Active Control of Laminar Separation Bubbles

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Summary

Control of a transitional laminar separation bubble using steady and unsteady 2D and 3D Tollmien-Schlichting (TS) like boundary-layer disturbances is investigated by means of direct numerical simulations. The specific influence of different disturbance modes which allow an effective reduction of the reverse-flow region is illustrated. It is shown that unsteady 2D or 3D control is more efficient than steady 3d control.

Introduction

Adverse pressure gradient (APG) boundary layers at low to medium Reynolds numbers are strongly susceptible to laminar separation. Due to the deceleration of the flow the laminar boundary layer separates from the surface, laminar-turbulent transition occurs at a certain distance from the separation line and the now turbulent flow reattaches subsequently. The area of reverse flow and therefore negative skin friction between separation and reattachment is called a “laminar separation bubble” (LSB) or alternatively a “transitional separation bubble”, because of laminar-turbulent transition. Despite the effect of lowering the skin friction within the bubble, the LSB has an undesired influence on the global pressure distribution of the airfoil and causes an undesired drag rise.

Numerical Method and Reference Case

To investigate laminar separation bubbles spatial direct numerical simulations (DNS) of a flat plate boundary layer with a 2D base flow and an applied APG at the free-stream boundary are performed. The DNS code has been used in different research programs for the investigation of transitional boundary layers without and with laminar separation The complete Navier-Stokes equations for incompressible flow are solved in a vorticity-velocity formulation based on three vorticity-transport equations and three Poisson equations (for the three vorticity and velocity components, respectively). Non-dimensionalisation is done with respect to (w.r.t.) the free-stream velocity $U_\infty = 30\ m/s$, a characteristic length $L = 0.05\ m$ and the kinematic viscosity $\upsilon = 15 \cdot 10^{-6}\ m^2/s$. The equations are discretised using fourth-order-accurate finite differences in streamwise and wall-normal directions and a spectral representation in spanwise direction. A fourth-order-accurate Runge-Kutta scheme is used for integration in time.

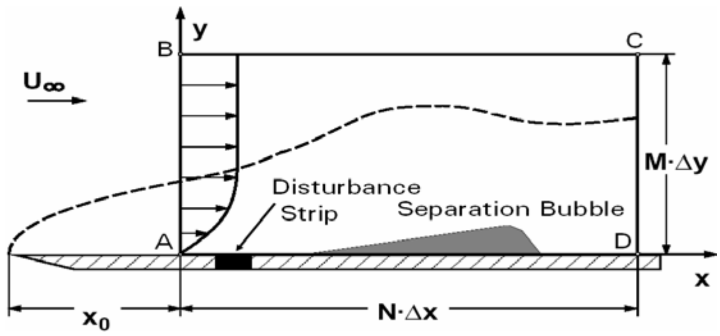

Figure 1: Integration domain for DNS of LSB control

The integration domain is sketched in Figure 1. At the inflow boundary (A-B) a Blasius boundary layer solution with $Re_{\delta^*} = 1722$ is prescribed and the potential flow at the free-stream boundary (B-C) is decelerated by *10 %* of U_∞ such that laminar separation takes place. The displacement effects of the LSB on the potential flow are captured by a viscous-inviscid boundary layer interaction model [5] at every time step of the calculation. On the surface of the plate the no-slip condition is applied except for a disturbance strip upstream of the LSB where controlled 2D and 3D boundary layer disturbances can be introduced into the flow by suction and blowing. However, the present LSB is so unstable that the small numerical disturbance background suffices to produce an unsteady flow which is characterized by unsteady vortex shedding in the rear part of the LSB (cf. [2]).

