Visualization in time-dependent CFD

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Abstract. Making a time-dependent simulations of turbulent flows has produced new challenges for visualization of CFD results. These are not only due to the large data sets that require new hardware and software solutions but also due to the time-dependent flows that require new approach of the user who is performing visualizations. Here we present some of the techniques used in visualization of CFD results and discuss their applicability.

1 Introduction

Solving the time-dependent Navier-Stokes equations for engineering flows requires large computational meshes and large number of time-steps making such simulations extremely computationally demanding in terms of CPUs, memory and storage. Although researchers knew that only time-dependent simulations can provide an accurate picture of many engineering flows, such an approach was not feasible using traditional parallel computers due to the overwhelming cost of the computation. Introduction of cost-efficient Linux cluster in 1990's has made some of these flows computable using a technique called large eddy simulation (LES). This technique computes in time all the flow features that are bigger than the size of the computational cell and models only the flow structures smaller than the cell. To illustrate the size of computational task in an LES we can give an example of the flow around vehicles. LES made by the author of such flows are using around 2×10^7 computational cells and several hundreds of thousands time steps. Such a simulation produces large number of data (around 50 MB per variable and time-step) that have to be stored and analysed using some visualization technique.

The results of the time-averaged equations usually solved in industry produce nice smooth vortices that are easy to identify plotting some streamlines or an isosurface of some appropriate variable such as vorticity or pressure. On the contrary the instantaneous vortices are often different from the time-averaged ones and they do not look as something that we normally recognize as a vortex. Besides they change from time to time and making some sense in such a time-dependent flow is quite a challenge. It should be also mentioned that even the time-dependent simulations such as LES are used to provide the time-averaged results with that difference that the computational mesh is much finer from the one used in the time-averaged simulation. This means that smaller flow structures can be identified but it also implies increased complexity when visualizing the flow.

2 Visualization tools

Combination of several different visualization techniques are required to analyze the data from LES calculations. The authors experience is that different techniques are needed in different parts of the flow. There are several visualization packages for visualization of CFD results on the market of which EnSight is used by the author. Here we shall describe some of the techniques that are used for exploration of the flow resulting from a LES. The isosurfaces of the instantaneous second invariant of velocity gradient $Q = -1/2 \partial u_i / \partial x_j \partial u_j / \partial x_i$ are often used to study the temporal evolution of the coherent structures in the flow. The time-averaged streamlines, velocity vectors and isosurfaces of low static pressure are efficient in visualization of the time-averaged flow features. Another powerful technique for identification of time-averaged flow structures are vortex cores that can be calculated using for example EnSight post-processing software. There are several different algorithms for calculation of these of which two are implemented in EnSight, the eigen-value analysis algorithm and the vorticity-based algorithm. We have found in our work that the eigen-value analysis algorithm is more suitable for the flows around vehicle bodies. Unfortunately, the eigen-value analysis algorithm may produce false cores if the flow contains several vortices located close to each other.

Critical point theory is another technique that is used when visualizing the time-averaged flows. Time-averaged trace lines and streamlines are used to reveal critical points (i.e. points at which all the spatial derivatives of the velocity are zero) and bifurcation lines in the flow. Critical points can be classified into three main groups – nodes, foci and saddles – of which nodes and foci can be stable and unstable. Bifurcation lines are lines drawn in the flow toward which the trajectories are asymptotic. They are denoted negative bifurcation lines (NBL) or positive bifurcation lines (PBL) depending on whether the trajectories on the wall are converging to or diverging from the bifurcation line. These lines are associated with flow attachment (PBL) or separation (NBL).

3 Time-averaged flow

Use of the critical point theory is demonstrated on the time-averaged flow around generic car in Fig. 1.

Here the trace lines are projected on the surface of the body and used in combination with velocity vectors close to the surface to identify critical points and bifurcation lines in the flow. This kind of picture is comparable with the oil-film visualization produced in experiments and can provide the

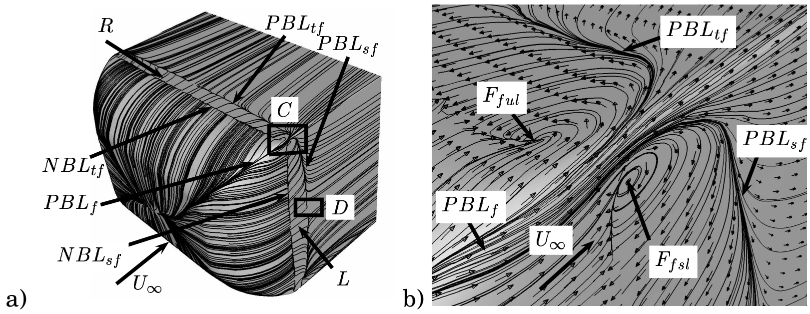

Fig. 1. a) Time-averaged trace lines on the surface of the body showing critical points and bifurcation lines. b) Zoom of region C.

