DNS OF THE GENERATION OF SECONDARY Λ-VORTICES IN A TRANSITIONAL BOUNDARY LAYER

D. MEYER, U. RIST AND S. WAGNER

Institut für Aero- und Gasdynamik, Universität Stuttgart
Pfaffenwaldring 21, D-70550 Stuttgart, Germany

1. Introduction

Especially for large-amplitude initial disturbances, so-called Λ-*vortices* develop during the non-linear late stages of laminar-turbulent transition. Once formed they may persist as so-called *hairpin vortices* well into the ensuing turbulent boundary layer. This makes their study important for understanding transition and turbulence in wall-bounded shear flows.

In Direct Numerical Simulations (DNS) as well as in controlled transition experiments, especially in K-type transition, Λ-vortices have been regularly observed by all authors studying this phenomenon. In such experiments or DNS, Λ-vortices may be generated periodically in time and in spanwise direction by the non-linear interaction of a large-amplitude Tollmien–Schlichting (TS-) wave with a spatially-periodic steady modulation in spanwise direction with a certain wavelength $\lambda_z = \lambda_{z0}$. In the present paper we shall demonstrate the influence of increasing λ_z with the idea of moving spanwise adjacent Λ-vortices further apart in order to identify their possible self interaction in the original case where $\lambda_z = \lambda_{z0}$.

Our DNS are a direct continuation of the work presented in [1]. A 2-D TS-wave of $u'_{max} \approx 4\%$ and a steady spanwise modulation are introduced within a narrow disturbance strip by suction and blowing at the wall. The flow-parameters are not changed compared to our earlier work. However, for the present simulations the steady 3-D disturbance is modified in such a way as to resemble the spanwise periodic disturbance in the vicinity of the so-called peak plane as close as possible and to move neighboring peaks further apart. Four different cases are studied: a case with spanwise periodic disturbance for reference and three cases with a local disturbance, as shown in fig. 1, with a respective peak plane distance of $2\lambda_{z0}$, $3\lambda_{z0}$, and $5\lambda_{z0}$.

2. Results

In fig. 2 the spanwise distribution of the disturbances in the boundary layer is shown. For the periodic case the amplitudes are larger than for the locally disturbed cases. For the case with $2\lambda_{z0}$ we can observe an overlapping and a mutual amplification of adjacent disturbances halfway between the peak planes. Especially for the cases with large distance between peak planes ($3\lambda_{z0}$ and $5\lambda_{z0}$) the boundary layer can be considered as locally disturbed, because the disturbance amplitudes in between two peaks go back to the level of the case with a pure 2-D TS-wave. When we look at fig. 3 we can notice a deferred development of the high-shear layers in the case with $5\lambda_{z0}$ compared to the periodic case. This means that the amplification rates are somewhat smaller in the latter case.

An explanation for this behavior can be found looking at the vortex structures in the boundary layer. Fig. 4 shows a top-view visualization of vortices within the numerical flow field using a technique described in [2]. The elongated parallel structures in fig. 4a are remains of the 2-D large-amplitude TS-wave for the case with $\lambda_z = 5\lambda_{z0}$. The primary Λ-vortices are centered around the peak plane at $z = 0$ while newly found secondary Λ's appear at the edges of the TS-part of the disturbance field. They seem to be generated by an inductive interaction of a Λ-vortex with the adjacent TS-wave. This assumption is supported by the fact that the generated secondary Λ's induce even more Λ's further downstream as can be seen in fig. 4b. In this way a cascade of Λ-vortices spreads out downstream until the TS-wave is "used up". In fig. 4c an overlapping and mutual amplification of the secondary structures can be observed, thus forming a new even stronger Λ-structure which develops downstream in much the same way as the Λ's in the original peak plane. We conclude that Λ-vortices are local, independent structures of the flow field, which can overlap and amplify each other. They have a strong inductive effect on their vicinity which leads to higher amplification rates and a subsequent earlier breakdown for the periodic case in which the Λ's are located very close to each other.

3. Conclusions

The results show that transition is somewhat delayed as soon as the spanwise distance of the vortices is increased. However, the qualitative nature of the transition process, i.e., the formation of Λ-vortices, high-shear layers, and their subsequent breakdown remains unchanged. The most important finding of the present study is, however, the observation of secondary Λ-vortices for $\lambda_z > \lambda_{z0}$ which are obviously formed by induction on each spanwise side of the Λ-vortices. It turned out that these secondary vortices are present in every simulation with $\lambda_z > \lambda_{z0}$ and that they can overlap forming a stronger secondary vortex as seen in the case with $\lambda_z = 2\lambda_{z0}$. Thus, we expect the newly found vortices to play a role in any flow involving Λ-vortices.

