Separation in Unsteady 3D Flows

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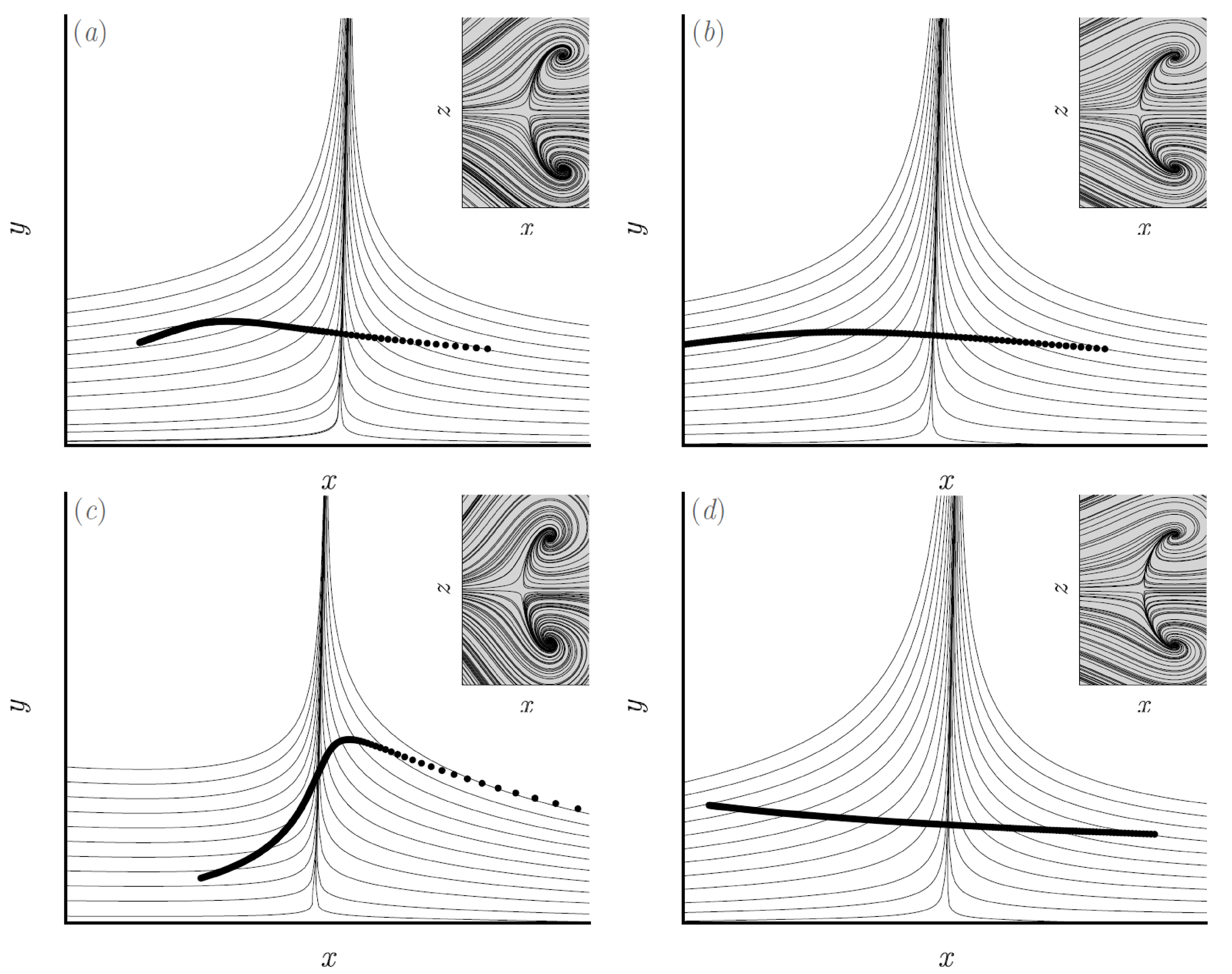
Introduction

