Direct Numerical Simulation of Secondary Λ−Vortices in a Transitional Boundary Layer

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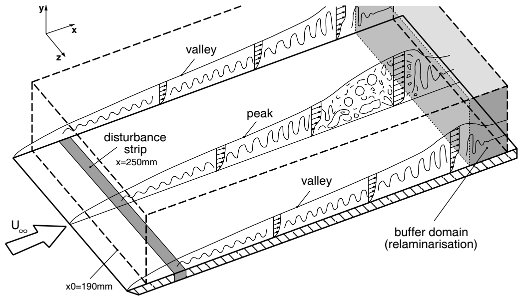
Integration Domain



– simulation of K−type breakdown using the full incompressible Navier−Stokes equations

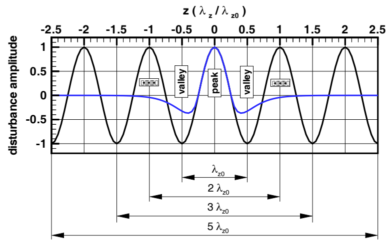
– 2D Blasius baseflow ($Re_{\delta 1}$[x0]=580)

– controlled disturbance generation by suction and blowing:

2D TS−wave (3−4%, 96.4 Hz) and 3D oblique waves generated by a steady modulation in spanwise direction

– disturbance waves grow downstream and give rise to the development of vortical structures in the flow field

Steady Spanwise Modulation of the TS−Wave



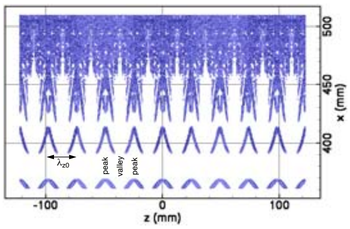
– comparison of periodic (black line) and local (blue line) modulations in spanwise direction allows to investigate whether Λ−structures can be generated by local or only by periodic disturbances

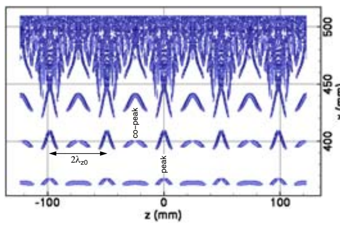
– simulation of more and more localized disturbances by increasing the width λ_z of the integration domain in spanwise direction in order to investigate the mutual influence of the vortical structures on each other:

the idea is to move neighboring peak planes further apart of each other (basic width in periodically disturbed case: λ_z=λ_{z0}=24.5mm)

Vortex Visualization

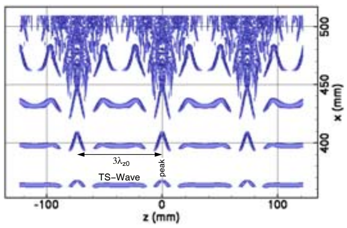
Periodic disturbance modulation in spanwise direction leads to a typical peak−valley splitting and the well known alignment of Λ−vortices for the K−type or fundamental breakdown process where Λ's are formed side by side to each other.

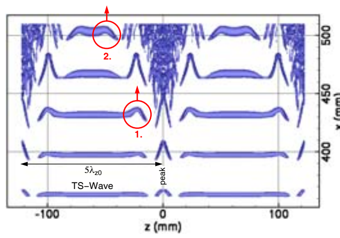




Side structures, called secondary structures in the following, emerge on each side of the Λ−vortices where they overlap and amplify each other forming a new peak plane (co−peak) with fully developed Λ's further downstream at the expected valley positions.

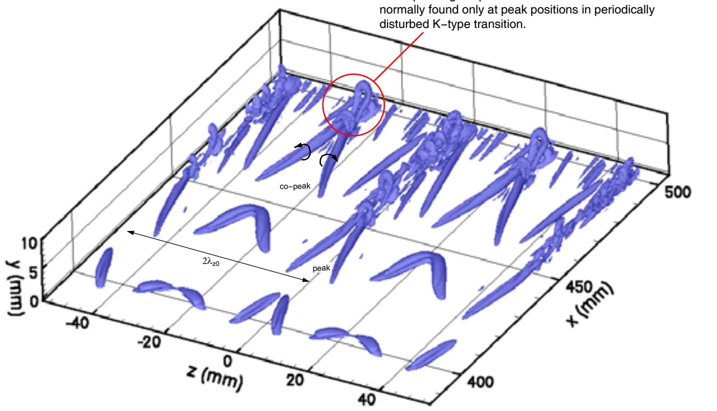
Secondary Λ−structures are stronger near to peak at first, they need some time until they become symmetric. This illustrates the local nature of the interaction of a Λ−vortex with the adjacent TS−wave which generates the secondary Λ's. The remains of the large amplitude TS−wave can be seen between the peak planes as elongated structures.