information that explains the soiling and accumulation of water on vehicles. However, particle traces can be computationally intensive for large models and a skilled user is often required for an optimal result. Another technique that has become popular for identification of vortices in the time-averaged flows is that of vortex cores. Two examples of this method are shown in Fig. 2. The technique is relatively sensitive to the algorithm used and can result in misleading results such as ring vortex shown in Fig. 2a. Here we have two vortices of approximately the same strength, and their cores appear to merge into one ring-like vortex core in Fig. 2a. In reality these two vortices exist as two separate vortices.

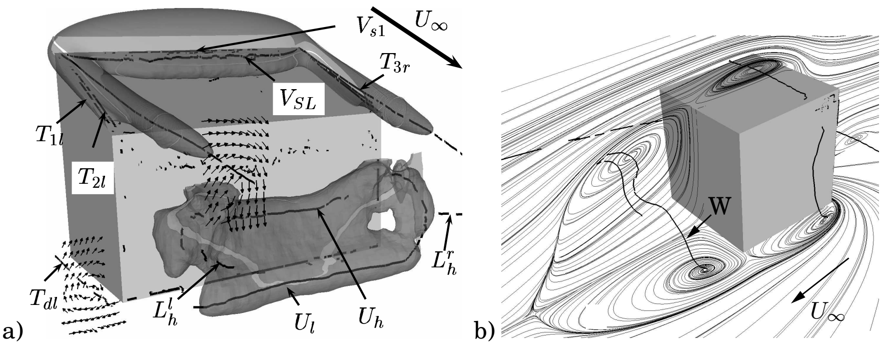

Fig. 2. a) Time-averaged flow behind a simplified Golf car. b) Votex cores in the time-averaged flow around a surface mounted cube.

4 Instantaneous flow

One powerful tool in following the instantaneous flow is plotting isosurfaces of some appropriate variable such as Q in Fig. 3a, vorticity or low value of static pressure in Fig. 3b. As seen in these figures the instantaneous vortices are complex flow structures and their identification is not trivial. There are no universal values of Q or pressure that identify vortices and the explorer of the flow has to use trial and errors technique in their identification. Volume rendering is another interesting technique that has potencial for visualization of instantaneous flow structures.

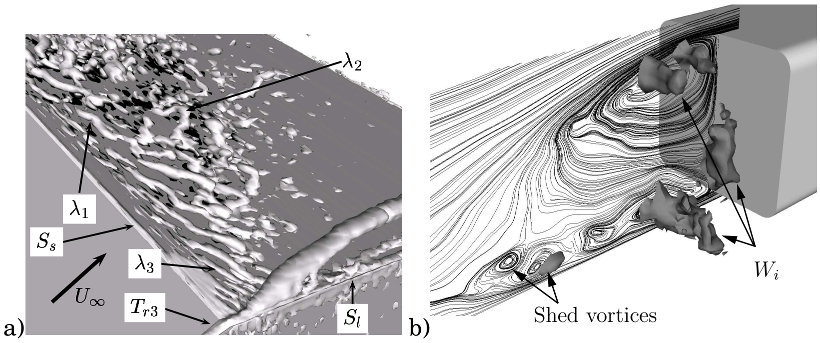

Fig. 3. a) The isosurface of Q on the rear window of a simplified Golf car. b) The isosurface of pressure in the instantaneous flow behind a simplified bus.

5 New trends

Until now the author has mainly run visualization on a single CPU or in parallel on a dual CPU machine where computation of e.g. isosurfaces was run in parallel and for their visualization a single CPU was used. The data sets are becoming too large for processing in a scalar manner and there are already versions of visualization software such as EnSight that are run on Linux clusters. In the past only expensive parallel computers were able to render large data sets. The author has for example used a shared memory SGI ORIGIN 2000 computer for visualization of the CFD results in a Cave Automatic Virtual Environment (CAVE). The new version of EnSight called EnSight DR can be run on a cluster of PCs for visualization of large data sets. This and similar approach where Linux clusters are used for visualization is the only way to work with the results of the future CFD simulations. Researchers in Sweden are already discussing plans for Linux clusters on a national level that will be designated for visualization purposes. Such and other local clusters will probably be the main tools for future explorers of CFD results.