Visualization of Unsteady Flow Structures in a High-Performance Computing Environment

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Summary

Simulation and interpretation of small-scale transitional flow structures needs high-performance computers and the appropriate software tools. Using the equipment installed at HLRS as an example, our possibilities to accomplish high-precision rendering of instantaneous flow fields are illustrated. These include the possibility to carry out collaborative visualizations between scientists via the internet. Different methods for feature identification and visualization are compared, mainly for vortices, but inclusion of shear layers is also possible. The developed tools for extraction and quantification of vortices can be used for a quantitative modeling of local flow dynamics which is necessary to increase our opportunities to understand such dynamics.

1 Introduction

In laminar-turbulent transition research we seek for a deeper understanding of small-scale unsteady flow details under controlled or close-to-natural conditions. Our research is based on the numerical solution of the complete Navier-Stokes equations using high-order accurate finite differences and spectral schemes together with the necessary fine spatial and temporal resolution. Such simulations are typically performed on supercomputers, like the NEC SX-5 or Cray T3E at HLRS, for instance. Part of the flow field is stored on a file server for later use. In contrast to physical experiments or the real flow, the simulation can provide the complete three-dimensional unsteady flow fields based on any scalar or vector field of interest. However, in order to give the raw data their proper physical meaning, post processing is needed. This does not necessarily mean visualization alone, because early transition is nicely described by stability theory. But once the disturbances of the laminar flow become sufficiently large and complex, it appears that flow visualization is the only means to detect possible mechanisms. Algorithms for feature detection, extraction, quantification, modeling, and for automation of this process are truly needed. All the more because of the multivariate nature of the numerical data. Several examples will illustrate our attempts to gain a deeper insight into transitional flow fields via feature detection, extraction and modeling. Because many transitional flow structures and events resemble those of turbulent flows there is also hope to gain a deeper understanding of turbulence by studying transition. Further motivation comes from new insights into flow control applications.

2 Hardware

The members of VSPP Transition have access to supercomputer platforms installed at several regional or national supercomputer centers. The installations of the Höchstleistungsrechenzentrum Stuttgart (HLRS) are shown in Fig. 1 as an example for such a center. Here, computers of different architecture, from massively parallel RISC clusters to weakly parallel vector supercomputers, offer the possibility to solve all kinds of problems in the most appropriate way. As a peculiarity of HLRS, acquisition, administration, and computer resources are shared among universities and industry. As can be also seen in Fig. 1, the equipment is installed at three different locations connected by high-speed networks.

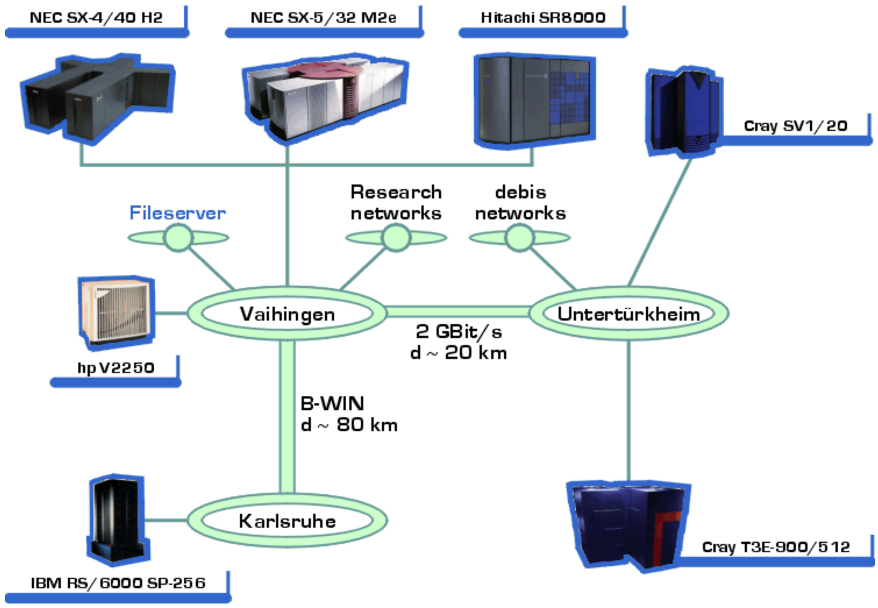


Figure 1 Overview of the hardware installations at the high-performance computing center Stuttgart (HLRS). Image courtesy of HLRS.

