Late stages of transition in flat-plate boundary-layer flows

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The occurrence and instability of low-speed streaks are now identified as a key element in transition to turbulence and in the dynamics of turbulence in wall-bounded shear flows. Indeed, low-speed streaks are observed at the late stages of different transition scenarios and streak breakdown is one of the phases of the regeneration cycle which is believed to sustain a turbulent flow. The so-called low-speed streaks are perturbations elongated in the streamwise direction consisting of negative streamwise velocity perturbation which induce a localised region of decelerated flow. These areas are always surrounded by regions of large shear both in the wall-normal and in the spanwise direction. The corresponding inflectional velocity distributions are thus able to support inviscid instabilities.

In a recent paper by Brandt (2006), the experimental configuration in Asai et al. (2002) is numerically reproduced in order to extract from the numerical results more detailed data about the characteristic flow structures at the late stages of the breakdown initiated by the varicose streak instability. A detailed picture of the relevant vortical structures just before the breakdown is given in figure 1, where both a top and a side view of the vortices are reported. It can be seen in the side view in figure 1(b) that the Λ-structures, i.e. the vortices pointing downstream, are tilted away from the wall, whereas the V-vortices are found at almost constant y-values. It can also be noted that, for $x < 85$, the V- and Λ-structures have comparable amplitude. Further downstream, the Λ-vortices become longer and occupy almost the whole wavelength of the instability mode, whereas the V-structures become wider. Moving downstream, as the Λ-vortices grow, their tip deforms into ring-like structures. These are almost aligned in the wall-normal direction and are very similar to the structures observed when transition is induced by the secondary instability of Tollmien-Schlichting waves.In that context, these vortex-rings are also referred to as Ω-vortices.

In this paper, the late stages of transition initiated by the streak varicose instability are compared with different scenarios previously studied in flat-plate boundary layers. In particular, we consider the transition scenario initiated by the exponential growth of two-dimensional Tollmien-Schlichting waves and their secondary instability (see among others Kachanov, 1994; Rist and Fasel, 1995), transition originating from the streak sinuous instability (Brandt and Henningson, 2002) and the by-pass transition scenario triggered by a pair of oblique waves (Berlin et al., 1999). In the latter case, streamwise aligned vortices are generated by nonlinear interactions between the oblique waves and, in turn, form streamwise streaks which then become unstable.

The common feature of these scenarios is the presence at the late stages of streamwise streaks and of quasi-streamwise vortices, located on the flanks of the low-speed region and tilted away from the wall. The latter are induced by the amplification of time and spanwise dependent modes (oblique waves). In the classic scenario, the initially growing two-dimensional Tollmien-Schlichting waves are in fact negligible at the breakdown. In the varicose scenario studied here, oblique waves arise from the streak secondary instability and create the V- and Λ-structures shown in figure 1.

In the case of sinuous instability, positive and negative quasi-streamwise vortices are staggered in the streamwise direction, whereas in all other cases the vortices are not staggered but join at the centre of the streak. This difference is due to the spanwise symmetry of the streamwise vorticity of the secondary instabilities. In the case of sinuous streak breakdown, the vorticity

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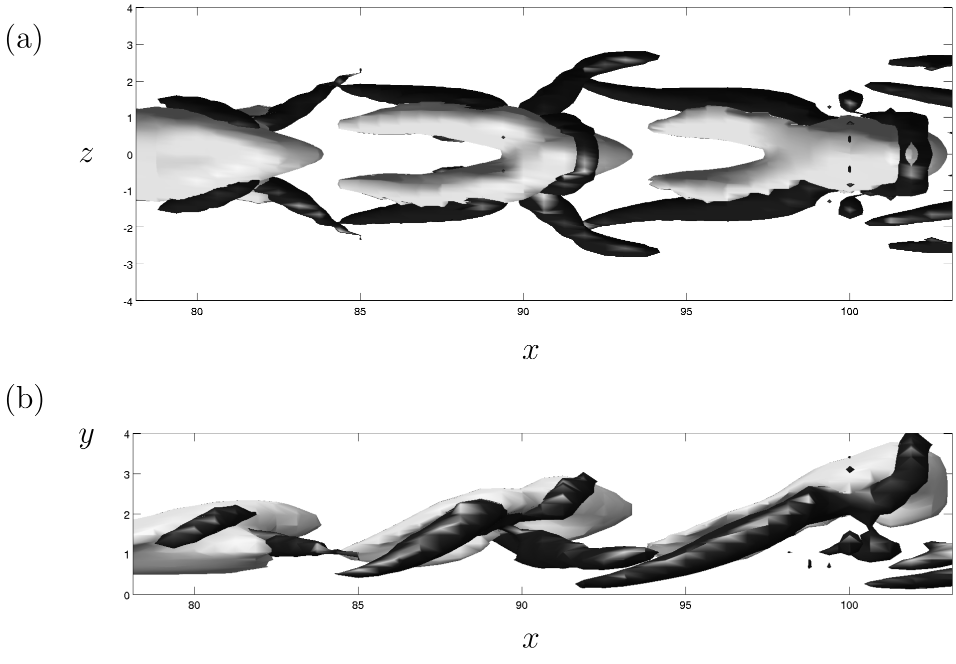

Figure 1: (a) Top and (b) side view of the flow structures at the varicose breakdown of the streamwise streak. Light gray represents negative perturbation streamwise velocity ($u' = -0.16$), while dark gray indicates regions of negative λ_2, used to identify vortical structures.

distribution is symmetric, whereas Λ-structures result from an antisymmetric distribution. The common physical process, able to explain the birth of the different structures, is the amplification at the late stages of the streamwise vorticity which can sustain the streak and induce stronger mean shear.

It is therefore not surprising that the varicose scenario considered here shows strong similarities with transition originating from the secondary instability of Tollmien-Schlichting waves, where the oblique modes of the secondary perturbation are also symmetric. In addition, the similarities with the oblique transition can be explained by the fact that this scenario is characterised by the amplification of streamwise streaks over the oblique waves originally inducing the streamwise vortices. Owing to the symmetric pattern created by the oblique waves with respect to the streaks, the breakdown can be seen as the result of varicose streak instability.

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