Flow separation is an extremely important issue in many engineering applications involving internal flows, such as diffusers, heat exchangers or combustors, and in external flows like those around airfoils and buildings. Boundary layer separation increases the drag of surfaces in contact with fluids and often triggers the transition to turbulence, leading to a significant loss of efficiency in turbomachines and in vehicle performance. The prediction of such phenomena is crucial for air, land and marine transport, and for energy production. In the hydropower sector, the unsteady separation of swirling boundary layers is responsible for the degradation of the efficiency of diffusers. In aerodynamics, the peak efficiency of a compressor is often reached close to -- and limited by -- the phenomenon of separation. As a consequence, industry is becoming increasingly demanding on control strategies.

There is an abundant literature on flow separation since the pioneering work of Prandtl [1] stating that the separation point is defined where the wall shear-stress vanishes. This is considered to be valid in two-dimensional (2D), steady flows, but not in three-dimensional (3D) flows, or in unsteady flows, and even so is still in use in the aerodynamics community. However, even in 2D steady flows, our perception of separation is not so well established.



Using the method of Perry & Chong [2] with the procedure developed by Surana [3], we obtain 3D separartion patterns of incompressible flows. The wall shear-stress is given by the skin-friction trajectories:

$$\tau = \begin{pmatrix} a + bx^2 + cz^2 + dx^3 \\ \alpha z + \beta xz + \gamma x^2 z \end{pmatrix}$$

Different constants produce different flows which are presented here.

Black dots show advected particles with the same initial position ($y = cte$). We observe that a material spike can develop upstream or downstream of the Prandtl separation point, or not be present at all.

Here particles are attracted to and ejected by the Prandtl separation streamline away from the wall. The question is if we can find a more pertinent separation criterion from a Lagrangian perspective.

Objectives

- To find a new, pertinent and original tool to detect Lagrangian separation in 3D flows with arbitrary time dependence.
- To find a proper decomposition of the velocity gradient tensor close to a wall.
- To formulate a decomposition with non-linear terms present.

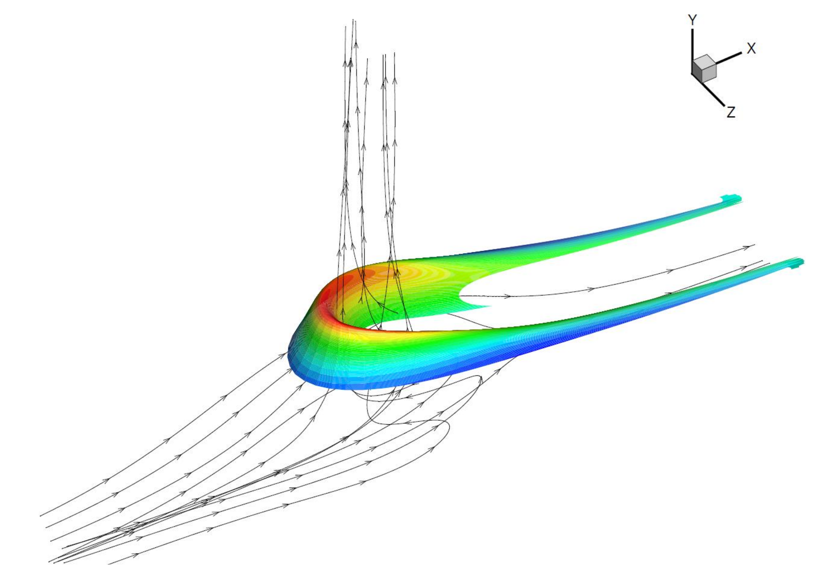
Methodology

Haller [4] defines a *repulsion rate*, which measures the normal component of an infinitesimal normal perturbation to a material surface. If the unit vector $\boldsymbol{n}_0(\boldsymbol{x}_0, t_0)$ is the normal to a material line at time t_0, the repulsion rate can be estimated by:

$$\rho_{t_0}^{t}(\boldsymbol{x}, t_0) = \frac{1}{\sqrt{\left\langle \boldsymbol{n}_0, \left[\boldsymbol{C}_{t_0}^{t}(\boldsymbol{x}_0)\right]^{-1} \boldsymbol{n}_0 \right\rangle}}$$