Before getting access to the HLRS platforms, proposals had to be submitted to the steering committee and reviewed by independent reviewers. In addition to this, the granted projects have to submit reports (i.e., scientific papers) for the yearly results- and review workshop held either in Stuttgart or in Karlsruhe. The papers of these workshops are published by Springer in the series [1].

For the results discussed in the present paper, the following hardware of HLRS has been used: the hp V2250 and a NEC PC-cluster for cross-compiling the numerical schemes for the NEC SX-4/SX-5, the Cray T3E for problems needing more than 6 Gbyte memory (before the SX-5 became available), the SX-4/-5 for numerical integration of the Navier-Stokes equations, and the fileserver for storing intermediate and final results. Precious results can be stored in a data migration facility attached to the fileserver for long-time data storage in a StorageTek tape robot silo.

Typically, each of our simulations is split into several subsequent runs. This allows to view and analyze the intermediate results from time to time and to abort the simulation if something goes wrong. First checks of the validity of a new numerical result are typically performed on the basis of some characteristic Fourier spectra which are computed during simulation in addition to the raw data (which consists of the complete vorticity and velocity vector of the flow). Typical grid sizes range from 50,000 to 10^8 grid points. More information on the different DNS performed can be found in the other papers of the present book.

For a visual inspection of the data, these must first be retrieved from the data migration facility. Once de-migrated, they can be processed on the supercomputer (if a lot of computation time or a large part of memory is required), on some smaller computers not shown in Fig. 1, or they can be transferred to the visualization server at the institute via the research networks indicated in Fig. 1. This server is a sgi Onyx 2 graphics workstation that fills the large performance gap between the high-performance supercomputers of HLRS and the desktop workstations of the scientists (cf. Table 1).

Table 1 Comparison of a desktop workstation (sgi O2) with supercomputers of HLRS.

Manufacturer & model	sgi O2	NEC SX-4/40	Cray T3E	NEC SX-5Be
Memory	64 MB	8 + 8 GB	64 GB	32 + 48 GB
Disk	4 GB	338 + 256GB	507 GB	560 GB
Processors	1	40	512	32
Peak performance	0,200 GFlops	80 GFlops	461 GFlops	128 GFlops

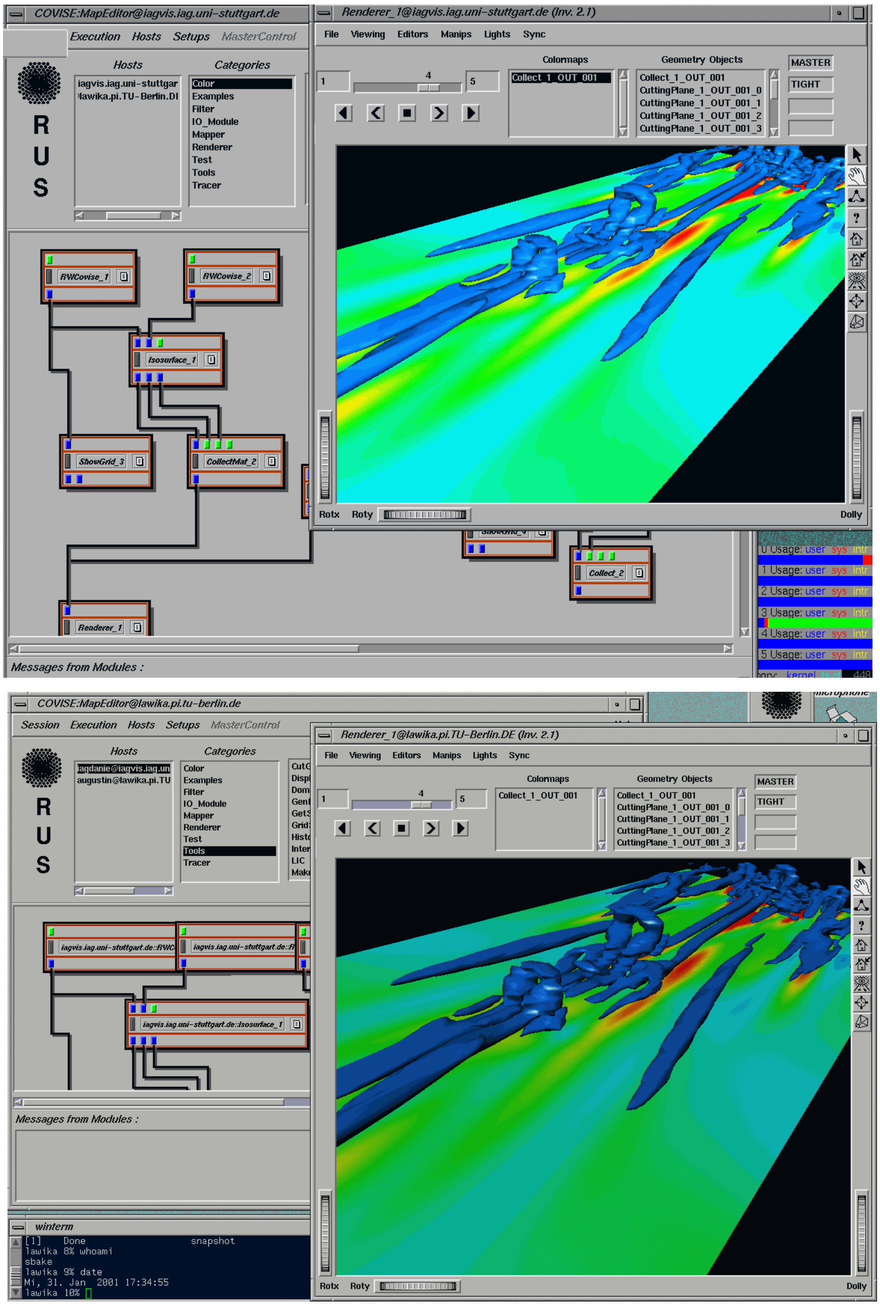
In addition to the computing platforms shown, HLRS offers access to a high-end visualization system based on a 16-processor sgi Onyx 2 graphics workstation which is connected to a 4-sided CAVE-like back projection environment for visualization in virtual reality [2]. Since this system must be shared with other users of the center, it is not available for daily or routine use by the members of the VSPP Transition. However, by using stereo glasses and the appropriate stereo rendering software in COVISE it is possible to view unsteady three-dimensional results in stereo at the institute.

