Secondary Disturbance Amplification and Transition in Laminar Separation Bubbles

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Abstract. In laminar separation bubbles a new mechanism of secondary instability is presented which exists for large boundary layer Reynolds numbers at separation. If a 2D wave is forced, temporal secondary amplification of 3D modes occurs. It is based on instabilities of instantaneously appearing high-shear layers with respect to 3D perturbations left over from the previous TS-period. After the 3D modes gain large amplitudes transition sets on. This phase is again characterized by the entrainment of 3D disturbances by the 2D shear layer in the re-attachment zone. The 3D disturbances pierce the detached shear layer from underneath and destroy it very rapidly, thus leaving spanwise rolls of turbulent flow.

1 Introduction, Numerical Method

In a transitional laminar separation bubble (LSB) separation is followed by laminar-turbulent transition which forces the flow to re-attach. Results of stability theory and many experimental observations show a non negligible bias towards two-dimensional instability. Since turbulence is inherently three-dimensional (3D), there must be mechanisms which produce 3D disturbances in a LSB. Secondary instability, i.e. amplification of small-amplitude 3D disturbances by large-amplitude Tollmien-Schlichting (TS) waves is one such possible mechanism. However, our earlier investigations in [6,8,9] have shown that such a mechanism is difficult to identify in a LSB because amplification rates caused by linear (primary) Orr–Sommerfeld-type instability are nearly as large as those from secondary instability. In addition, it turned out that a large-amplitude 2D TS-wave at re-attachment and in the wake of the LSB reduces the amplification of secondary disturbances. Therefore, Rist [6] proposed to consider the non-linear interaction of weakly-oblique waves (large spanwise wave length) which are nearly as unstable as perfectly 2D waves and which lead to small-scale 3D disturbances by the so-called "Oblique Breakdown" mechanism.

A 4th-order accurate finite-difference method with explicit time-stepping (Runge-Kutta $\mathcal{O}4$) which was originally developed by Rist, Konzelmann & Fasel [7] and improved by Kloker [2] is applied to solve the complete incompressible Navier-Stokes equations in vorticity-transport formulation in a rectangular integration domain (Fig. 1a). The spanwise direction is discretized with a spectral ansatz implying periodicity. At the free-stream boundary a decelerated velocity distribution is prescribed (Fig. 1b, solid line) which approximates the experiment when separation is suppressed by a turbulator (triangles). An improved boundary-layer interaction-model is used to capture displacement effects by the separation bubble [4]. Thus, compared to the prescribed velocity a modified velocity distribution develops during the DNS, as in the experiment with separation bubble (squares).

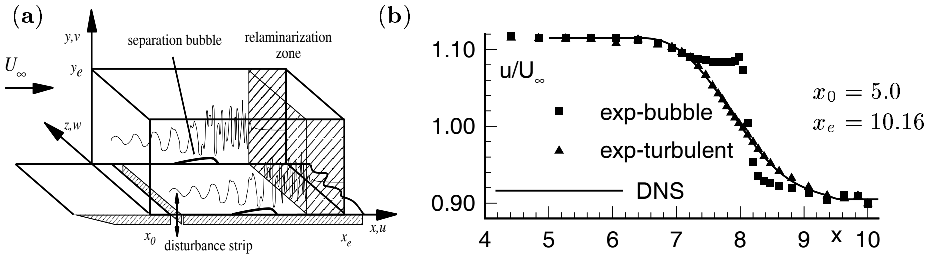

Fig. 1. Integration domain (**a**) and edge-velocity distribution (**b**) in the experiment (symbols) and in DNS

In the present computations which have been performed for the boundary layer on a research airfoil *XIS40MOD* at $Re_c = 1.2 \times 10^6$ (at separation: $Re_{\delta_1} \approx 2500$, where δ_1 is the displacement thickness), a new mechanism of secondary disturbance amplification has been found (Maucher *et al.* [3]). As will be shown, the mechanism has two distinct characteristics. First, there is a temporal amplification of definite initial disturbances in the presence of a large-amplitude TS wave near re-attachment which is described in Sect. 2, and second, there is a periodic entrainment of 3D disturbances by the roll-up of the 2D free shear layer at re-attachment, which causes this shear layer to break down very rapidly, as described in Sect. 3.