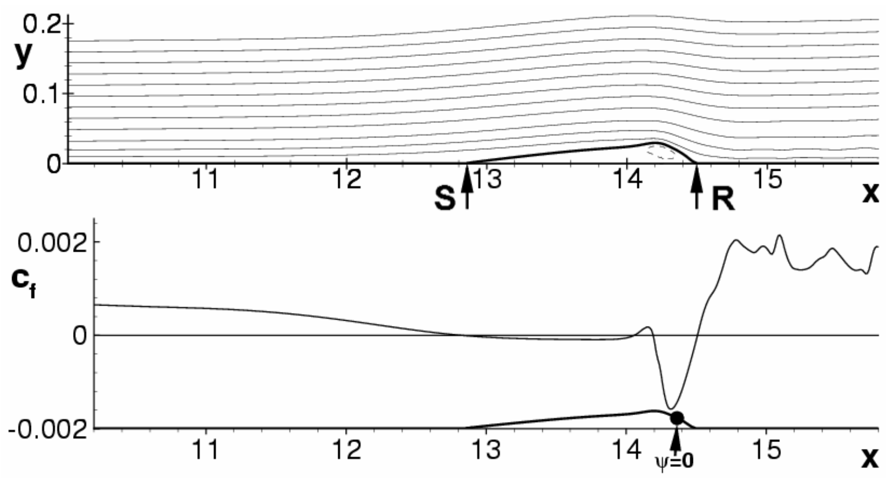

Figure 2: Illustration of time-averaged streamlines and wall-friction coefficient.

The resulting time-averaged flow with LSB is illustrated in Figure 2 by means of streamlines and wall-shear stress. Laminar separation and (temporal mean) re-attachment are marked by the letters ‘S’ and ‘R’, respectively. The separation streamline $\Psi = 0$ is shown as a thick line to exemplify the shape of the LSB. The oscillations of the skin friction behind ‘R’ are due to non-periodicity and an insufficiently long time series for averaging of the instantaneous data. They have no influence on the following investigations.

The next step is to control the flow using periodic suction and blowing at the wall. Primary parameters for the specification of disturbances are the maximum amplitude of the wall-normal velocity component v', the disturbance frequency β and whether the disturbance is two- or three-dimensional. This latter case is identified by multiples of the fundamental spanwise wave number γ of the Fourier method used in z direction. After a Fourier analysis of the unsteady flow w.r.t. time one obtains the so-called frequency-spanwise-wavenumber spectrum, whose modes are indicated by two indices (h/k), where h, and k indicate multiples of β and γ, respectively, such that $k = 0$ indicates two-dimensional disturbances and $h = 0$ represents steady wave components.

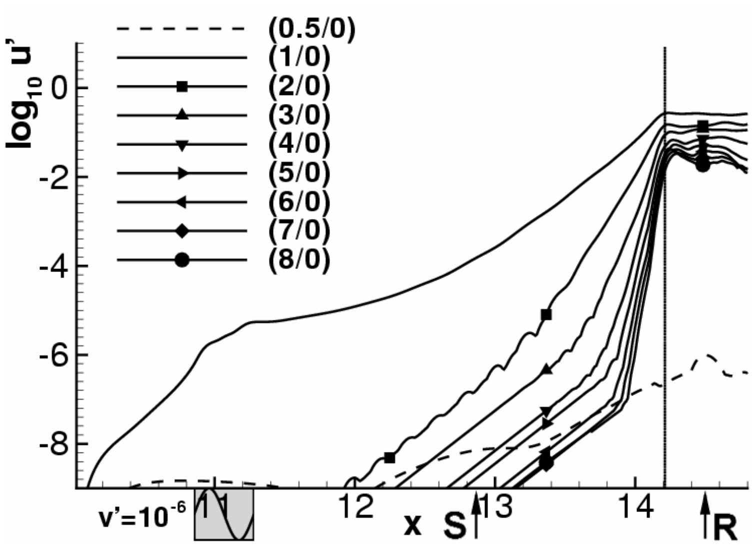

Figure 3: Disturbance amplification of modes in the frequency-spanwise-wavenumber spectrum

The spatial evolution of two-dimensional disturbances from a 2D disturbance strip placed at $x \approx 11$ are shown in Figure 3. The fundamental disturbance frequency corresponds to $\beta = 2\pi fL/U_\infty = 5$, where f is the frequency in Hertz. Disturbance growth due to hydrodynamic instability starts already far upstream of laminar separation (S). Many higher harmonic wave components develop with increasing amplitude until non-linear saturation (indicated by a vertical line). This non-linear saturation corresponds to formation of large-amplitude vortices in the separated shear layer which are then convected downstream at practically constant amplitude. The enhanced wall-normal momentum transfer forces the shear layer to re-attach at (R) in the temporal mean. The small subharmonic *(0.5,0)* indicates that a high degree of periodicity has been obtained.