For security reasons the HLRS computers are only accessible through firewalls which analyze and filter the transferred data packages. In order to reduce the data traffic through this bottleneck, a large data storage unit has been attached to the visualization server at IAG after it had been operating for a while without it. This allows now to keep local copies of the data from the fileserver for several users, as well as their intermediate or new data sets from their visualization and post-processing activities for a longer time.

3 Software

The examples shown in this paper have been visualized either with TECPLOT or COVISE. The first is a commercially available software by Amtec Engineering with a menu-guided number of options well-suited for fluid flow visualization. The second has been developed by the visualization group of RUS (Rechenzentrum Universität Stuttgart) in the frame of several international collaborations. It means COllaborative VIsualization Software Environment. Here, a certain visualization task must be implemented by connecting the necessary modules in a network. Two special features should be emphasized: First, the possibility to easily adapt the program to new algorithms and new hardware by simply exchanging the according modules. Second, the efficient data management that makes it possible to execute different modules on different computers and to work on the same data set in a collaborative session of several users. By 'collaborative' we mean that these users share their resources and knowledge for performing a common visualization task via the internet. Both features have been used for the present results.

Our first successful applications of COVISE via internet have been performed between the University of Stuttgart (IAG) and the Technical University of Berlin (HFI) because two researchers have been working very closely together on the investigation of the late-stages of K-type transition in a Blasius boundary layer. Wind-tunnel experiments performed at HFI have been compared with DNS at IAG [3]. Figure 2 presents two screenshots of such a session, one taken at IAG (top) and the other at HFI (bottom). Shown is a visualization of so-called Λ-vortices via λ_2 iso-surfaces (see further down) together with pseudo-colored instantaneous wall shear. Although the example picture is based on the DNS data only, the experimental and numerical results agree in a quantitative manner, as can be seen in [3], for instance. Different brightness in the two visualizations is due to different graphics hardware. The high-end graphics Onyx 2 used at IAG displays the visualization in full



```
[1]    Done                     snapshot
lawika 8% whoami
sbake
lawika 9% date
Mi, 31. Jan  2001 17:34:55
lawika 10%
```

Figure 2 Screenshots from a collaborative session between IAG (top) and HFI (bottom).

color mode while the entry-level desktop workstation at HFl, an sgi O2, uses an approximation of the colors via dithering. Manipulation of the underlying data-flow network (shown in the left part of the figures) could be done on either side of the session equally easy. Because of the largely different power of the two workstations used, manipulation of the view direction resulted in an immediate update of the visualization on the IAG-screen while the other reacted with a considerable delay. However, this delay wasn't really too disturbing because the low-end workstation tries to keep up with the high-end computer by dropping intermediate frames from the animation in such a way that the final (steady) picture (after stopping the user interaction) is met as fast as possible.

