When turbulence matters in vortex dominated flows

G. Winckelmans[a*], D.-G. Caprace[b], M. Duponcheel[a], L. Bricteux[c], I. De Visscher[d], F. Trigaux[a] and P. Chatelain[a]

[a] University of Louvain (UCLouvain), iMMC, Louvain-la-Neuve, Belgium

[b] Brigham Young University (BYU), FLOWlab, Provo, Utah, USA; UCLouvain

[c] University of Mons (UMONS), Mons, Belgium

[d] Wake Prediction Technologies (WAPT), Louvain-la-Neuve, Belgium

*Correspondence: *gregoire.winckelmans@uclouvain.be*

1 Introduction

This contribution reflects on the role that turbulence plays in various flows that contain coherent and dominating vortical structures. We hence don't consider flows where turbulence is everywhere and has continuous spectrum of scales, such as decaying homogeneous isotropic turbulence, or the canonical channel and pipe flows, and the boundary layers without separation (canonical ZPG and others). We also don't consider the far wake of non-lifting bodies: their wake is solely due to drag and it too has a continuous spectrum of scales; it is also found to be self-similar with self-similar profiles of the mean velocity components $\overline{u}_x$ and $\overline{u}_r$ and for the turbulent fluctuations.

The focus is here on flows at high Reynolds numbers and where large scale coherent vortices are present and dominating. For that to happen, one needs to consider bodies with significant lift. The intensity of the coherent vortical structures is then associated with that lift. It is then of interest to consider the wake of bodies where the lift is much higher than the drag, such as aircraft and rotorcraft. The Reynolds number associated with real scale aircraft and rotorcraft is very high; hence it is not possible to use scale-resolved simulations to compute both the details of the flow near the wing/blade surfaces and the wake development (from the vey near wake to the mid wake and then to the far wake). Even when using the unsteady version of the Reynolds-averaged Navier-Stokes equations (URANS) to compute the details of the flow past the wing or blades, it is not possible (or extremely expensive) to combine that with a long domain simulation of the wake itself (say up to 30 wingspans downstream) and for long time simulations (as required to gather the proper statistics of the flow).

Concerning the simulation of the wake itself, use of the URANS formulation is inadequate as this formulation assumes time-averaging of the physics over a large time window and hence it does not allow to capture the relevant turbulent scales that develop in the wake; nor they dissipation. The proper way to proceed is to use the large-eddy simulation (LES) formulation of the Navier-Stokes equations; a truncation of the physics is then done in physical space (the scales smaller than the grid size are not captured by the simulation; yet their effect of the captured scales is modelled, using a subgrid-scale (SGS) model) but no time-averaging of the physics is done. LES simulation are thus scale-resolving simulations, down to scales limited by the grid size.

The quality of the numerical code used for the LES also matters. We use in-house developed codes that have good conservation properties (using centred stencils so as to have negligible numerical dissipation and high order for low dispersion errors): either our Eulerian code in the velocity-pressure formulation and using a fourth order method on a staggered grid; or our mixed Eulerian-Lagrangian code in the vorticity-velocity formulation that uses particles for the convection step and a grid for all the rest; also for a spectral Poisson solver that can handle unbounded, bounded or periodic direction(s) [8]): the so-called Vortex Particle-Mesh (VPM) code. The codes having negligible numerical dissipation, the dissipation of the turbulent kinetic energy is handled by the SGS model. Hence, we also developed multi-scale SGS models that mostly act at on the high wavenumbers of the function captured by the LES grid (velocity or vorticity, depending on the code) and leave the small to medium wavenumbers unaffected [1]. Those codes have both been developed for HPC.

In this work, we use various types of actuator models to impose the presence of the wing or blade elements within the flow computational grid. In the VPM code, we use an immersed lifting line (and also dragging [4]) method that sheds into the wake the proper wake vorticity field emanating from each wing/blade element, and also allows for a time-step larger than that from the classical CFL limitation. In the Eulerian code, we use an improved actuator line model that avoids the smearing of the forces in the wing/blade span direction [6]; it is limited by the CFL; it also handles flexibles curves and is coupled to various beam models so as to also perform aeroelastic studies [9].

2 Results

We will present various examples of wake flows where the turbulence that develops within the wake plays an important role in what is obtained as a net result in the far wake and how it decays. For the case of a simple wing, the addition of parasitic drag (= friction and form drag from each wing section) is mandatory to obtain a wake that becomes turbulent, with obtention of a turbulent two-vortex system (T-2VS) at statistical equilibrium in the far wake [5]. Alternatively, a wing without parasitic drag flying in some atmospheric turbulence (e.g., fed as inflow using a box of Mann synthetic turbulence or using a box of turbulence co-computed in LES) will have its developing wake "resonate" with the various scales of the inflow turbulence (from scales larger than the wingspan to scales of the order of the wing chord); also leading, in fine, to a T-2VS. One can also consider the combination of both: effects of parasitic drag together with atmospheric turbulence.

The T-2VS in itself constitutes an interesting and important canonical flow, and is characterised: distribution of the circulation $\Gamma(r)$ as measured from the center of each vortex, turbulent kinetic energy in the Rankine oval and dissipation rate of that turbulent kinetic energy; decay rate for the total circulation Γ_{tot} of each vortex; those quantities being of importance for support to air trafic safety studies.