Simulation of LSB Control

The present control scheme relies on a careful and efficient adjustment of the laminar-turbulent transition location in the LSB. Starting with 2D investigations using DNS and linear stability theory (LST) [2], [8] the scope of the present work also includes the effects of steady and unsteady 3D disturbances [1], [3].

The effect of increasing the upstream suction and blowing amplitude for 2D forcing is illustrated in Figure 4 by means of the separation streamlines for six different cases. For the largest disturbance amplitude $v' = 2 \cdot 10^{-4}$ the LSB has just disappeared. These results illustrate that the LSB not only shrinks by an earlier re-attachment because of earlier laminar-turbulent transition as the forcing amplitude is increased, but that laminar separation occurs also later then. We attribute this latter effect to less displacement of the boundary layer for shallower bubbles [7].

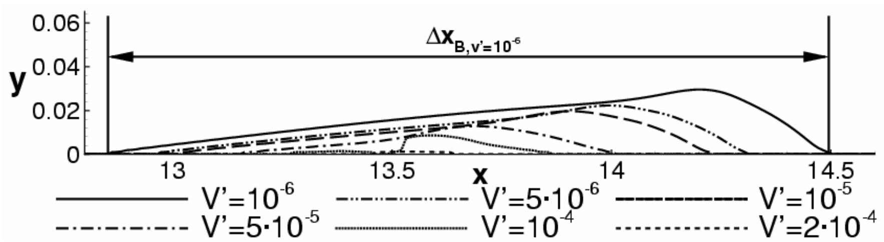

Figure 4: Separation streamlines for different wall-forcing amplitudes

Comparing the case with the smallest to the one with largest forcing amplitude in Figure 5 one observes a considerable reduction in displacement thickness δ_1 and shape factor H_{12} as the bubble disappears. Since the momentum thickness δ_2 is also reduced w.r.t. the reference case, an according drag reduction is also observed. Thus, the aim of the present control scheme, to contribute to drag reduction, can be fully achieved by using 2D disturbances.

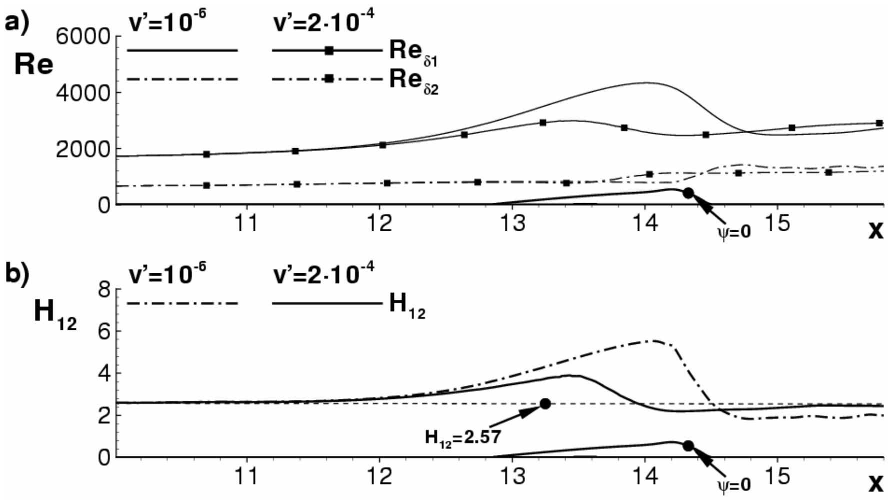

Figure 5: Comparison of Reynolds numbers based on displacement thickness (δ_1) and momentum thickness (δ_2) as well as the shape factor $H_{12} = \delta_1 / \delta_2$ for the case with smallest and with largest forcing amplitude.