We currently use the DNS (direct numerical simulation) open source code Incompact3d, which is a powerful high-order flow solver for academic research [5,6], written in Fortran 90. The modeling of a solid body inside the computational domain is performed with a special immersed boundary method that allows to reproduce any complex geometry [7]. Simulations are performed on Calcul Canada compute servers, up to 8,000 cores.

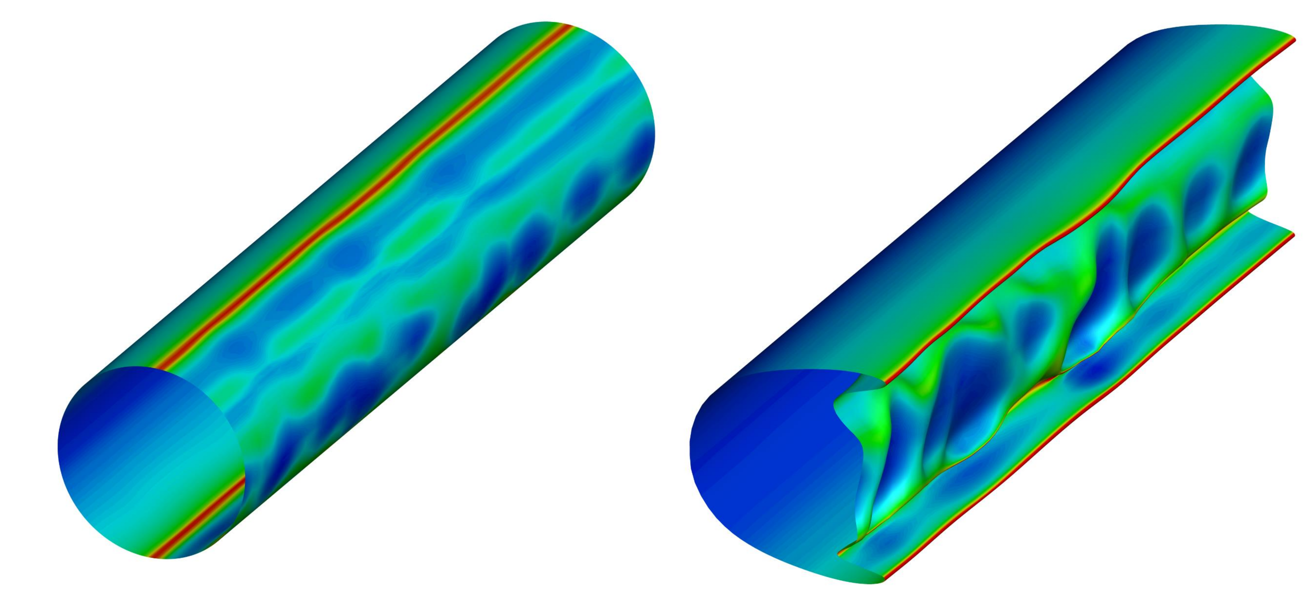
Preliminary Results



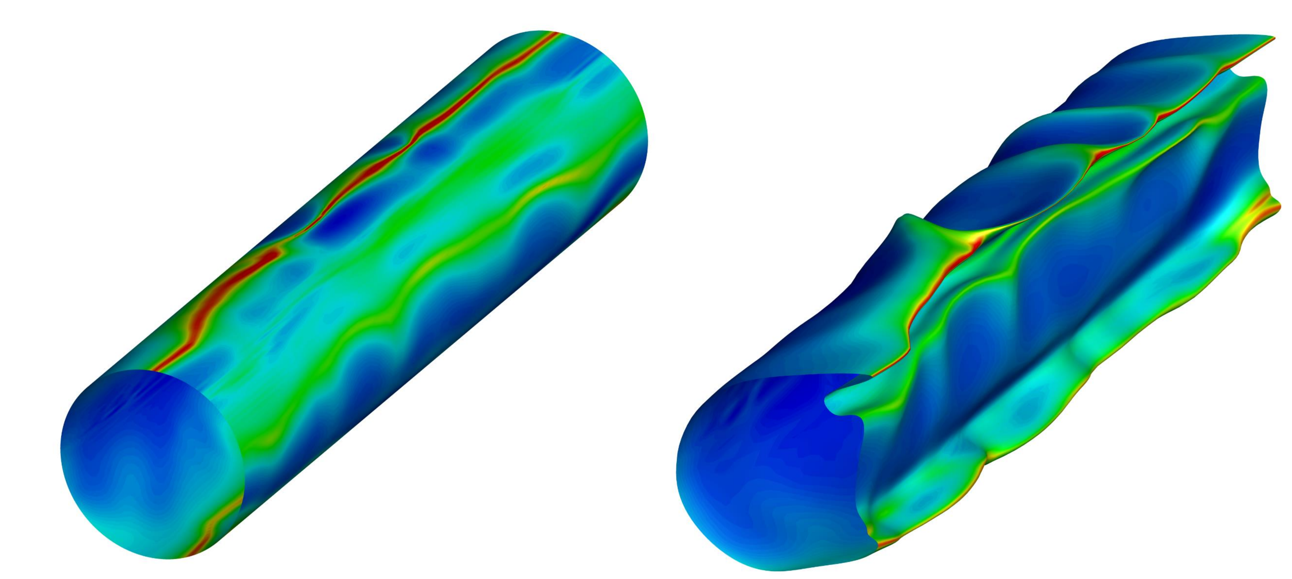
Particles initially located on a horizontal plane close to the wall are advected in time, and the plane is colored with $\rho_{t_0}^{t}$. It is observed that the criterion seems to capture most repelling particles from the wall.

A simulation was also performed on a configuration of two solid cylinders of diameter D placed in tandem, separated by a distance of $10D$, and exposed to an incoming flow of constant and uniform velocity.

A cylinder of particles, initially centered on the first solid cylinder axis, is deformed with the non-dimensional time t. Contours of $\rho_{t_0}^{t_0+0.6}$ are plotted on the surface formed by particles, and show that two main quasi-2D separation lines are detected on the top and bottom sides of the cylinder, which adequately follow the deformed pattern.