2 Transient Phase, Secondary Instabilities

A 2D Tollmien-Schlichting (TS) wave is forced by periodic wall-normal suction and blowing in a disturbance strip at the wall upstream of the LSB leading to an initial amplitude of $u_{TS} \approx 10^{-5}$. Downstream, the amplitude grows rapidly in the separated region of the boundary layer and finally saturates at almost 30% U_∞ in the re-attachment region. The large-amplitude TS-wave produces spanwise rolls of vorticity and a sequence of instantaneous re-attachment and separation points ($\omega_z = 0$) which travel downstream (cf. Fig. 2). Perhaps the most important point is that the re-attachment point of the separation bubble appearing at the downstream end of the newly forming "vortex roll" oscillates with the frequency of the TS-wave between $x \approx 7.8$ and 8. Thus, the flow field in the re-attachment zone somehow resembles the stagnation flow of an oscillating cylinder [5].

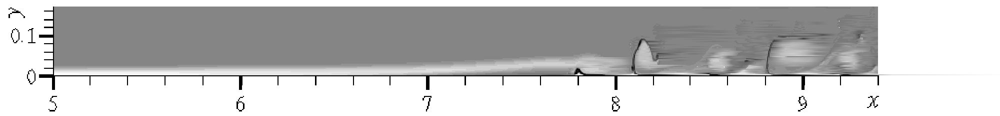

Fig. 2. Instantaneous 2D vorticity

To investigate the instability of the present flow with respect to 3D disturbances, 3D modes with fixed spanwise wavenumber $\gamma = 2\pi/\lambda_z$ are superimposed on the 2D TS-wave by short pulse-like 3D excitation in the LSB with extremely low amplitude ($u'_{max} \approx 10^{-15}$). Similar to the mechanisms of secondary instability according to the theory of Herbert [1], 3D amplification with subharmonic and fundamental frequency with respect to the forced 2D wave is observed for different spanwise wave numbers (Fig. 3). The amplification rates have been validated in computations using different discretizations (240 instead of 160 grid points per TS wave length, circles and diamonds, resp.). Only for large $\gamma > 300$ differences appear. However, they are moderate even for $\gamma > 400$. (For comparison: the streamwise wave number of the TS-wave is $\alpha \approx 20$.)

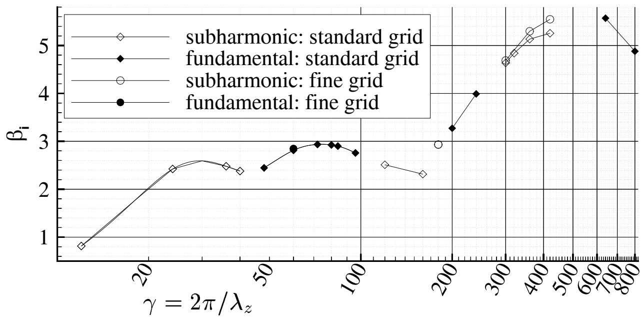

Fig. 3. Secondary temporal amplification rates β_i vs. spanwise wave number γ from computations using two different grids

Comparisons with linear stability theory confirmed that there is no primary 2D nor 3D absolute instability which could explain the large 3D temporal amplification rates observed here. Clearly, the 3D instability must be connected with the presence of the 2D periodic forcing as in the investigations of Menter & Wedemeyer [5] or Herbert [1]. However, closer examination of the flow field in the re-attachment zone shows that a phase with strong reverse flow alternates with a phase of downstream flow during each TS-period. It turned out, that the phase with reverse flow is decisive for the secondary temporal amplification.

The instantaneous vorticity field shows the roll-up of the 2D free shear layer in the re-attachment region (Fig. 4 (a), emphasized by contours of high vorticity) generating small-scale high-shear layers (see boxes). These small-scale shear layers are unstable with respect to 3D perturbations and 3D u maxima occur at their very positions (boxes in Fig. 4(b)). When the 2D velocity becomes positive the 3D perturbations are convected downstream. At the begin of the roll-up of the shear layer in the next TS-period, however, 3D disturbances are partially captured and again entrained into the separated region thus offering the basis for a continuous temporal amplification of 3D modes. Finally, the amplitudes of the secondary 3D modes saturate and an equilibrium state between the forced 2D wave and self-sustaining 3D modes ends the transient phase.

