THE EFFECT OF SWEEP ON LAMINAR SEPARATION BUBBLES

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Abstract: The effect of a systematic variation of the sweep angle on the disturbance amplification and onset of transition is studied in a generic family of swept laminar separation bubbles (LSB) by means of direct numerical simulation. The detailed analysis of a transition scenario with fundamental resonance in a 30°-LSB shows, that the saturation of background disturbances is the key event, after which a rapid breakdown of transitional structures to smaller scales and thus turbulent flow occurs. The stages of transition are similar to unswept LSB, but two-dimensional disturbances lose their dominance for sweep angles larger than 15°. Instead, oblique Tollmien-Schlichting waves which travel approximately along the direction of the potential streamline experience the maximal amplification in the linear stage and stimulate the strongest growth of background disturbances after saturation.

Key words: Laminar separation bubble; sweep angle; transition; direct numerical simulation.

1. INTRODUCTION

Laminar separation bubbles (LSB) are observed where laminar boundary layers encounter strong adverse pressure gradients, as on high-lift devices of commercial aircraft or turbine blades. For instance, a LSB was measured by Greff (1991) on the slat of an Airbus A310. Although most technical applications are inherently 3D, research efforts have been focussed almost exclusively on the easier 2D-case. Since the extensive experiments of Horton (1968) little was published about swept LSB until Kaltenbach and Janke (2000) demonstrated that the problem is now treatable by DNS.

The goal of this paper is twofold: Firstly, a transition scenario based on fundamental resonance in a 30°-LSB is discussed. Later, the impact of different sweep angles Ψ_∞ and propagation directions Ψ of chosen disturbances on such scenarios are investigated to identify the most effective disturbance combinations. To this end, a family of short leading-edge separation bubbles on a swept plate was calculated by means of DNS. This steady, laminar base flow allows for a systematic variation of Ψ_∞ from 0° to 45° and was already described in Hetsch and Rist (2004). Physically, it is characterized by a free-stream velocity of U_∞=30 m/s, a reference length L=0.05m and a Reynolds number $\mathrm{Re}_{\delta_1}(x_0) = 331$, based on the displacement thickness at the inflow of the integration domain. Under the influence of an adverse pressure gradient caused by a prescribed deceleration of the edge velocity $U_e(x)$ shown in figure 1, the laminar boundary layer separates at x_s=1.75 and reattaches at x_r=2.13. Arbitrary disturbances are excited in a disturbance strip by periodic suction and blowing through the wall. The DNS-code utilizes 6^{th}-order compact finite differences to solve the complete, incompressible Navier-Stokes-equations in vorticity-velocity formulation. For an in-depth description see Wassermann and Kloker (2002).

2. DISTURBANCE PROPAGATION IN SWEPT LSB

For each scenario one selected “primary disturbance” (PD) is excited with an initial amplitude 5 orders of magnitude larger than the one of all other modes. Additionally a group of 10 small “background disturbances” (BD) with the same fundamental frequency $\omega=2\pi\cdot L/U_\infty\cdot f$ and varying spanwise wave numbers γ=[-50, -40,…,50] are introduced. Different modes are referred to as modes (β/γ). This mimics a situation where a single high-amplitude disturbance hits a swept separation bubble in the presence of discrete background disturbances. Note that all angles are taken with respect to the X-axis throughout the paper. Three hypotheses about which type of PD is able to stimulate the strongest fundamental resonance of the BD were investigated: *Earliest transition for a given swept LSB may be expected for a PD with*: (i) A propagation direction of Ψ=0°, because 2D-disturbances are the dominant modes in unswept LSB, see Rist (1999). (ii) Ψ in the direction of the potential streamline, as those modes are most amplified in attached swept flows. (iii) The integrally most amplified mode in the linear domain, as it will reach earliest the high-amplitude level necessary to influence base flow and BD non-linearly. For each sweep angle the linearly most amplified representative of each class (i)-(iii) was determined by spatial linear stability theory (LST). The results are summarized in table 1. Note that the maximal amplification (iii) always occurred for modes which spread nearly in the direction of the potential streamline. As DNS results of both types in non-linear stages are also almost identical, we can identify the types (ii) and (iii).