4 Results

In a low-turbulence environment the boundary-layer transition process is a rather gradual process, initiated by some kind of instabilities and followed in downstream direction by increasingly complex fluid dynamics. The initial stages are now well understood mostly because they can be described in terms of the instability of the so-called "base flow" with respect to a manageable number of disturbances (or Fourier modes). Since a complex flow field can no longer be reduced to a few entities via Fourier transform, we are investigating whether the underlying flow physics could be better described based on flow-field items (vortices and shear layers in the present case). Thus, new algorithms to compute feature-related information from the velocity field become increasingly necessary as the flow complexity increases.

Before these could be applied with confidence, their behavior and their limitations had to be investigated in comparisons with other methods [4–6]. An example of this process is shown in Fig. 3, where iso-surfaces of the second largest eigenvalues of $S^2 + \Omega^2$ are compared to instantaneous particle traces (time lines) for a transitional Blasius boundary layer undergoing K-type transition. In this so-called λ_2-method, introduced by Jeong & Hussain [7], S and Ω are the symmetric and the anti-symmetric part of the velocity gradient tensor, respectively. From the visualization point of view the eigenvalue λ_2 is a scalar that can be computed for every grid point and visualized by standard techniques, like e.g., iso-surfaces. It turned out that not only areas of negative λ_2 identify regions containing vortices but that stronger swirling rotation can be identified by more negative λ_2.

Based on experimental dye and hydrogen-bubble visualizations, Hama et al. have already identified characteristic transitional flow structures in the 1950's which they termed Λ- and Ω-vortices because of their shape. However, flow visualizations based on such streak- or time lines are rather sensitive to the spatial position where the particles are introduced into the flow, so that they can easily miss the relevant structures or yield other misleading results.

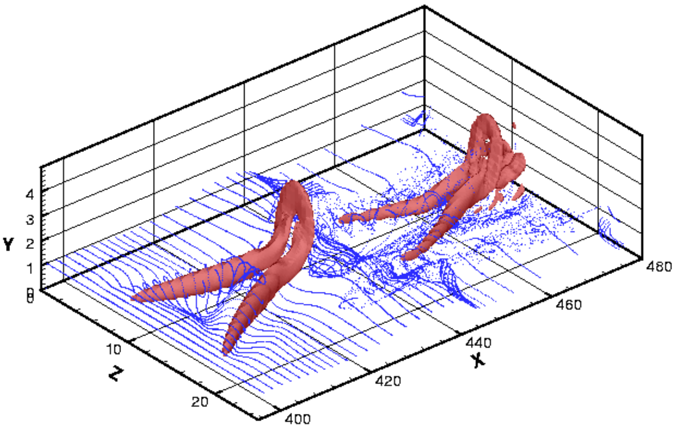


Figure 3 Comparison of λ_2 iso-surfaces with time lines in a transitional Blasius boundary layer [6].

This problem is clearly avoided with the λ_2-method, as can be judged from the comparison of the two methods in Fig. 3.

A deeper insight is possible by comparing two volume renderings of the same data set in Fig. 4 (situated further downstream than the previous one). In a volume rendering (imaginary) rays are cast through each pixel of the image into the data volume on the basis of some geometrical projection. In the present case each pixel in the resulting image was assigned a gray scale proportional to the pressure- or λ_2-minimum encountered along the ray. The comparison of λ_2 with pressure minima clearly indicates the advantage of the new method for the identification of vortices, since these are more clear-cut. As pointed out by Jeong & Hussain [7], a flow field contains additional pressure minima besides those due to swirling motion (and the according centrifugal forces) that blur the view on the vortices. This problem has been eliminated in their λ_2-method.