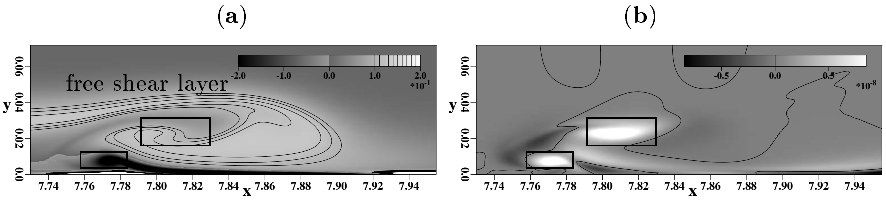

Fig. 4. Comparison of instantaneous 2D vorticity (**a**) with respective instantaneous 3D u-distribution (**b**)

3 Amplitude-Saturation Phase

For better comparison with the wind-tunnel experiments (airfoil), a smaller TS initial amplitude of $u_{TS,0} = 10^{-6}$ has been forced upstream of separation for the results presented in this section. A comparison of the amplitudes of several modes in the frequency spanwise wave number spectrum (Fig. 5) indicates a close agreement of the downstream amplification of the TS-wave (mode (1,0), fat solid line) with locally parallel linear stability theory (for the mean-flow profiles extracted from the DNS). 3D modes with the TS-frequency and spanwise wave numbers of $K\gamma_0$ are negligible upstream of the LSB. But at $x \approx 7.4$ they suddenly reach amplitudes only one to two decades lower than the forced TS-wave. Actually, they are due to upstream transport from the roll-up of the free shear layer. The secondary 3D amplification is only weakly stronger than the primary 2D instability ($7.4 < x < 8.0$). Every amplification ceases when the 2D wave saturates at $x \approx 8$ with an amplitude that is almost one decade larger than the largest amplitude of the 3D modes.

The subsequent breakdown of the free shear layer is visualized by iso-surfaces of the instantaneous spanwise vorticity in Fig. 6. Note, that only the immediate re-attachment zone of the bubble is shown here. In (a) the shear layer is almost 2D until $x = 8.05$. Afterwards, it is pierced by 3D perturbations from inside the reverse-flow zone and longitudinal vorticity structures build up at $x \approx 8.0$ (b). A 3D strongly perturbed roll which consists of fine scale structures leaves the separation bubble (c+d). This large-scale structure is still very dominant at the beginning of the next TS-cycle

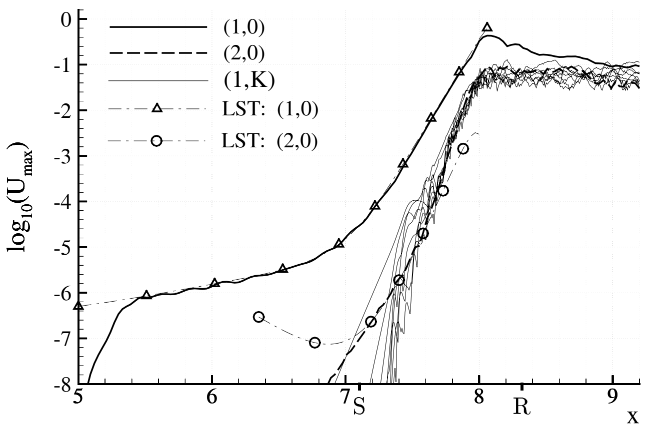

Fig. 5. Comparison of spectral amplitudes after 3D saturation with linear stability theory (LST, symbols); (1,0) = forced 2D wave, (2,0) = its first higher harmonic, and self-sustaining 3D modes (1,K), where $\gamma = K\gamma_0$; S, R = separation and mean re-attachment points, resp.

at $x \approx 8.2$ (a) and it takes a considerable streamwise distance until the dominance of the 2D wave (respective of the turbulent rolls) vanishes and an equilibrium turbulent boundary layer is reached.

Acknowledgements

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References

1. Herbert T. (1988) Secondary instability of boundary layers. Ann. Rev. Fluid Mech., 20: 487–526
2. Kloker M. (1993) Direkte Numerische Simulation des laminar-turbulenten Strömungsumschlages in einer stark verzögerten Grenzschicht. Dissertation, Universität Stuttgart
3. Maucher U., Rist U., Wagner S. (1997) Secondary instabilities in a laminar separation bubble. In: Körner H., Hilbig R. (Eds.) New Results in Numerical and Experimental Fluid Mechanics, NNFM 60, Vieweg, 229–236
4. Maucher U., Rist U., Wagner S. (1998) A refined method for DNS of transition in interacting boundary layers. AIAA 98-2435
5. Menter F., Wedemeyer E. (1992) Stability analysis of the stagnation flow of an oscillating cylinder. ZFW 16:114–118
6. Rist U. (1993) Nonlinear effects of 2D and 3D disturbances on laminar separation bubbles. In: Lin S. (Ed.) Proc. IUTAM-Symp. Nonl. Instab. of Nonparallel Flows, Springer, New York, 324–333
7. Rist U., Fasel H. (1995) Direct numerical simulation of controlled transition in a flat-plate boundary layer. J. Fluid Mech. 298:211–248
8. Rist U., Maucher U. (1994) Direct numerical simulation of 2-D and 3-D instability waves in a laminar separation bubble. In: Application of Direct and Large Eddy Simulation to Transition and Turbulence, AGARD-CP-551:34-1–34-7