Table 1. LST within linear domain: Integrally most amplified mode (ω,γ) for each sweep angle Ψ_∞ with: propagation direction Ψ=0°, propagation direction in direction of potential streamline ($\Psi=\Psi_\infty$) or strongest overall amplification (amp-max) in the base flow.

Ψ_∞	2D-PD: Ψ=0°	Pot: $\Psi=\Psi_\infty$	Ψ	amp-max	Ψ
0°	(18/0)	(18/0)	0°	(18/0)	0°
15°	(18/0)	(18/10)	12°	(18/10)	12°
30°	(18/0)	(18/20)	27°	(20/20)	25°
45°	(18/0)	(22/30)	44°	(24/30)	39°

2.1 Stages of transition in a swept LSB

In order to compare the transition mechanism in swept LSB with the known 2D case, one such scenario – namely the most amplified PD-(20/20) of the 30°-LSB – was analysed and visualized in detail in figure 3 and 4. Shown are alternating isosurfaces of the pure disturbance-component of the spanwise vorticity $\omega_z=\pm0.0001$ in region I and a single λ_2-isosurface inside the regions II, III and IV. For the sake of a clearer layout, only one BD and two non-linearly generated modes are displayed as examples in the lower picture of figure 4. The distinguished alternating ω_z-pattern at stage I represents the "footprints" of a single Tollmien-Schlichting wave. This is the PD (20/20) as indicated by the common propagation direction of Ψ=25° and the insignificant amplitude of all other modes. Until the PD reaches the critical amplitude of about 1% of U_e at $x\approx1.8$, all BD grow in very good agreement to LST, nicely demonstrated by BD (20/-10) in figure 4. At this point the PD has achieved an amplitude high enough to deform the base flow itself and the linear regime (a little larger than region I) ends. The λ_2-method indicates the onset of a PD-vortex in region II, which is still amplified as predicated by LST until it saturates. For the unswept bubble, Rist (1999) has proven that the short stage between the end of the linear domain and the saturation of the 2D-PD (18/0) is governed by secondary stability theory. In the present case, a sudden increase of the amplification rates can also be noticed for the higher harmonic (40/40) and the BD. As soon as the PD and its higher harmonics saturate simultaneously the third stage starts. Together they form a coherent structure with a weak secondary vortex near the wall. After leaving the LSB its phase velocity $c_r=\omega/(\alpha_r^2+\gamma^2)$ increases by 20% (α_r denotes the streamwise wave number). In the visualisation of figure 4 this acceleration is visible as a bending of the vortex at x=2.15. At the same time its propagation direction $\Psi=\arctan(\gamma/\alpha_r)$ is adapted until it exactly matches that of the potential streamline, as demonstrated in figure 2. The amplification rates of all BD are damped compared to the previous stage. Immediately after the BD saturate, the coherent structures rapidly break down to smaller scales and an early stage of turbulent flow appears.

2.2 The effect of sweep angle and propagation direction

As a general trend, the resonance of BD with the 2D-PD (18/0) is diminishing for larger sweep angles. Compared to the reference scenario $\Psi_\infty=0°$, only the 15°-case reaches slightly larger amplitudes for the most amplified BD at x=3. The amplitude level of the associated 45°-scenario is already more than one order of magnitude lower. Even though amplification in the linear domain generally *increases* with Ψ_∞, the growth in region III significantly decreases for scenarios with a 2D-PD. Contrary to this series, the resonance of BD to the most amplified PD rises continuously with Ψ_∞. They saturate at $x\approx3.15$ in the 0°-base flow for the PD (18/0), for $\Psi_\infty=15°$ with the PD (18/10) at $x\approx3.0$ and in the 30°-scenario with PD (20/20) already at $x\approx2.80$. Table 2 shows additional calculations with PD in intermediate propagation directions Ψ in the 30°-LSB. They confirm that the soonest saturation of BD indeed appears for the PD (18/20) and (20/20), which propagate approximately in the direction of the potential streamline.

Table 2. X-Position of saturation of background disturbances in the 30°-LSB for different PD.