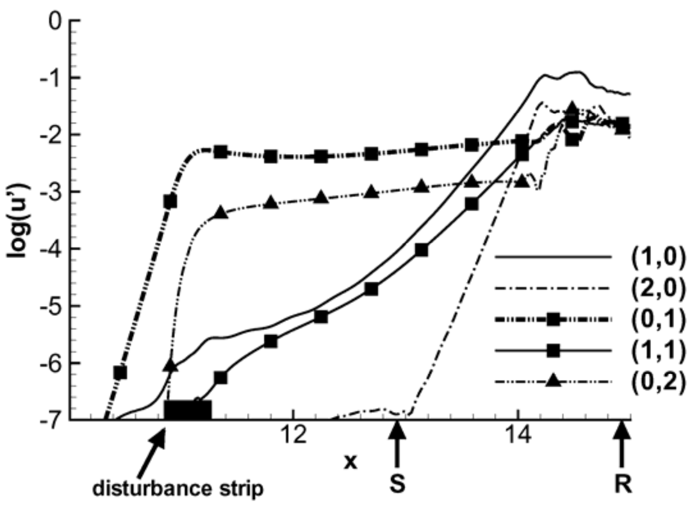

Figure 6: Disturbance amplification of selected modes for the case with steady 3D forcing

Now we turn our attention towards a case forced by a steady 3D disturbance mode (0,1) (bold dash-dot-dotted line with squares) excited at the disturbance strip with a wall-normal amplitude $v'_{(0,1)} = 10^{-3}$, see Figure 6. It turns out that the disturbance amplitude of mode (*0, 1*) is weakly damped at first and then weakly amplified far into the bubble. Only at $x \approx 14.2$ it grows close to the point of non-linear saturation which marks transition. A higher spanwise harmonic mode (*0, 2*) (dash-dot-dotted line with deltas) is generated by non-linear interaction of the mode (*0, 1*) with itself. At the disturbance strip an additional 2D mode (*1, 0*) (solid line) of fundamental frequency has been excited to mimic background disturbances with an initial amplitude $v'_{(1,0)} = 10^{-6}$, three orders of magnitude below the amplitude of the 3D mode (*0, 1*). This TS mode becomes strongly amplified by base-flow instability and exceeds the amplitude of the 3D mode (*0, 1*) at $x = 13.8$. It supersedes the steady mode (*0, 1*) as the most dominant disturbance. An oblique fundamental mode (*1, 1*) is generated by nonlinear interaction of the (*1, 0*) and (*0, 1*) modes continuously and finally reaches the amplitude of the 3D steady mode. The whole scenario is dominated by unsteady 2D effects and three dimensionality plays only a minor role. Figure 7 shows the 3D modulation of the separation stream surface Ψ_0 with the spanwise wavelength of mode (*0, 1*), marked by $\lambda_{z,(0,1)}$. The separation stream surface Ψ_0 has been defined as the value of the *y*-coordinate where the stream function $\Psi = \Psi(x, y, z)$ becomes zero.

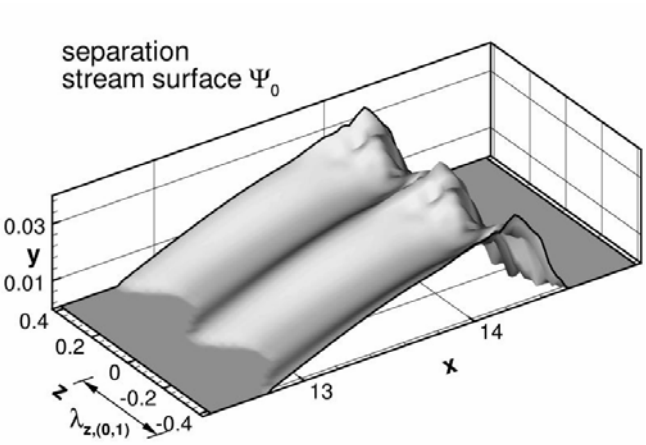

Figure 7: Time averaged separation stream surface for the case with steady 3D forcing