It is then also important to consider the interaction of such T-2VS with a ground; also because the safety studies in landing consider aircraft wakes near the runway, after they have interacted with the ground and gone back up, potentially encountering a follower aircraft. A wall-resolved LES was performed at $\Gamma_{\text{tot}}/\nu = 2\,10^5$ and the various important diagnostics were collected: trajectories of the vortices, decay of their circulation in time, etc. The fact that there is turbulence in the vortex system is seen to be very important, with large differences when compared to LES using a vortex system without turbulence: smoother interaction of the wake vortices with the ground, lower rebound and enhanced decay. Cases with addition of a turbulent cross-wind were also investigated, hence with a different behaviour for the port and starboard vortices [3].

The wake of a four-blade rotor with the typical advance ratio of a rotorcraft is considered next [7]. The formation of the wake is then far more complex than behind a wing, and much turbulence is generated by the complex interactions of the vorticity field shed by the various blades (even without considering any parasitic drag that here plays no significant role). The far wake is also obtained as a T-2VS which is characterised and found to be much different from that of a wing of same size, flying at the same speed and with same lift. The wake development is also quite different when considering low advance ratios, as in Fig. 1. A vehicle made of four rotors (a quad-rotor) is considered next. The wake development is also investigated and is compared to that of the single rotor.

Finally, we illustrate how wake turbulence strongly interacting with the ground can also be beneficial for wind farms (here a small farm made of two rows, each with with five wind turbines in tandem) in an atmospheric boundary layer (itself obtained using a co-simulation that is fed at inflow).

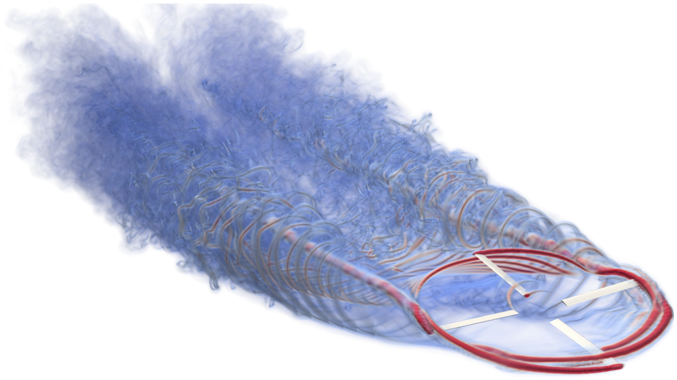

Figure 1: View of the norm of the vorticity field for the case of a rotor at a low advance ratio.

We compare the baseline configuration with a configuration where the turbines are tilted by 25^o so as to deviate their wake towards to ground [6]. The stronger turbulent interaction of the deviated wakes with the ground, together with the entrainment downward of fast air from above the wind turbines, increase significantly the recovery rate of each wake; here resulting in a 14 % increase of the produced total power.

3 Conclusion

We presented wake flows with dominating coherent vortices and where turbulence plays a major role in the way the wake develops towards the far wake, where a turbulent two-vortex system is obtained. The fate of that system further downstream will depend on its interaction with the turbulence and/or stratification of the atmosphere (as investigated in [2]); or the interaction with a ground. The case of tilted wind turbines, although not with strong coherent vortices, further illustrated how the increased interaction of a turbulent wake with a ground can be beneficial.

References

[1] Laurent Bricteux, et al. A multiscale subgrid model for both free vortex flows and wall-bounded flows. *Phys. Fluids* **21**, 105102, 2009.

[2] Ivan De Visscher, et al. Aircraft vortices in stably stratified and weakly turbulent atmospheres: simulation and modeling. *AIAA Journal*, Vol. 51, No. 3, 2013.

[3] Laurent Bricteux, et al. LES investigation of the transport and decay of various strengths wake vortices in ground effect and subjected to a turbulent cross-wind. *Phys. Fluids* **28**, 065105, 2016.

[4] Denis-Gabriel Caprace, et al. Lifting line with various mollifications: theory and application to an elliptical wing. *AIAA Journal*, Vol. 7, No. 1, 2019.

[5] Denis-Gabriel Caprace, et al. An immersed lifting and dragging line model for the vortex particle-mesh method. *Theor. Comput. Fluid Dyn.*, 2020.

[6] François Trigaux, et al. Tilted wind turbines in farm configuration for improved global efficiency. *J. Phys.: Conf. Ser.* **1618** 062035, 2020.

[7] Denis-Gabriel Caprace, et al. Wakes of rotorcraft in advancing flight: A large-eddy simulation study. *Phys. Fluids* **32**, 087107, 2020.

[8] Denis-Gabriel Caprace, et al. FLUPS: a Fourier-based library of unbounded Poisson solvers. *SIAM J. Sci. Comput.*, Vol. 43, No. 1, C3-C60, 2021.

[9] François Trigaux, et al. A flexible actuator curve model for aeroelastic simulations of wind turbines in atmospheric boundary layers. *J. Phys.: Conf. Ser.* Submitted Jan. 2022 for TORQUE 2022.