On the downstream cylinder located on the wake of the first one, the separation is no longer 2D, and again, $\rho_{t_0}^{t_0+0.6}$ captures adequately the two main spanwise-oriented separation mechanisms. In addition, some streamwise-oriented separation profiles are also detected due to the irregular incoming flow generated by the wake of the first cylinder.



References

[1] Prandtl, L. Über Flüssigkeitsbewegung bei sehr kleiner Reibung. Verh. III, Intern. Math. Kongr. Heidelberg. 1904.
[2] Perry, A. E. & Chong, M. S. A series-expansion study of the Navier–Stokes equations with applications to three-dimensional separation patterns. J. Fluid Mech. 1986.
[3] Surana, A., Grunberg, O.&Haller, G. Exact theory of three-dimensional flow separation. Part 1. Steady separation. J. Fluid Mech. 2006.
[4] Haller, G. A variational theory of hyperbolic Lagrangian Coherent Structures. Physica D. 2011.
[5] Laizet, S. & Lamballais, E. High-order compact schemes for incompressible flows: A simple and efficient method with quasi-spectral accuracy. J. Comp. Phys. 2009.
[6] Laizet, S. & Li, N. Incompact3d: A powerful tool to tackle turbulence problems with up to $O(10^5)$ computational cores. Int. J. Numer. Methods Fluids. 2011.
[7] Gautier, R., Laizet, S. & Lamballais, E. A DNS study of jet control with microjets using an immersed boundary method. Int. J. Comp. Fluid Dyn. 2014.

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