In a second scenario an oblique 10^o unsteady mode (*1, 1*) only (bold solid line with squares in Figure 8) is introduced into the same base flow as before. The initial disturbance amplitude of mode (*1, 1*) has been set to $v'_{(1,1)} = 10^{-5}$ at the wall. Again, an unsteady 2D background disturbance (*1, 0*) (solid line) is also present with the same initial amplitude $v'_{(1, 0)} = 10^{-6}$, as before. For verification purposes the development of the 2D mode (*1, 0*) is compared to linear stability theory. Due to its very low amplitude even inside the LSB the mode shows very good agreement with the theory up to saturation. In contrast to the first case the wall-forced unsteady TS mode (*1, 1*) is strongly amplified by boundary layer instability and continues to be the most dominant mode. Although equally amplified, the 2D mode ($1, 0$) stays below the oblique one due to its lower initial amplitude. Because of the strong amplification of mode ($1, 1$) non-linear stages of the disturbance development ($\approx 1\% \ U_\infty$) are reached at $x = 14.0$, i.e. somewhat further upstream than in the steady 3D case. The point of laminar-turbulent transition and thus the reattachment is shifted upstream likewise. In this case the separation stream surface Ψ_0 (not shown) has no spanwise undulations. Compared to the previous one in Figure 7 the LSB is now reduced in length and height to about *72 % – 76 %* of the undisturbed bubble, despite the fact that the initial disturbance amplitude of the ($0, 1$)–mode in the steady 3D case was hundred times larger than the amplitude of the ($1, 1$)–mode in the unsteady case. This is due to the feature of hydrodynamic instability that unsteady waves with small angles of obliqueness are nearly as amplified as 2D waves [8]. This clearly shows the superiority of unsteady control compared to steady control. Additional simulations [1] showed that the bubble vanishes totally at an initial disturbance level of $v'_{(1,1)} = 10^{-3}$.

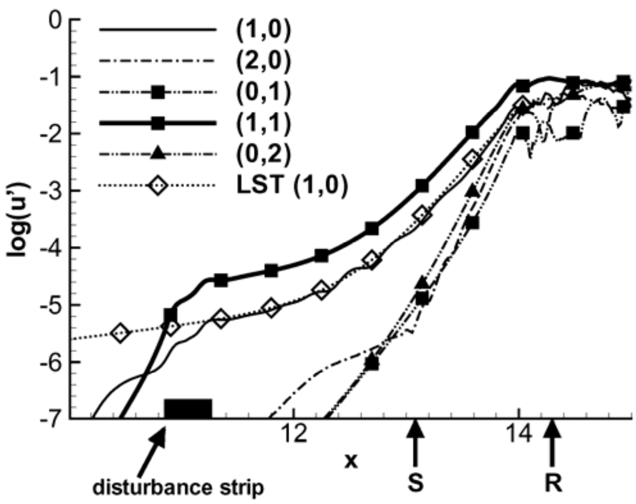

Figure 8: Disturbance amplification of selected modes for the case with unsteady 3D forcing

Conclusions and Outlook

Laminar separation bubbles have been investigated by means of direct numerical simulations in an adverse pressure gradient flow over a flat plate. Different steady and unsteady boundary layer disturbances were introduced within a disturbance strip upstream of the separation and their effects on the separation bubble have been studied. 2D or weakly 3D unsteady disturbances have a stronger impact on the size of the bubble than steady disturbances because they make use of hydrodynamic base-flow instability. An initial amplitude for an unsteady 2D or

3D disturbance two to three orders of magnitude lower than a steady disturbance is sufficient to attain the same or even larger effect on the LSB. As already shown in [3], the necessary unsteady disturbance amplitude for an efficient LSB control can be obtained by a signal feedback mechanism, where instantaneous amplitude signals of the skin-friction downstream of the LSB are used as an unsteady input to the disturbance strip (actuator). Extended by an automatic adjustment of the amplitude gain to the currently detected size of the LSB, a fully automatic system appears feasible that does not need any interaction by the pilot or the flight management system. In order to arrive at this end, an automatic sensor array is needed to detect the extent of the LSB. An according suggestion based on instantaneous wall shear-stress measurements is also made in [3].

Acknowledgments

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