Ψ_∞=30°	(18/0)	Ψ	(18/10)	Ψ	(18/20), (20/20)	Ψ	(18/30)	Ψ
BD-saturation	x≈3.20	0°	x≈2.95	13°	x≈2.75, x≈2.80	27°, 25°	x≈2.95	43°

3. CONCLUSIONS

Disturbance amplification and the onset of turbulent flow have been studied in a family of small, leading-edge laminar separation bubbles (LSB) for sweep angles $\Psi_\infty=0°$, 15°, 30° and 45°. An analysis of a transition scenario with fundamental resonance in the 30°-LSB showed similar stages as in unswept LSB: I) linear amplification of disturbances until the dominating primary disturbance (PD) reaches sufficient amplitude. II) Strong resonance of the background disturbances (BD) to a high-amplitude PD-vortex, which still grows according to LST until saturation. III) A coherent structure is formed by the saturated PD and its higher harmonics, which slightly dampens the amplification of BD. IV) Rapid breakdown to smaller scales immediately after the saturation of the BD, which was thereby identified to be an appropriate criterion for the onset of turbulent flow. As a comparison of different PD showed, oblique TS-waves propagating approximately in the direction of the potential streamline were linearly most amplified and additionally stimulated the strongest growth of BD in the non-linear stages. In spite of being dominant in unswept LSB, 2D-disturbances became unimportant with growing sweep angle. It follows that investigations of unswept LSB are *not* transferable to cases with sweep angels higher than about 10°-15°.

4. REFERENCES

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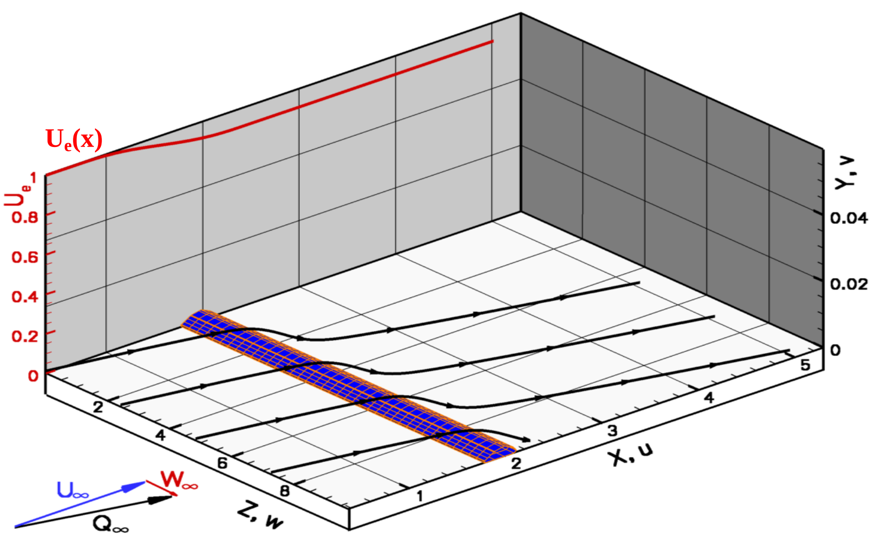

Figure 1. Integration domain of the 30°-LSB with bubble surface and outer streamlines.

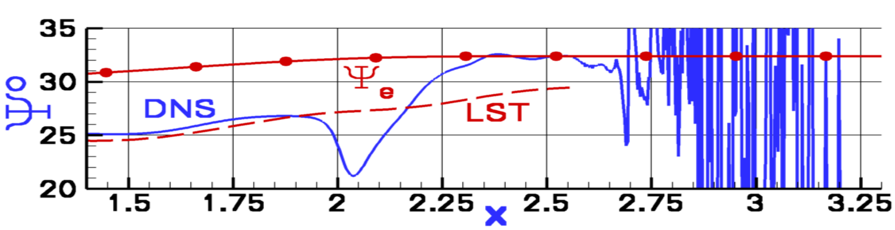

Figure 2. 30°-LSB: Propagation angle Ψ in [°] for PD (20/20), Ψ_e: potential streamline.

