Large-Eddy Simulation in Mechanical Engineering

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Outline

Goal

Some useful techniques will be introduced and explained to investigate average flow-field topology.
Most of the examples are taken from Lohász *et al.* (2006).
It is believed that for the understanding of turbulent flows that average flow-filed topology should be understood as well.
Techniques for this purpose will be presented.

Flow Topology

Steady, constant density flowfield is assumed.

$$\partial_j u_i(x_j) = 0 \quad (1)$$

The averaged flow-field of a constant density LES can be considered also as steady.

Streamlines

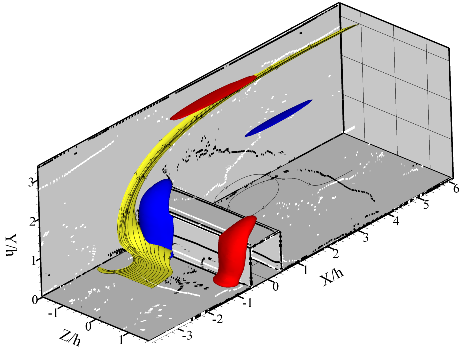
Streamlines

- Lines tangential to the vector field of the velocity vector field.
- A very important tool for visualisation of vector fields is to plot some of them.

Streamlines

Example

A streamline is drawn in the wake of the rib, showing the approximate shape of the wake, i.e. separation bubble.



Wall Streamlines

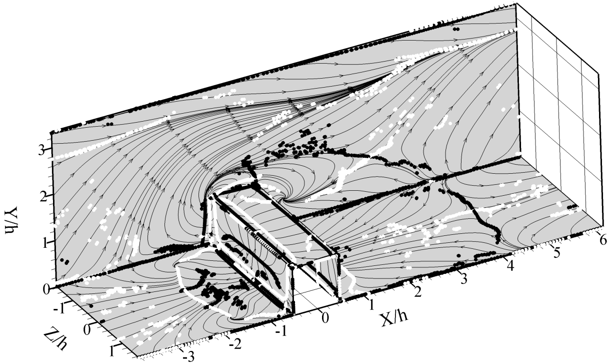
Wall Streamlines

- The extension of streamlines to solid walls
- Wall shear stress vectors are used to create a corresponding wall streamlines
- Showing the foot-print of the flow
- Will be used to investigate separation, reattachment

Wall Streamlines

Example

The approximate borders of the recirculation regions are visualised. Main character of the flow is clearly demonstrated.



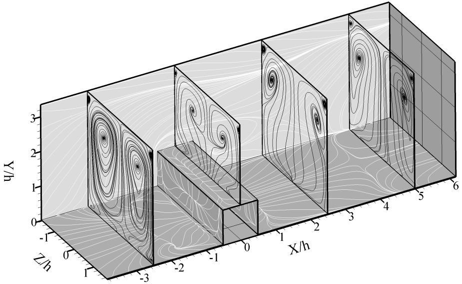
Sectional Streamlines

Sectional Streamlines

- Two dimensional streamlines on a sub surface of the 3D flow-field
- Are not directly physical (there is no fluid following the lines, since in general there is an out of surface velocity)
- Still can be useful to visualise secondary flow.

Sectional Streamlines
Example

The secondary flow, mainly the corner vortices are visualised by the sectional streamlines plotted on surfaces perpendicular to the mean flow direction.



Streamsurfaces

Definition

The streamsurface (Hornung & Perry, 1984) is a set of streamlines passing through a fixed curve inside of the flowfield.

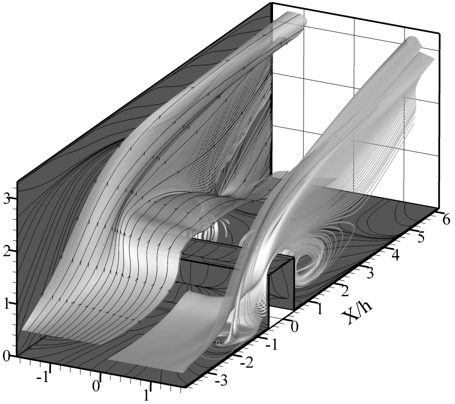
Usefulness

- This streamsurface is, by definition, tangential to the velocity vector-field.
- Dived parts of the flow (no fluid is crossing the stream-surface)
    - Very useful to investigate mixing by the mean flow
- Together with streamlines on it gives an overview of the flow
    - A special type of sectional streamlines
    - There is know flow trough the surface
    - The sectional streamlines are real (material) streamlines.

