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Wake Characterization, Mitigation and Exploitation Scenarios using the Vortex Particle-Mesh Method

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SUMMARY

Wakes are ubiquitous in nature and are generated downstream of any object subjected to a viscous fluid flow. These regions of perturbed flow may interact with other objects positioned downstream of the generating one. This interaction can be hazardous, e.g. when it involves aircraft or rotorcraft, or it can be detrimental to the function of the object, e.g. when considering wind turbines. However, the wakes can sometimes be exploited to obtain a benefit, e.g. in birds or aircraft formations.

To study these external aerodynamic problems, the Vortex Particle/Mesh (VPM) method is the numerical technique of choice since it allows to accurately transport vortical structures over long distances in unbounded domains thanks to its low dispersion and dissipation errors. VPM is a hybrid Lagrangian-Eulerian method to solve the incompressible Navier-Stokes equations in vorticity-velocity formulation. The vorticity field is discretized using Lagrangian particles but a mesh is also used to improve the computational efficiency for the evaluation of the differential operators, hence the hybrid nature of the method. The Poisson equation is also solved on the mesh using a spectral solver which can handle unbounded boundary conditions using the Hockney-Eastwood algorithm. When needed, the particle quantities are interpolated onto the mesh and finite differences permit the straightforward evaluation of the right-hand-side of the Navier-Stokes equations. This method is implemented to run efficiently on High-Performance Computing (HPC) infrastructures [1]

For the investigation of wings or rotors, the lifting surfaces are modelled in the VPM method as immersed lifting lines [2]. The bound vorticity of the lifting surfaces is computed thanks to the Kutta Theorem using the local airfoil aerodynamic characteristics, and a vortex sheet is shed in a Lagrangian fashion similar to the unsteady vortex lattice method.

As a first application in the aeronautical domain, we will present the use of the VPM method to characterise complex rotorcraft wakes in order to assess their severity regarding potential Wake Vortex Encounter (WVE). The WVE risk has been widely studied for aircraft wakes and has led to the definition of the separation standards used in Air Traffic Control (ATC) operations. However, rotorcraft wakes are more complex because of their generation mechanism and because of the wider operating speed range of helicopters, i.e. from hover to cruise. We will show results obtained for a rotor at different speeds and how they compare with aircraft wakes [3].

The wake of a wind turbine is a low velocity region resulting from the kinetic energy extraction from the wind by the wind turbine. In wind farms, these wakes are detrimental to the total power production when downstream turbines are impacted by the wakes of upstream ones. In order to improve wind farm efficiency, several wake mitigation strategies have been proposed to deviate the wakes or to enhance their diffusion. The helix wake mitigation was investigated using the VPM method [4]. This strategy relies on the cyclic variation of the pitch of the blades, i.e. Individual Pitch Control (IPC), in order to offset the thrust application point away from the rotor axis and to make it rotate about the axis at a lower frequency than the rotor speed. The simulations show that this perturbation of the near wake results in a significant helical deformation of the far wake which increases the available energy flux available to a downstream rotor.

Finally, migrating birds flying in V-formations exploit the wake of the preceding bird to reduce the power required to fly. They use the updraft region on the periphery of the

vortical wake in order to decrease the thrust required to maintain horizontal flight. A lifting line model of a flapping bird was developed in the VPM solver including the control of the flapping motion to achieve equilibrium flight [5]. A second bird was then placed in the complex unsteady wake of the leading bird in order to determine the optimal position and flapping parameters. The simulated optimal configuration is shown to be close to the actual behavior of birds.

Keywords: Wake flows, Vortex Particle-Mesh method, lifting lines, rotorcraft wakes, wind turbine wakes, bird wakes, formation flight

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