Vortex sensing and uncertainty propagation for aircraft formation flight

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1 Introduction

Formation flight is known to improve the efficiency of a two-aircraft formation (leader+follower). Indeed, the follower benefits from substantial apparent drag reduction when flying in the upwash region of the leader wake. This bio-inspired technique can therefore lead to significant fuel savings as recently showed in commercial aviation [1, 2]. For civilian applications, the concept of extended formation flight is favored due to evident safety concerns: the follower then flies several tens of wingspans downstream of the leader and nevertheless benefits from the wake. This requires, however, an accurate tracking of the wake position to preserve the efficiency gains: 50% of the benefit is lost if the follower cannot ensure a wake tracking accuracy within 10% of the span of the leader.

A corollary lies in the hazard posed by such formation scenarios to downstream air traffic. Indeed, as the follower flies close to the leader's wake vortices, the inboard vortices of the resulting wake are very close to each other and undergo drastically faster dynamics. Furthermore, the uncertainty on the relative position between the follower and the wake of the leader that is inherent to any tracking strategy, further increases the complexity and uncertainty of the resulting vortex dynamics over large distances, making the prediction of the wake hazard extremely challenging.

In this work, we design and assess a wake sensing method based solely on the assimilation of the aircraft dynamics [3]. The wake dynamics of the two-aircraft formation are then simulated over large distances using a combination of space- and time-developing Large Eddy Simulations, enabling the quantification of the uncertainty of the wake hazard far downstream. This also allows us to assess the feasibility of commercial formation flight with more than two aircraft.

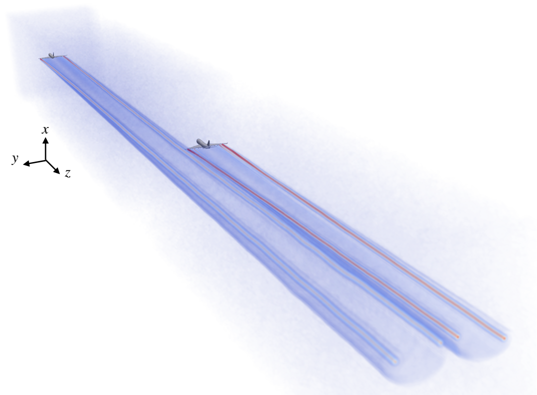

Figure 1: Large Eddy Simulation of an aircraft Formation within a turbulent flow field

2 High fidelity simulation of formation flights

We use a state-of-the-art Vortex-Particle Mesh (VPM) method [4] to simulate the vortex-dominated flow within the formation. It combines the advantages of a particle method and of a mesh-based approach, which makes it an hybrid approach among the many variants of vortex methods [5]. The method is based on the vorticity-velocity formulation ($\omega - u$) of the Navier-Stokes equations for incompressible flows.

The generation of vorticity along the lifting surfaces of an aircraft is accounted for through an Immersed Lifting Lines (ILL) method [6]. Ambient turbulence is added to the simulation to reproduce as closely as possible actual flight and wake conditions. Synthetic turbulence, reproducing the spectrum of Homogenous Isotropic Turbulence (HIT), and generated using the Mann algorithm [7], is smoothly injected at the inlet of the computational domain. The 6 degrees-of-freedom dynamics of the aircraft are handled by a Multi-body system integrator, Robotran [8].

[1] This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement no. 725627).
The development work benefited from the computational resources provided by the supercomputing facilities of the Université catholique de Louvain (CISM/UCL) and the Consortium des Équipements de Calcul Intensif (CÉCI) en Fédération Wallonie Bruxelles (FWB) funded by the Fond de la Recherche Scientifique de Belgique. The production simulations were performed on the Tier-1 supercomputer of the Fédération Wallonie-Bruxelles, infrastructure funded by the Walloon Region under the grant agreement n°1117545.

3 Data assimilation of aircraft wake parameters

Following the methodologies pursued in [9] and [10], the proposed approach relies on an Ensemble Kalman Filter that propagates a surrogate model of the formation. The model output is here corrected within the estimator through a comparison with measurements of the full 6 degrees-of-freedom dynamics of the follower, as well as geometric characteristics of the leader. This essentially waives the need for dedicated hardware devices and only requires episodic communication between the leader and the follower. The chosen combination of estimator and dynamics measurements are found to be able to detect the position of the impacting wake as long as the dynamics are accurately reproduced by the surrogate model. Additionally, it is shown that a lack of observability hinders the concurrent estimation of the wake position and strength in the presence of uncertainty.

One final observation concerns the energy gains. In a perturbed environment, the follower endowed with the wake sensing capability is able to track the wake and therefore the energy-optimal position, ensuring a 10% gain whereas a straight-flying follower loses most of the benefit.

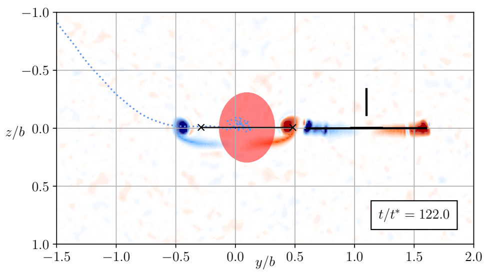

Figure 2: Cross section of the streamwise vorticity behind the follower ( ). The dotted line (····) is the history of the estimated position of the leader's wake, with the current estimation ( ). The shaded area ( ) represents the $1-\sigma$ confidence interval of the estimate.

4 Uncertainty propagation of wake trajectories

The uncertainty on the relative position between the follower and the leader's wake leads to an uncertainty on the dynamics of the wake vortices from their emission to the far-wake. The propagation of this uncertainty is performed through a sampling of the relative positions and the simulation by means of LES up to the far-wake conditions. Every single simulation presents a markedly multi-scale spatio-temporal problem as one has to capture the wake development from its generation to its development one minute later or, equivalently, 10 km downstream.

For that purpose, we have developed a numerical methodology that combines 3D Space Developing (SD) and 3D Time Developing (TD) VPM simulations in order to capture the roll-up of the vortex sheets originating from the leader and follower, their mutual interactions, and their evolution within ambient turbulence.

The probabilistic analysis led us to observe the impact of a formation wake in an operational context, and to compare it to the wake of an isolated aircraft. By computing a Rolling Moment Coefficient in the wake of both the formations and the isolated aircraft, we observed that the wake of a formation was less constraining in terms of Rolling Moment Coefficient intensity. However, it did not decrease as fast as the one computed in the wake of an isolated aircraft. We also defined a Vertical Force Coefficient that characterized the increase in vertical force experienced by an aircraft flying in a wake because of upwash winds. That Vertical Force Coefficient was shown more intense in the wake of a formation, compared to the wake of an isolated aircraft. This observation would justify the deployment of larger aircraft formations, as a third aircraft would enjoy even greater savings.

5 Conclusions

The present wake sensing and uncertainty quantification frameworks bring concrete contributions to the operational feasibility of formation flight.

While limited to a two-aircraft scenario, our work clearly hints at the potential and the challenges of multi-aircraft formations. The string stability of such formations for instance will require specific precautions for the flight controllers that result from sensing and tracking tasks.

Finally, the used assimilation techniques can be exploited to provide observability estimations of the assumed flow structures and should then enable the optimization of wake tracking trajectories that maintain the system observable.

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