Once verified and validated (cf. [4, 5]) the λ_2-method served as a basis for our next steps towards a better description (and understanding) of the transition process. Starting from the λ_2-minimum in the considered data set, individual structures could be extracted by a procedure that marches through the volume from grid point to grid point and extracts the encountered λ_2-data into a new file until the border of the structure specified by some threshold for λ_2 has been crossed. The according structures can then be viewed in isolation or in their original place, but colored individually, as illustrated in Fig. 5 for one time instant of the K-type transitional Blasius boundary layer again. The next step consisted of analyzing all time steps of an unsteady sequence and following the individual structures with time in order to study their evolution and interactions [8].

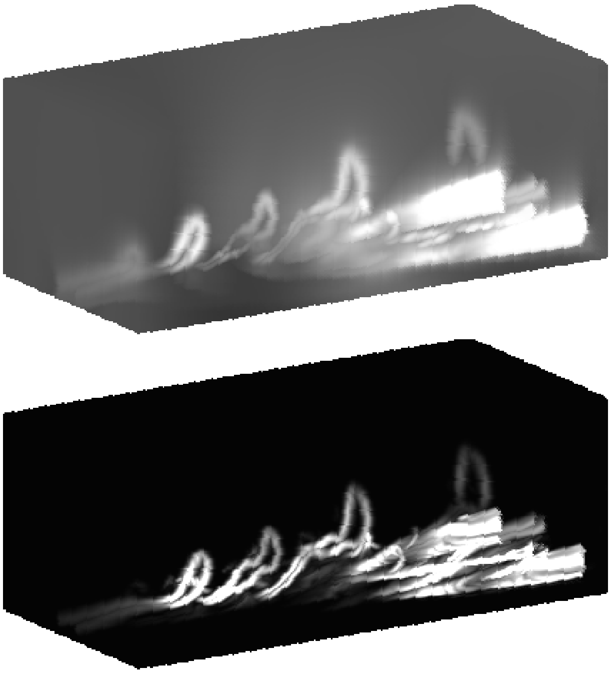


Figure 4 Comparison of low pressure volume (top) with negative λ_2 (bottom).

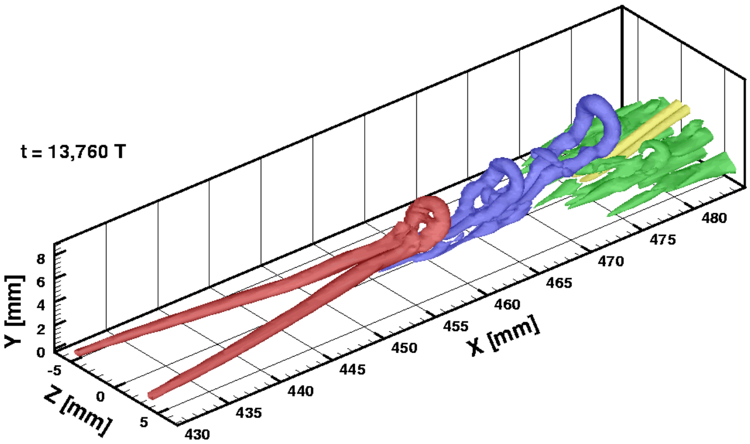


Figure 5 Identification and extraction of vortices in a transitional Blasius boundary layer [8].

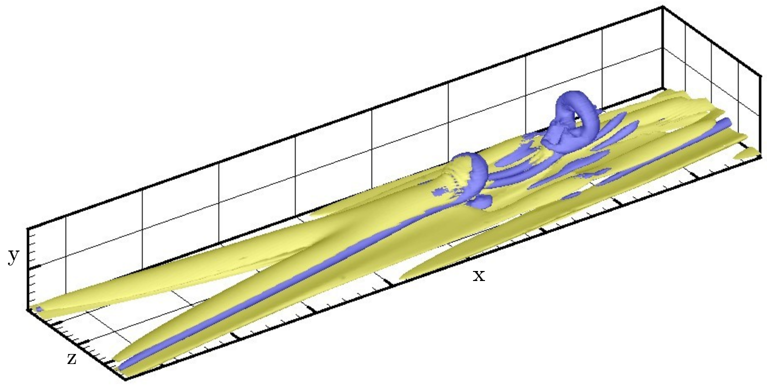


Figure 6 Combined visualization of high-shear layers (yellow) and vortices (blue) in a transitional Blasius boundary layer.