Streamsurfaces

Example

Streamsurfaces (with sectional streamlines) starting from a straight line parallel to the ribbed wall.



The mixing is clearly demonstrated.

Bifurcation Lines, Wall Bifurcation lines

The question

Separation and reattachment is a very important phenomena (see conditions and conclusions in Basic Fluid Mechanics)!

For 2D flows definition and detection is very clear

- Find zero shear stress points at the wall
- Decide intuitively (or mathematically) if it is separation or reattachment

3D flow have only separation/reattachment points of zero shear stress

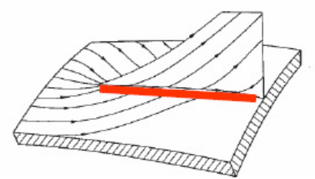
- Separation/reattachment lines are expected!
- A spanwise flow can superimposed on a 2D separation/reattachment point it will be still separation/reattachment line
- How to exactly define them for a general case?

Bifurcation Lines, Wall Bifurcation lines

Hornung & Perry (1984) proposed the definition of bifurcating streamsurfaces:

> *In many flowfields there exists special streamsurfaces which bifurcate. An example of what we call positive bifurcation is the stagnation streamsurface on an infinite swept cylinder, which divides along the stagnation line.*

The curve of this bifurcation is defined as the bifurcation line
If the streamsurface bifurcates in the flow direction it is called a positive bifurcation, if it bifurcates opposite to the flow direction it is called a negative bifurcation.



- Negative bifurcating surfaces
- Red curve is the bifurcation line

Bifurcation Lines, Wall Bifurcation lines (cont.)

Corresponding physics

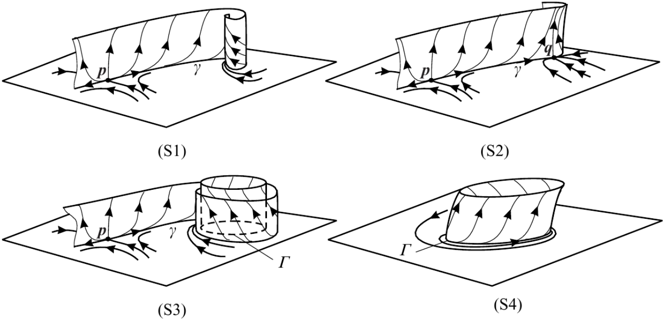
Bifurcation lines (negative and positive) at walls are corresponding to special physical phenomena of separation and reattachment respectively (Surana *et al.* , 2006).

Mathematical theory

- Surana *et al.* (2006) redeveloped the theory of steady separation and reattachment using strict mathematical theory
- proves that separation or reattachment lines are always:
  - shear stress lines connecting critical points (points with zero shear stress)
  - closed stress lines

Bifurcation Lines, Wall Bifurcation lines (cont.)

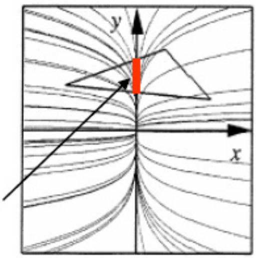
Surana *et al.* (2006) shows the four basic types of separation lines.



Bifurcation Lines, Wall Bifurcation lines (cont.)

Approximate extraction

The exact theory is usually difficult to be applied since it is not local (can not be evaluated using local quantities).
An old approximate but local technique is implemented in many post-processing tools (e.g. Tecplot)



Method of Kenwright (1998):

- Triangle: cell of the computation
- Thin lines: wall streamlines computed based on wall shear stress derivatives inside the cell
- Thick red solid line: the extracted wall bifurcation line.

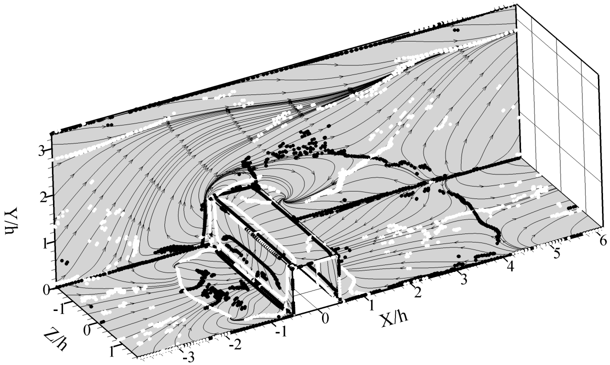
Bifurcation Lines, Wall Bifurcation lines (cont.)

