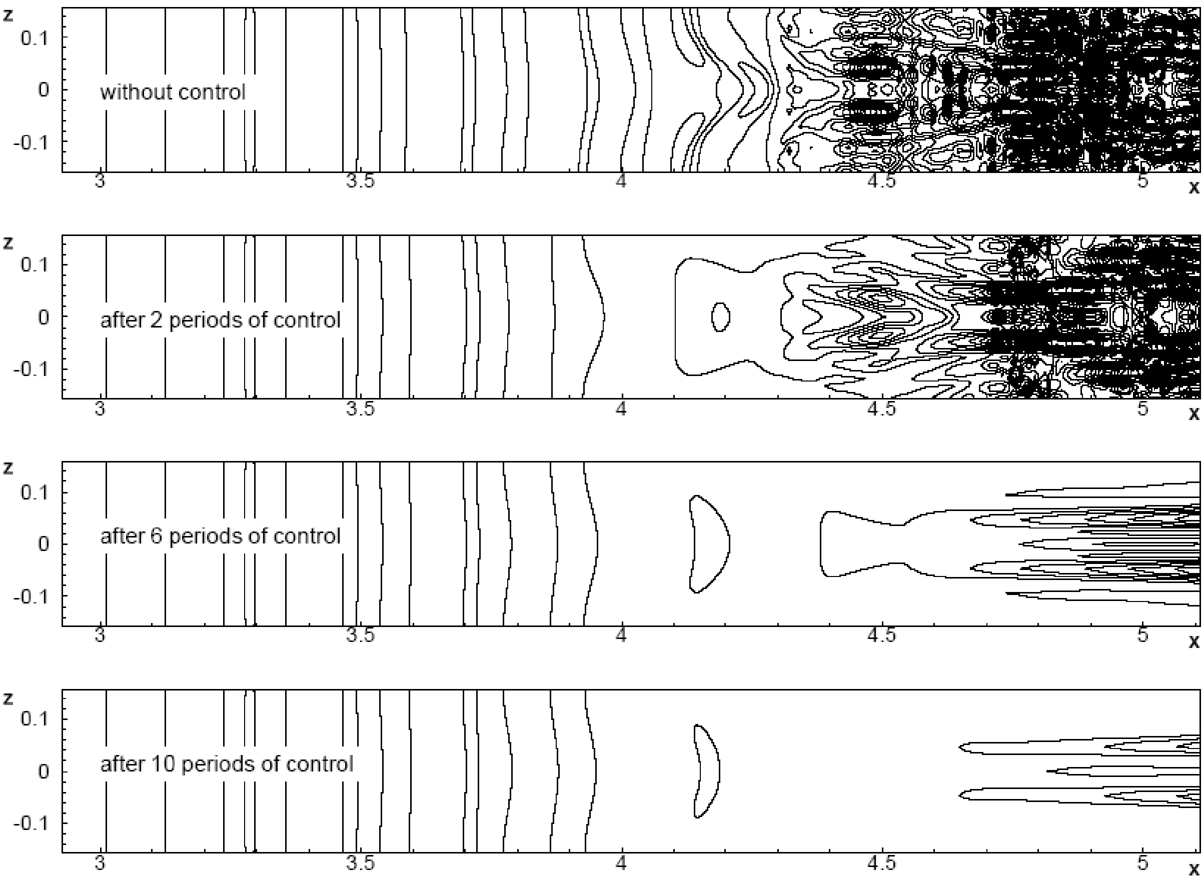

Figure 6: Contours of spanwise vorticity at the wall for the K-breakdown scenario with and without ω_z-*control* at different time steps.