Late-Stage Transitional Boundary-Layer Structures. Direct Numerical Simulation and Experiment.

D.G.W. Meyer[1], U. Rist[1], V.I. Borodulin[2], V.R. Gaponenko[2], Y.S. Kachanov[2], Q.X. Lian[3], and C.B. Lee[4]

[1] Universität Stuttgart, Institut für Aerodynamik und Gasdynamik, Stuttgart, Germany
[2] Institute of Theoretical and Applied Mechanics, Novosibirsk, Russia
[3] Beijing University of Aeronautics and Astronautics, Beijing, China
[4] Institute of Atmospheric Physics, Beijing, China

1 Introduction

A large number of experimental as well as numerical studies have been devoted to the study of the generation and development of specific structures in the transitional boundary layer in order to investigate their relevance for laminar-turbulent transition in wall-bounded flows, but the origins of turbulence via the process of flow randomization are still not well understood. For this reason a detailed comparison of experimental and numerical results was performed to document the important shape and configuration of the late-stage transitional structures and to enlighten some of the still insufficiently known mechanisms of flow randomization.

2 Development of Coherent Structures

At non-linear stages of the transition process so-called Λ-structures [1] appear which consist mainly of a Λ-vortex and a 3D high-shear layer. Further downstream, an increasing number of very intensive streamwise velocity fluctuations, known as 'spikes' [2], occur whose characteristics are already very well investigated [3]. In particular it was found experimentally [4], [5] and numerically [6] that the spikes are attributed to a set of ring-like vortices formed by the Λ-structure. (At late stages the spikes themselves are observed in time-traces inside the vortex ring.) These spikes are caused by repeatedly generated loops at the tip of the Λ-vortex. Each spike is connected initially to an Ω-shaped vortex which lifts up in the boundary layer and travels ahead of the Λ-structure with a higher speed thus leaving the Λ-structure behind. This behavior can be observed in visualizations of DNS-data [6] using feature identification and extraction techniques based on the work in [7] and [8]. The dynamics of this evolution process is shown in Fig. 1 where the repeatedly generated ring-like structures are labeled (I-V) in order of their appearance.

The first of these structures develops into a nearly perfect ring with two long tails extending down towards the wall while the others turn into similar Ω-like loops. As mentioned above the loops travel much faster than the Λ-vortex and eventually snatch away from the 'body' of the Λ as a new hairpin vortex whose tails move towards the wall. In the meantime, the next loop has already started to form as a small 'bridge' between the legs of the Λ-vortex. The rather 'clean' shape of the first hairpin might be due to the fact that this one evolves into a rather undisturbed flow, while the others might interact with each other. The generation of new structures beside $z = 0$ could also be caused by such interactions of vortices with each other or with the wall, but this has to be clarified in further investigations. Nevertheless it will be shown further down that there is a clear connection between events close to the wall and the Ω-vortices in the flow. As more and more vortices/structures evolve, the picture and possible interactions get increasingly complex. Initially this sequence of events was found in the K-regime of transition, but it was found recently also at late non-linear stages of the N-regime [9]. Even in the developed turbulent boundary layer similar processes are known [10], [11]. It is therefore quite probable that a common universal mechanism for turbulence production related to the occurrence of these structures in the boundary layer exists (see also a discussion in [3]).

3 Comparison of Experimental and Numerical Results

To document the properties and the spatial extent of the late stage transitional structures a detailed comparison of experimental and numerical data for K-type transition at the so called 1- and 3-spike stages [12] was carried out. Localized forcing in spanwise direction was used in order to avoid additional interactions between neighboring vortex structures as they occur in flows disturbed periodically in spanwise direction. Such interactions would additionally influence the development of the structures as shown in [13]. In Fig. 2 a comparison of the spanwise vorticity component at the 1-spike stage is presented at an off-peak and a peak position. The very similar shape of the high-shear layer and the typical kink positioned directly above the location of the spike is noticeable. Even the spatial distributions of the disturbances agree very well. In Fig. 3 the velocity disturbances are compared at the 3-spike stage. Again we see a quite good agreement between experiment and DNS. At the peak-position the three spikes are visible as a set of rather compact regions with a negative velocity disturbance observed ahead of the tip of the Λ-structure. The latter is 'visualized' by the presence of a large-scale low-speed region positioned under the high-shear layer. A strong influence of the ring-like vortices on the fluid motions much closer to the wall can be noticed. The induced near-wall perturbations are seen especially good at the off-peak position (that is, however, still close to peak) as some positive velocity disturbances which have characteristic time scales very similar to those observed for the ring-like vortices moving on above them in the external part of the boundary layer. The initial conditions of the compared flows are quite different in experiment and simulation but nevertheless the same dominant structures are found in both cases. This illustrates the universal character of the observed structures.

