Bird formation flight: vortex dynamics, flight control and energy savings

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1 Introduction

For long, the organization of large migratory birds, such as geese or ibises, into line- or V- formations has been suspected to provide substantial energy savings, i.e. through the exploitation by a following bird of the upwash in the wake of a leader. In truth, this phenomenon has seldom been mimicked, due to safety and operational constraints. Advances in Air Traffic Management and control algorithms should however make it an operational reality in the near-future for transoceanic commercial flights [1].

Interestingly, this wake exploitation appears more challenging for flapping flight. Whereas the wakes of rigid wing flyers exhibit a simple topology, i.e. a potentially long-lived counter-rotating vortex pair, flapping birds generate an oscillatory vortical flow which rapidly undergoes extensive deformations. For a following bird to enjoy a wake benefit, it then needs to stabilize itself close to these undulating vortical structures. Such a feat is yet another demonstration of birds' flow awareness and outstanding maneuverability and invites to a closer examination.

Formation flight of birds has been studied by tracking the relative position and wingbeat phasing of ibises in a V-shaped formation [2, 3]. These results show the organisation of birds in such a formation and confirms hypotheses regarding wake exploitation, but they do not show the interactions between the birds and the flow, and provide no quantitative data on the energy savings of the birds in the formation. On the other hand, flying birds in a wind tunnel provides valuable data on their wakes and their flight power (see e.g. [4, 5]), but no experimental data on multiple birds flying in formation in a wind tunnel have been published yet.

We thus propose a numerical framework able to reproduce the free flight of birds and their wakes. This tool relies on a vorticity-based Large-Eddy Simulation solver and the approximation of the bird wings as morphing lifting lines.

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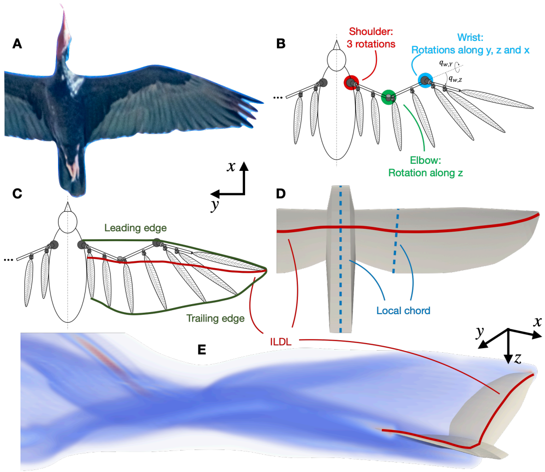

Figure 1: Bird modeling chain (A): Picture of the simulated bird. (B) Bio-mechanical model of the skeleton and feathers, with the joints highlighted and two rotations of the wrist represented as example. (C) ILDL obtained in a particular configuration. (D) the final planform represented in the fluid solver. (E) Simulated bird and its near wake.

This approach allows to observe the 3D wake of a bird, from its shedding to its deformations in the far wake. By simulating the flight of another bird in the wake, we evaluate the influence of its relative position and phase shift on its energy savings. Finally, the observation of the evolution of the vortices downstream from the follower shows the vortex interactions between the wakes shed by both birds.

2 Methodology

Our simulation framework is based on the modeling chain presented thoroughly in [6]. It consists of a bio-mechanical model of a bird skeleton coupled to a vortex particle-mesh-based flow solver with immersed lifting and dragging lines (ILDL) [7].

The motion of the bird and its wings are computed using the bio-mechanical model; the resulting planform is then generated in order to extract the ILDL, on which the aerodynamic forces are computed. These forces are then applied to the feathers of the bio-mechanical model, which computes the required moments to actuate the skeleton.

Flight controllers are implemented to stabilize the freely flying bird. Through small variations in its wing kinematics, the simulated bird generates aerodynamic forces and moments that ensure that it follows a prescribed trajectory and compensates for parasitic forces (e.g. induced by the wake of another bird).

3 Results

A snapshot of the bird wake modeled with our framework is represented in Fig. 2. Near the bird, it is shed as a vortex sheet with a circulation that varies along the span and through time. The sheet rolls up into distinct vortices. As these vortices are not straight and display a varying circulation, their self-induced velocities create large deformations as the wake is advected downstream from the bird.