References

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2. Jeong, J. and Hussain, F. (1995): On the identification of a vortex, *J. Fluid Mech.* **285**, pp. 69–94

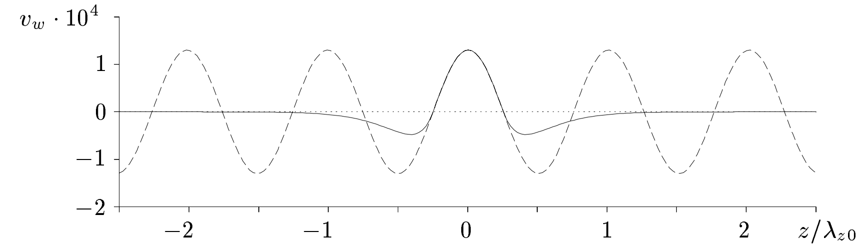

Figure 1. Comparison of the steady 3-D part of the wall-normal velocity amplitude v_w vs. spanwise coordinate of the periodic case (dashed line) with the locally disturbed cases (solid line).

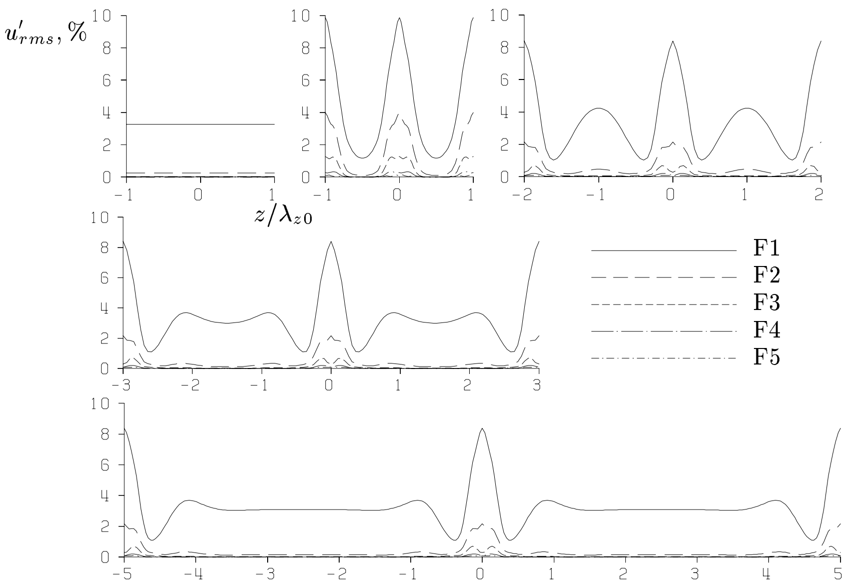

Figure 2. Maximum disturbance amplitudes of streamwise velocity component u_{rms} in % at downstream position x=400mm vs. normalized spanwise coordinate z/λ_{z0}. Plotted cases from left to right: pure 2-D TS-wave, spanwise periodic disturbance, local disturbance with $2\lambda_{z0}$, $3\lambda_{z0}$, and $5\lambda_{z0}$, respectively.

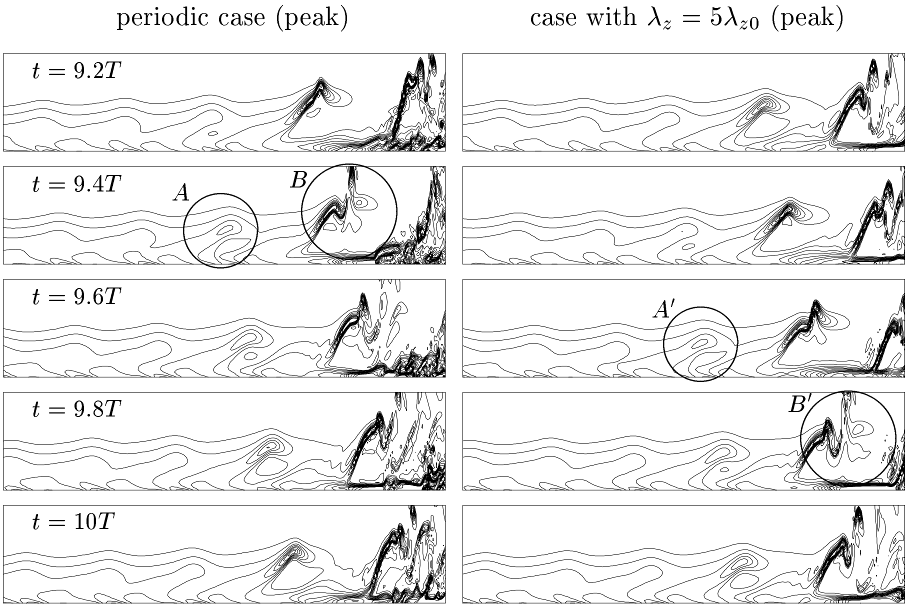

Figure 3. Comparison of isovalues of vorticity component ω_z at peak position. Downstream coordinate x between x=283mm and x=475mm; normal to wall coordinate y between y=0mm and y=4.75mm. Similar structures are marked with circles in both cases.

a)

b) c)

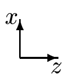

Figure 4. Top-view vortex visualization: a) case with $\lambda_z = 5\lambda_{z0}$, b) the same as in a) but further downstream, c) case with $\lambda_z = 2\lambda_{z0}$. All positions are given in mm.