4 Investigation of Flow Randomization

Despite periodic forcing in time and otherwise steady boundary conditions, increasing randomization of the flow takes place with downstream growing non-periodic disturbance parts, i.e. spatio-temporal varying occurrence of the same coherent structure from one period to another is observed. The complete periodicity of the initial disturbances can be guaranteed at least in the simulations, where no background disturbances are present which could be held responsible for the flow randomization otherwise. This means that the flow randomization cannot be a mere result of amplified non-periodic random background disturbances, but should at least partly be explained by the interaction of the structures developing in the boundary layer itself. The following possible mechanisms of flow randomization were suggested in previous studies: (a) breakdown of the Ω-vortices found in the vicinity of the Λ-vortex tip [1], (b) local 'secondary' instability of the high-shear layer leading to formation and 'multiplication' of the spikes [2], (c) 'secondary' instability of the Λ-vortex legs [14], [15], (d) low-frequency breakdown of the deterministic flow in the near-wall region at the peak position under the Λ-vortex [16], [17], and (e) growth of low-frequency background perturbations with a continuous frequency spectrum due to their resonant interaction with deterministic disturbances [18]. In very recent visual observations [5] it was found that the mechanisms (a), (b) and (c) are not observed in the transition process studied here. The Λ-structures were found to develop downstream in a very deterministic manner similar to the present experimental case. Later they produce a series of ring-like vortices developing near the outer edge of the boundary layer. These observations seem to agree very well with the visualizations of DNS-data in Fig. 1. Every ring-like vortex is very stable and conserves its main properties until very late stages of the transition process. But the ring-like structure itself has, by means of induction, a very large influence on fluid that is closer to the wall (to be seen in Fig. 3 off-peak). In the experiments [5] growth of some non-periodic perturbations was found in the wall region near the peak position under the ring-like vortices. The non-periodic perturbations looked like waves having a characteristic streamwise scale close to the streamwise distance between the ring-like vortices. These observations are consistent with the results in [18].

The direct comparison of experimental and DNS results as presented here demonstrates that the ring-like vortices (attributed to spikes) play an important role in the late stages of transition. They excite the near wall region around the peak position producing very intensive vortical fluctuations close to the wall which trigger the flow randomization process. There is much evidence that the non-periodic (irregular) components of these fluctuations are caused by some instabilities associated with interactions between different ring-like vortices as well as between ring-like vortices and near-wall perturbations. These mechanisms need further investigation in the future.

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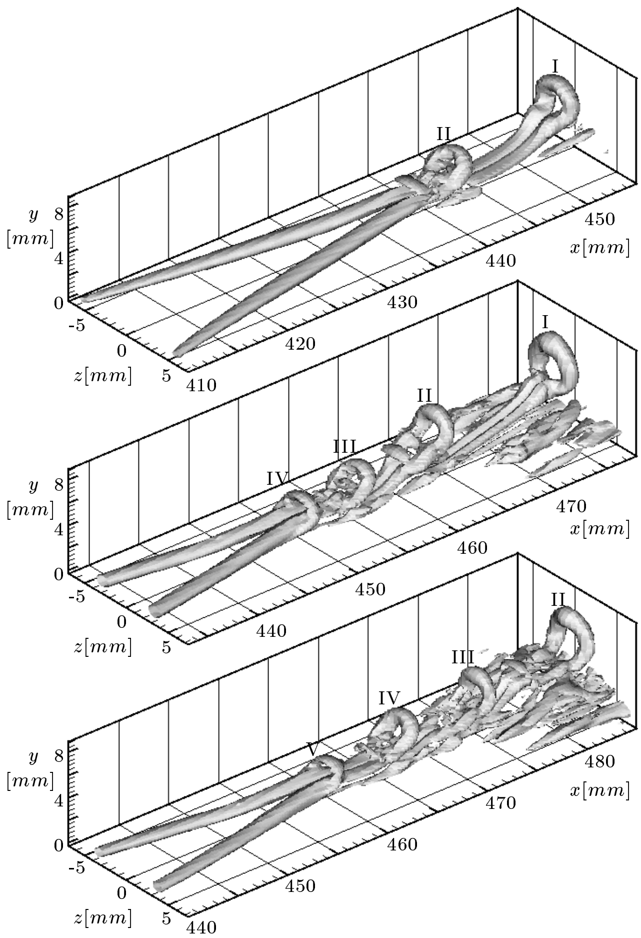