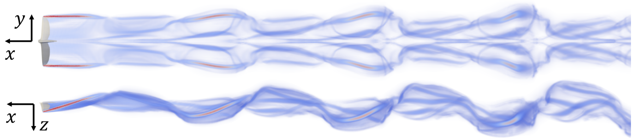

Figure 2: Wake of a freely flying bird: top view (top) and side view (bottom)

The vortices in the bird wake induce upward velocities outboard of the vortex system. These can be exploited by other birds to reduce the energy cost of their flight. There is evidence in nature that birds try to follow the tip vortex with their own wingtip while flying in formation [2]. However, as the wake deforms downstream from the leader, this may require that the follower moves its wings with sub-optimal kinematics, which would increase its energy expense.

To quantify the energy savings for a bird flying in the wake of another, we expand our framework to simulate the flight of a formation of two. We conducted these simulations for varying relative positions of the follower in three dimensions, and for varying phase shift between both birds. We notice that the follower bird saves the maximal amount of power at a distance of approximately one span downstream and laterally from the leader, and approximately in the median plane of the wake. For it to achieve these savings, it needs to flap its wings with a phase shift such that it follows the tip vortices of the leader with its own wingtips.

We observe the interplay between the position of the follower, its phase shift, and its energy savings. Using the adequate phase shift, energy savings only decay slowly with the streamwise position. Vertical departure from the optimal position can be compensated with variations in phase to mitigate the increase in flight power. Regarding the spanwise position of the follower, maximal savings are achieved with a slight overlap of its wings with the wake. The benefit decays as the bird moves away from the wake, but it becomes less sensitive to the phase and vertical position.

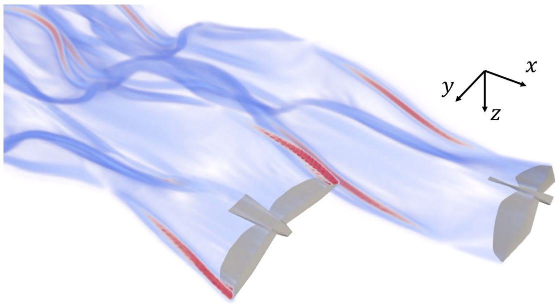

Figure 3: Two birds in formation flight: vortical structures

Finally, we observe the vortical interactions between the wakes of the birds downstream from the leader, as represented in Fig. 3.

4 Conclusions

In this abstract, we have presented a computational framework that can capture, in a unique and quite exhaustive fashion, the phenomenological chain of bird flight, from the social interactions, through biomechanics, to the flow-mediated interactions.

We have discussed the the role of fluid dynamics in the self-organisation of birds into formations, and the quantification of the benefits for various leader-follower offsets; the framework is now exploited to shed light on the flight control strategies and interactions (social or biological) that are necessary to reproduce the emergence and dynamic nature of such formation patterns.

References

[1] SESAR JU GEESE project. `https://www.sesarju.eu/projects/geese`. Accessed: 2023-11-03.

[2] Steven J. Portugal, Tatjana Y. Hubel, Johannes Fritz, Stefanie Heese, Daniela Trobe, Bernhard Voelkl, Stephen Hailes, Alan M. Wilson, and James R. Usherwood. Upwash exploitation and downwash avoidance by flap phasing in ibis formation flight. *Nature*, 505(7483):399–402, 01 2014.

[3] Bernhard Voelkl, Steven J. Portugal, Markus Unsöld, James R. Usherwood, Alan M. Wilson, and Johannes Fritz. Matching times of leading and following suggest cooperation through direct reciprocity during V-formation flight in ibis. *Proceedings of the National Academy of Sciences*, 112(7):2115–2120, 2015.

[4] L Christoffer Johansson, Masateru Maeda, Per Henningsson, and Anders Hedenström. Mechanical power curve measured in the wake of pied flycatchers indicates modulation of parasite power across flight speeds. *Journal of The Royal Society Interface*, 15(138):20170814, 2018.

[5] Linus Hedh, Christopher G. Guglielmo, L. Christoffer Johansson, Jessica E. Deakin, Christian C. Voigt, and Anders Hedenström. Measuring power input, power output and energy conversion efficiency in un-instrumented flying birds. *The Journal of Experimental Biology*, 223(18):jeb223545, 2020.

[6] Victor Colognesi, Renaud Ronsse, and Philippe Chatelain. Model coupling biomechanics and fluid dynamics for the simulation of controlled flapping flight. *Bioinspiration & Biomimetics*, 16(2):026023, feb 2021.

[7] Denis-Gabriel Caprace, Grégoire Winckelmans, and Philippe Chatelain. An immersed lifting and dragging line model for the vortex particle-mesh method. *Theoretical and Computational Fluid Dynamics*, 34(1):21–48, 2020.