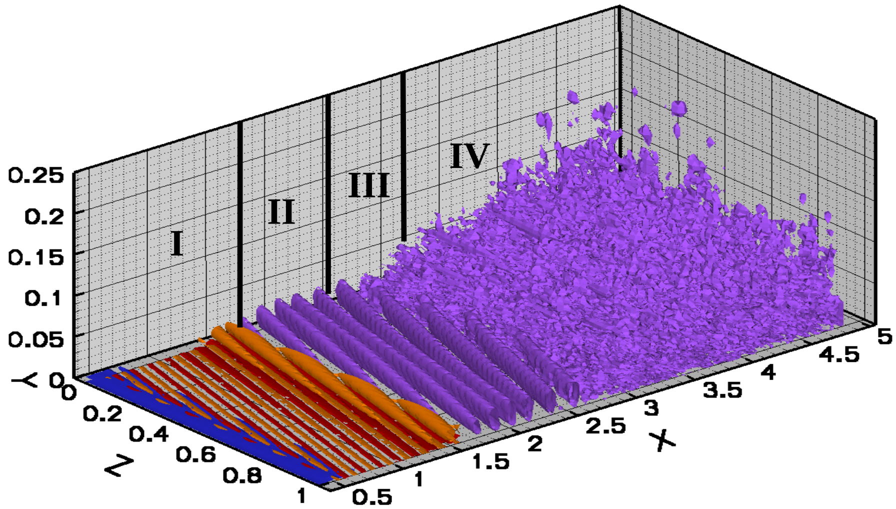

Figure 3. Stages of transition in a 30°-LSB. Fundamental resonance of background disturbances to a primary disturbance (20/20): I) linear amplification, II) PD: high-amplitude vortex, III) coherent structure of saturated PD and higher harmonics, IV) early turbulence.

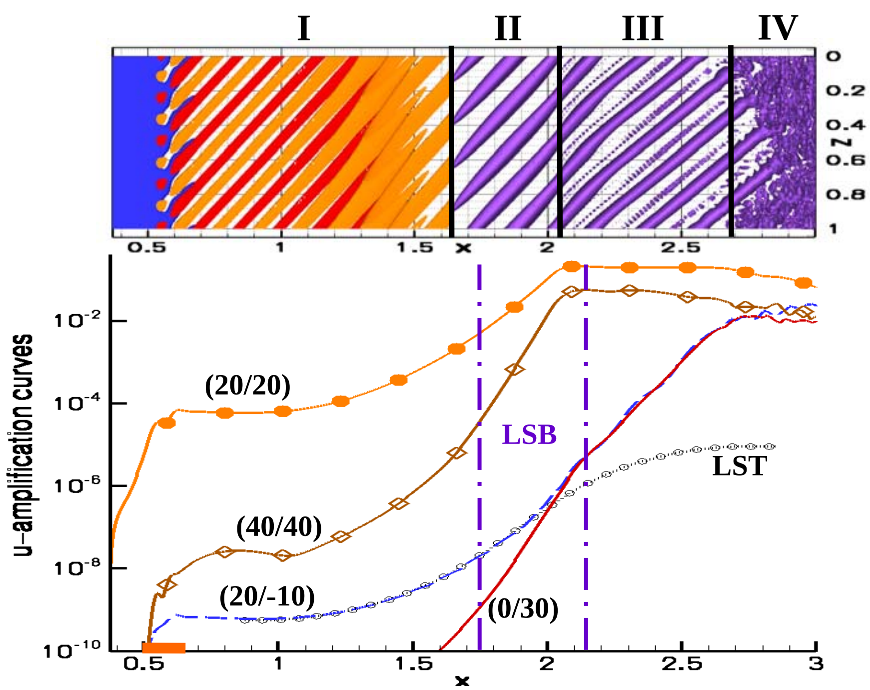

Figure 4. 30°-LSB: Comparison of amplification curves with top view of figure 3. Lines: DNS, doted line: spatial LST. Rapid breakdown of coherent structures (III) to turbulence (IV) by saturation of background disturbances. LSB: Separation x=1.75, reattachment x=2.13.