Since a transitional boundary layer also contains shear layers which are distorted by the ever increasing number of vortices (with x) it was necessary to find an algorithm for identification and visualization of 'pure' shear, as well. Meyer [9] suggests to use the second invariant of the symmetric part (S, see above) of the velocity gradient tensor for that purpose. In Fig. 6 we show iso-surfaces (yellow) of the shear layers together with the λ_2-surface that depicts vortices (blue). The swirling motion of the elongated legs of the Λ-vortex induce a high-shear layer above the Λ-vortex, while the no-slip condition on the flat plate produces a shear layer at the wall. Far away from the wall both entities (Λ-vortex and high-shear layer) merge because the rotation in the symmetry plane can be interpreted in either way. Two disadvantages with a visualization like Fig. 6 are that many structures are now hidden by the opaque high-shear layer iso-surface and that local concentrations or gradients of the shear cannot be visualized. This problem is overcome when λ_2 iso-surfaces are mixed with a volume rendering of the shear layer as in Fig. 7. Such visualizations are now possible with COVISE and texture hardware of the sgi Onyx 2. Now the shear appears as a semi-transparent 'fog' colored according to its magnitude. Gradients and "hot spots" of the shear become part of the resulting image, as well. However, to fully benefit of a volume-rendering visualization it is necessary to view the spatial structure of the data via stereo equipment or an animation that oscillates around the chosen view direction.

The third and fourth steps after identification and extraction of flow structures towards a better understanding of the flow consists of quantification and modeling of the flow. An example of such a quantification is displayed in Fig. 8 which shows integration paths around the vortex for computing the circulation $\Gamma(s)$ at different positions s along its core line (here defined as a

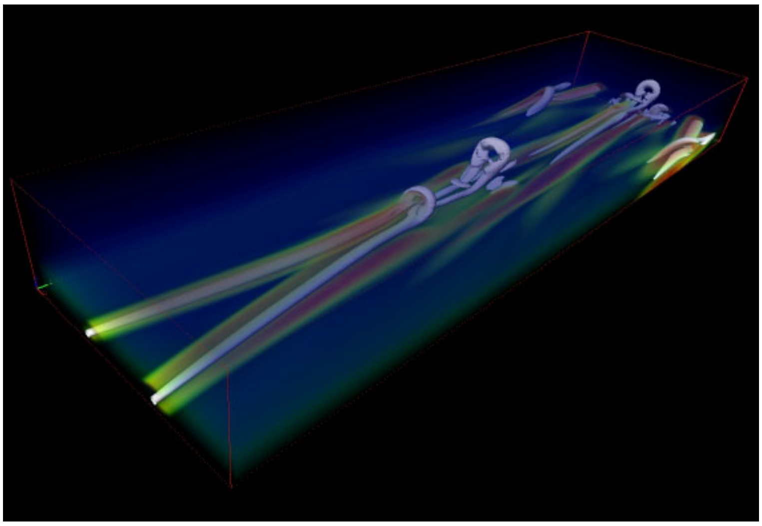


Figure 7 Volume rendering of shear layers and vortices (white) in a transitional Blasius boundary layer.

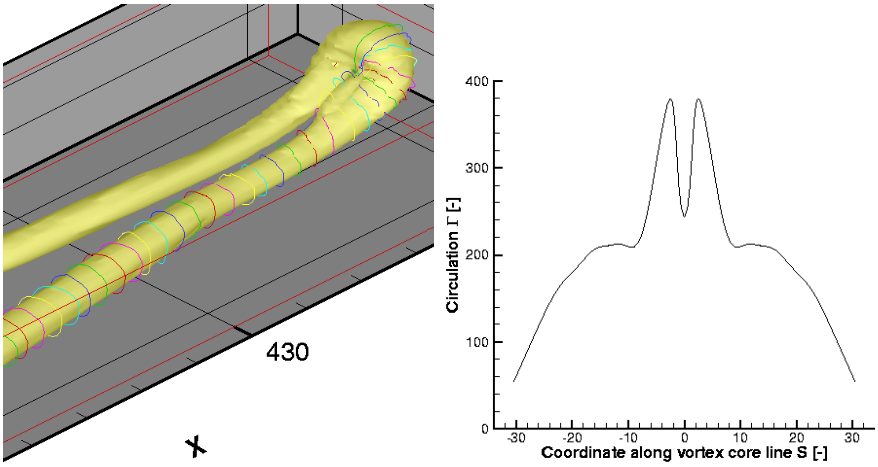


Figure 8 Quantification of circulation for a Λ-vortex. Integration paths (left) and result (right) [10].

line connecting the λ_2-minima for $x = const$; $s = 0$ in the symmetry plane of the Λ-vortex). Interestingly, the two maxima appear to the left and to the right of the spanwise symmetry plane and the Ω-shaped head of the Λ-vortex induces 50-100% more circulation than the rest. The quantified $\Gamma(s)$ has then been used for an inviscid dynamical simulation of the structures' evolution based on the Biot-Savart law [10]. Comparisons with the (fully viscid) DNS results indicated that the evolution of the Ω-vortices is a partially inviscid process.