Fig. 1. Iso-surfaces $\lambda_2 = -200$ for three time instants, $t/T_0 = 0.335$, 0.605, and 0.845, from top to bottom, respectively

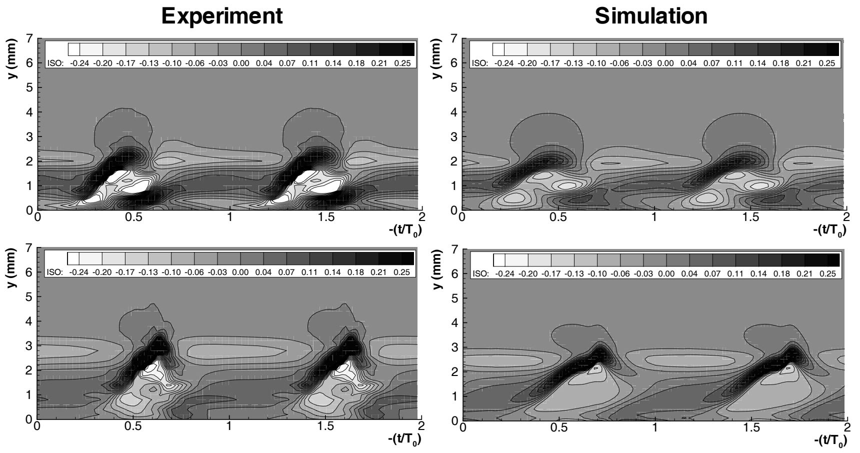

Fig. 2. Comparison of the spanwise vorticity component of experiment (left column, $\omega_z' \approx \frac{\partial u'}{\partial y}$) and simulation (right column, $\omega_z' = \frac{\partial u'}{\partial y} - \frac{\partial v'}{\partial x}$) at 1-spike stage. Top row $\Delta z \approx 2\,mm$ off-peak, bottom row at peak position $z = 0\,mm$

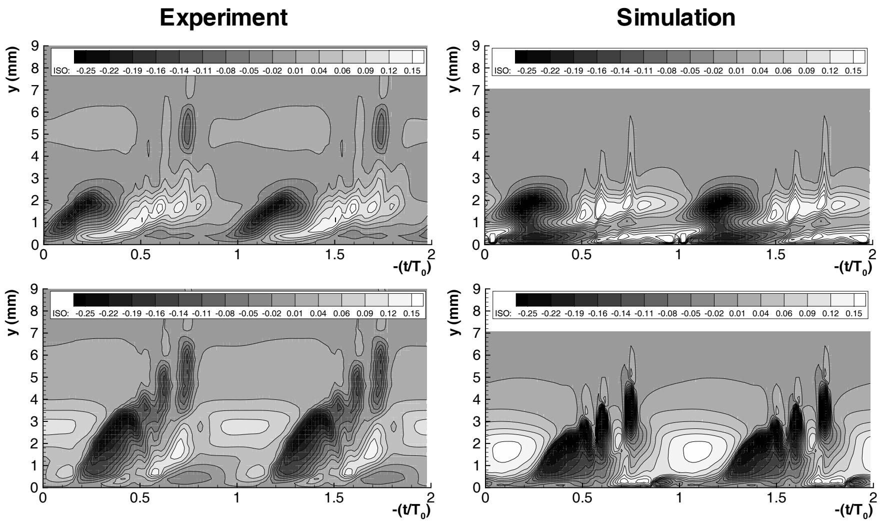

Fig. 3. Comparison of the u' component of experiment (left column) and simulation (right column) at 3-spike stage. Top row $\Delta z \approx 2\,mm$ off-peak, bottom row at peak position $z = 0\,mm$

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