Approximate extraction (cont.)

Short and clear description is given in Haimes & Kenwright (1999):

> *The three velocity vectors at the vertices of each triangle are used to construct a two dimensional linear vector field with a constant velocity gradient tensor. Tensors with two real eigenvalues produce flow patterns that contain separation and attachment lines. The trajectories for these curves are found by solving a non-homogeneous second-order ordinary differential equation. The separation and attachment lines are special lines along which the stream function is zero or singular. If one of these lines happens to cross its associated triangle, the line segment bounded by the triangle is collected for rendering.*

Wall Bifurcation lines
Example



The method is noisy but still useful. The connection between critical points can be intuitively evaluated.

Vortex Core
The question

A second important feature of 3D complex flow topologies is the location of vortices.

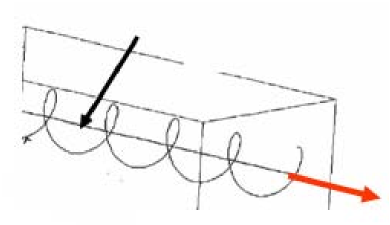
2D interpretation is easy

Intuitive definition of a vortex:

- A region of the flow where streamlines are closed and approximately circular

Such regions rarely exist in 3D flowfields. There is a flow perpendicularly to the vortex, which makes the evaluation more difficult.

Vortex Core (cont.)



A more general definition of a vortex can be given if the velocity components pointing in the axis of the vortex are removed (subtracted).

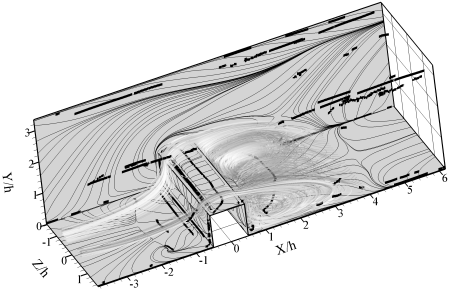
Exact description of the method can be found in Sujudi & Haimes (1995), and a short summary is given in Haimes & Kenwright (1999).

Vortex Core

Example

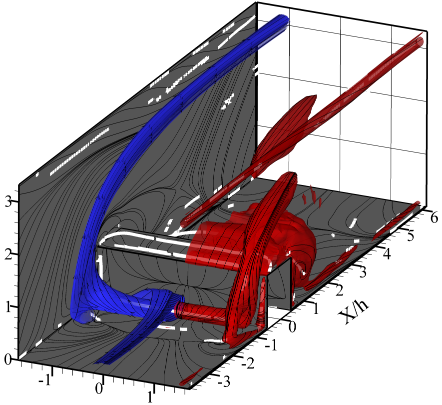
Black "lines" show the vortex cores.

The shape of the recirculation region is nicely shown, how the side wall effects the length of the recirculation bubble.



Vorticity Dominance

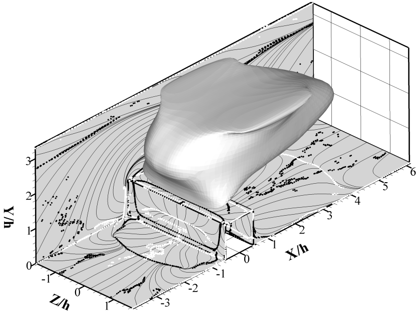
Ooi *et al.* (2002) proposed to highlight the highly vortical regions of the flow.
The same method is widely used for coherent structure detection for instantaneous flow-fields. The second scalar invariant of the velocity gradient tensor (Q) is investigated, since its positive value regions highlight vorticity over shear dominated regions and are believed to detect vortices.

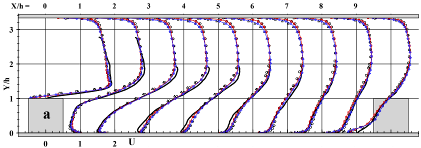


The red translucent surface is a $Q = \text{const.}$ surface with section streamlines on it.
The sectional streamlines clearly show the rotation in the upstream separation bubble.

For characterising 3D flows isosurfaces of well selected levels are frequently useful to highlight interesting features of the flow. Usually they need to be used in companion with profiles, which give an information about magnitudes.

Iso surfaces
Example





- Streamwise velocity isosurface
  - Secondary flow pushes high streamwise velocity to the corner
- Streamwise velocity profiles in the symmetry plane

Bibliography I

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