In our last example in Fig. 9 the elongated tubes of λ_2 iso-surfaces indicate longitudinal vortices in the three-dimensional boundary layer investigated by Wassermann [11]. Two time instants are shown. Cross-stream cuts with pseudo colors of the u-velocity disturbance indicate the sense of rotation of these vortices because low-velocity fluid is drawn away from the wall around the vortices. Superposed is a small-amplitude high-frequency wave-packet (arrow!) introduced to investigate the breakdown mechanism of these cross-flow vortices. Visualizations like this certified that a convective mechanism (in contrast to the supposed absolute instability) is at work here, because the extra disturbances caused by the wave packet move downstream while they amplify.

5 Conclusions

In the present work we have presented some of our attempts to contribute to a deeper understanding via feature identification, extraction, tracking, quantification and modelling. Because of the large amount of raw data that a single simulation run can provide, such visualizations are an excellent tool to reduce the data which is necessary for identifying important mechanisms. Considering transitional boundary layers has several advantages compared to the fully turbulent case: starting from a laminar but unsteady flow, the complexity increases in downstream direction, first by the action of some instabilities, then by spreading and interaction of flow structures. Thus, it can be observed how the involved structures become increasingly smaller and more complicated.

However, the methods described here are not restricted to transitional boundary layers. They can be used in all kinds of scenarios as long as the necessary spatial and temporal resolution requirements are met. One such completely different example is the visualization of the blade-tip vortices of a helicopter in hover flight found in [12]. At present we are studying extensions of the λ_2-method for high-Mach-number compressible flows, as well.

6 Acknowledgements

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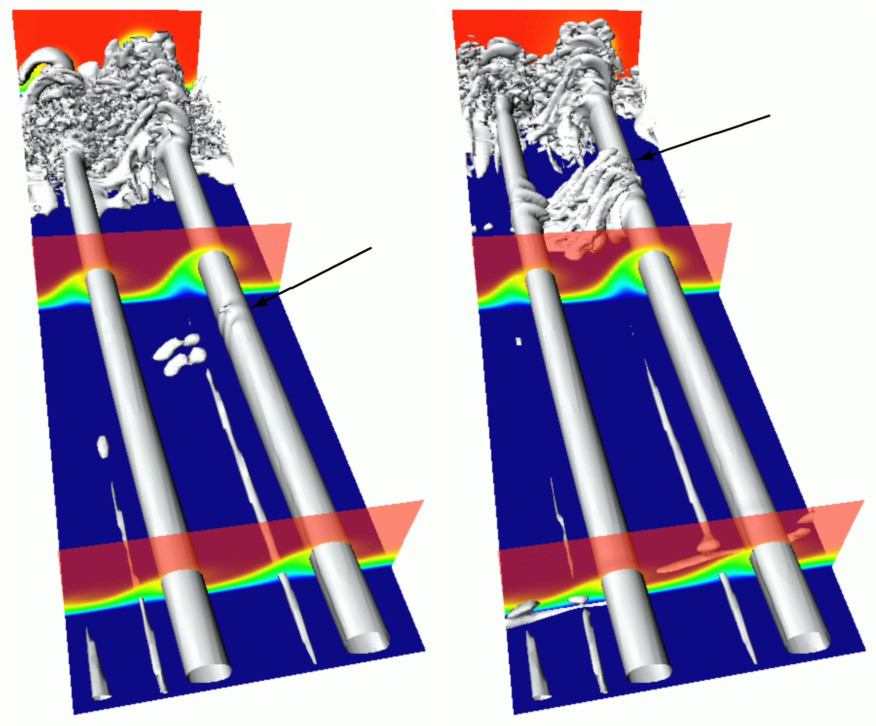

Figure 9 Visualization of cross-flow vortices and their breakdown at two time instances. The arrows point to an artificially introduced wave packet.

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