9. Rist U., Maucher U., Wagner S. (1996) Direct numerical simulation of some fundamental problems related to transition in laminar separation bubbles. In: Désidéri, J.-A. *et al.* (Eds.) Computational Methods in Applied Sciences '96, Wiley, New York, 319–325

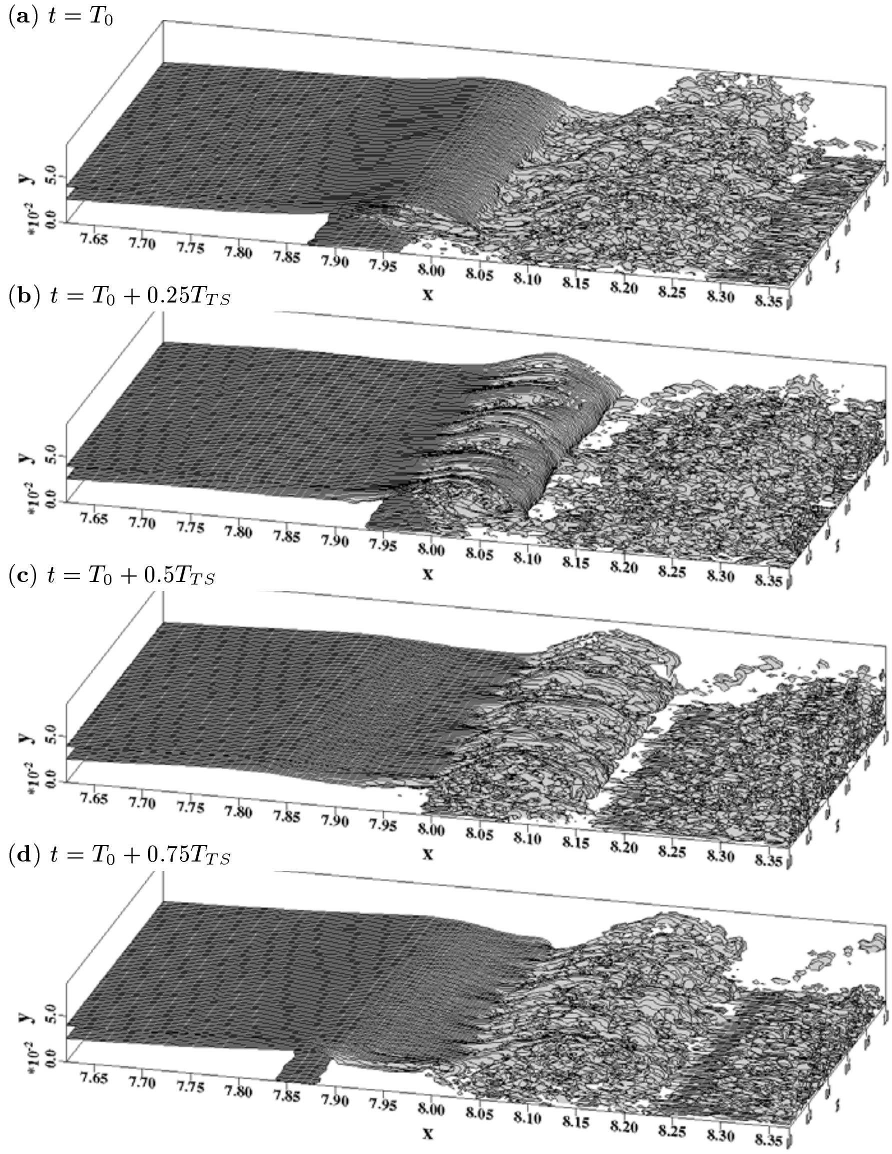

Fig. 6. Iso-surfaces of the spanwise vorticity at four time instants during one TS-cycle T_{TS}