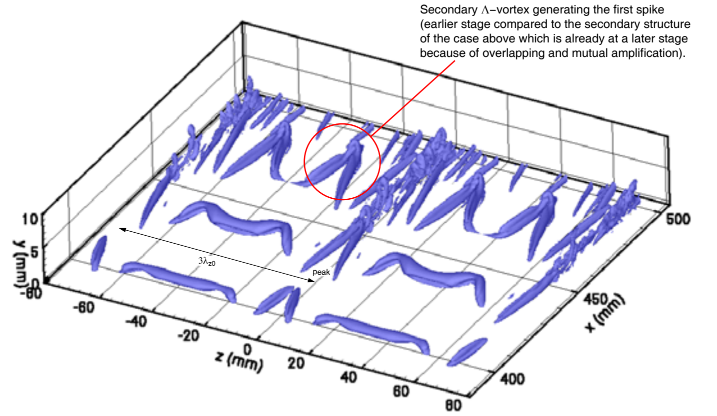


Secondary Λ−structures produce even more secondary Λ's by the same interaction process when they are fully developed, thus a cascade of new structures emerges away from peak initiating the following breakdown process.

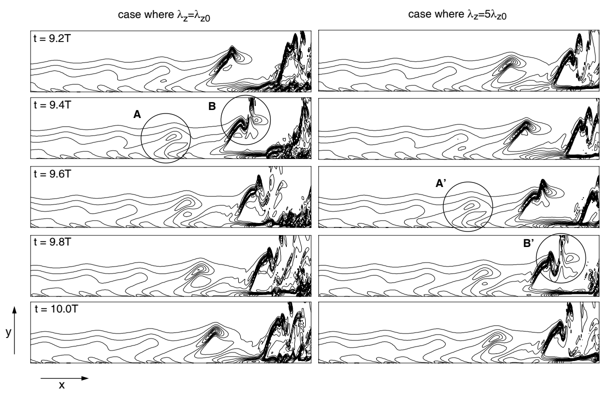
Fully developed secondary Λ−vortex at co−peak position with all expected features, especially ring−like vortices which generate strong negative velocity disturbances corresponding to spikes in timetraces of measurements − normally found only at peak positions in periodically disturbed K−type transition.



Secondary Λ−vortex generating the first spike (earlier stage compared to the secondary structure of the case above which is already at a later stage because of overlapping and mutual amplification).



Vorticity component ω_z at peak position



The process of formation of high−shear layers and spikes in the peak position is very similar in periodically (left) and locally (right) disturbed cases. The only difference is a slightly deferred development of these structures in the locally disturbed cases. This indicates that neighboring Λ−structures in the periodically disturbed case influence each other leading to higher amplification rates and an accelerated breakdown process compared to the locally disturbed cases.

Conclusions

1.) Λ−vortices can be generated by periodic as well as by local disturbances in spanwise direction, despite the very different initial disturbance spectra the same structures evolve. Once formed from wave−like disturbances they can be considered as local structures which can overlap and amplify each other. They have a very strong influence on the surrounding fluid by an induction effect from the legs and the ring−like vortices.

2.) The K−type breakdown process is independent of periodicity of disturbances in spanwise direction. Around the peak planes there is only a quantitative difference between locally and periodically disturbed cases (a slightly accelerated breakdown is observed in the latter case, because of mutual interaction of neighboring Λ's), but the formation process of vortical structures, high−shear layers, and spikes is very similar in all cases. At off−peak positions also a qualitative difference can be observed, namely the formation of secondary Λ−vortices.

3.) The newly found secondary Λ−vortices are generated by an interaction of an existing Λ−vortex with an adjacent TS−wave. This interaction consists of the combined effects of induction and of fluid displacement in spanwise direction away from and towards the peak plane caused by a Λ−structure when it passes a fixed downstream position. The TS−wave will be deformed this way and a new Λ−structure develops. This mechanism can generate a cascade of new secondary structures which then initiate the breakdown process downstream of their respective position. Experimental evidence exists that such secondary structures exist in actual transitional wall−bounded flows with local disturbances (Prof. Kachanov 1998, personal communication).

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