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Aerodynamics of hovering wings with the overset method and surrogate models

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Million years of evolution have shaped and optimized the outstanding flight capabilities of natural flyers. Birds and insects stably hover, catch preys in the blink of an eye and glide for hours continuously morphing their wings as a function of the flight requirements. Their unique features have inspired engineers throughout the centuries. Leonardo Da Vinci's flight machine and the Wright brothers' airplane are two remarkable examples of bird biomimicry. More recently, Flapping Wings Micro Air Vehicles (FWMAVs) take inspiration from insects and hummingbirds to reproduce their high maneuverability, stable hovering and good adaptability to various wind conditions. Such hand-sized devices could outperform quadcopter drones in demanding operations such as rescue, surveillance or even leisure activities.

Nevertheless, state-of-the-art FWMAVs are still far from extracting nature's full potential. Major challenges arise from the complex flapping aerodynamics, characterized by highly unsteady flows at low-Reynolds numbers. The main tools to model the flow physics are the surrogate models, experiments and Computational Fluid Dynamics simulations (CFD). They represent a different trade-off between accuracy and computation time that makes them separately not efficient to optimize flapping strategies. This forms a major drawback in the development of FWMAVs.

The present research proposes a comprehensive numerical environment to teach a bio-inspired drone how to learn and continuously optimize its flapping strategies. The framework combines three disciplines (figure 1). First, a surrogate model cheaply estimates the aerodynamic performance of given flapping motions. The estimation continuously feeds an optimizer relying on reinforcement learning. Then, the optimizer learns, by trial and error and experience, the best flapping strategies driven by various objectives and constraints in different conditions. At last, the optimization loop sparsely calls high fidelity CFD simulations for two purposes. It verifies and analyzes the flow details of few optimized strategies as well as it improves the surrogate models thanks to data regression techniques. In this frame, the present work focuses on a prescribed wing motion and the analyze of its aerodynamic performance thanks to a quasi-steady model and overset CFD simulations.

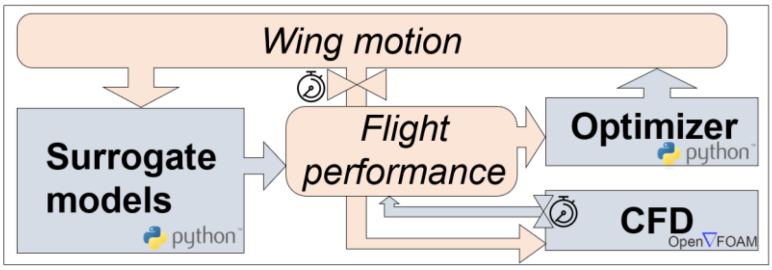

Figure 1: Simulation methodology

Depending on the flight regime and their morphology, birds and insects execute various flapping strategies. Typically, the hovering regime includes flapping, pitching, twisting and out-of-plane motion. A rough approximation of hovering considers only two degrees of freedom (figure 2). The wing flaps in the stroke plane with a cyclic azimuthal rotation $\dot{\phi}$ along $\hat{z}$ and centered around C. For each period T, a dorsal to ventral motion (the downstroke phase) leads the ventral to dorsal upstroke phase. With the same frequency and duty cycle, the wing also varies its pitch angle α.

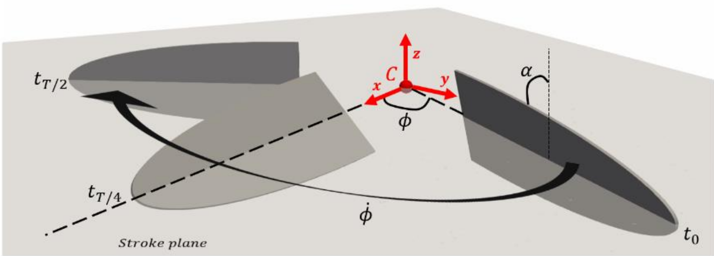

Figure 2: Downstroke of a semi-elliptical wing

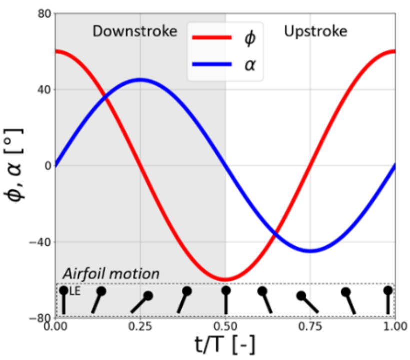

Figure 3: Angular motions of the wing

The authors of [1] have analyzed this test case with a thin, rigid, semi-elliptical wing characterized by the following dimensionless numbers and two harmonic functions (figure 3).

Reynolds number Re	*Rosby number Ro*	*Aspect ratio AR*
4000	2.97	3.25

With the definition of a wing geometry and motion, surrogate models can evaluate the aerodynamic forces, moments and powers. Compared to CFD computations, the surrogate models benefit from significant lower prediction times at the expense of less accurate results. This research uses an analytical, quasi-steady model based on fundamental aerodynamic theories, the blade element method and semi-empirical constants. Its derivation originates from Dickinson's work [2] and is described in [1]. In a nutshell, the model decomposes the total aerodynamic forces in three contributions related to the motion type. Firstly, a translational force is directly function of the flapping motion. A high-pitched flapping induces a strong Leading Edge Vortex (LEV) on the wing top surface which delays or even prevents stall. The LEV increases then significantly the lift and drag of hovering flyers. Secondly, the pitching motion generates a rotational force thanks to the additional circulation induced to respect the Kutta-Jukowski condition [3]. Finally, the added mass contribution models the additional non-circulatory force needed to put the surrounding air in motion during flapping and pitching. A similar surrogate model had already been validated thanks to force measurements on a rectangular wing that rotates at low Reynolds numbers in a water-glycerin tank [1]. Unsteady contributions (wake-capture, Wagner effect, etc) or data-based contributions could extend this model. Nevertheless, they increase its complexity and can severely decrease its generality.

CFD simulations offer more accurate predictions of the forces where any bio-inspired flying bodies can experience various aerodynamic environment (gusts, wind, closeness of other bodies, etc). The meshing approach forms one particularity regarding the numerical simulations of flapping wings. OpenFOAM proposes four main techniques [4]: the morphing-remeshing meshes, the sliding meshes, the Immersed Boundary Method (IBM) and the overset method [5]. The latter can handle any complex motion (unlike the deforming mesh and the sliding interface techniques) and can accurately compute fields everywhere, even close to moving walls of complex geometries (unlike the IBM). However, the overset method suffers generally from a higher computation time and requires a tedious setting of its numerical parameters.

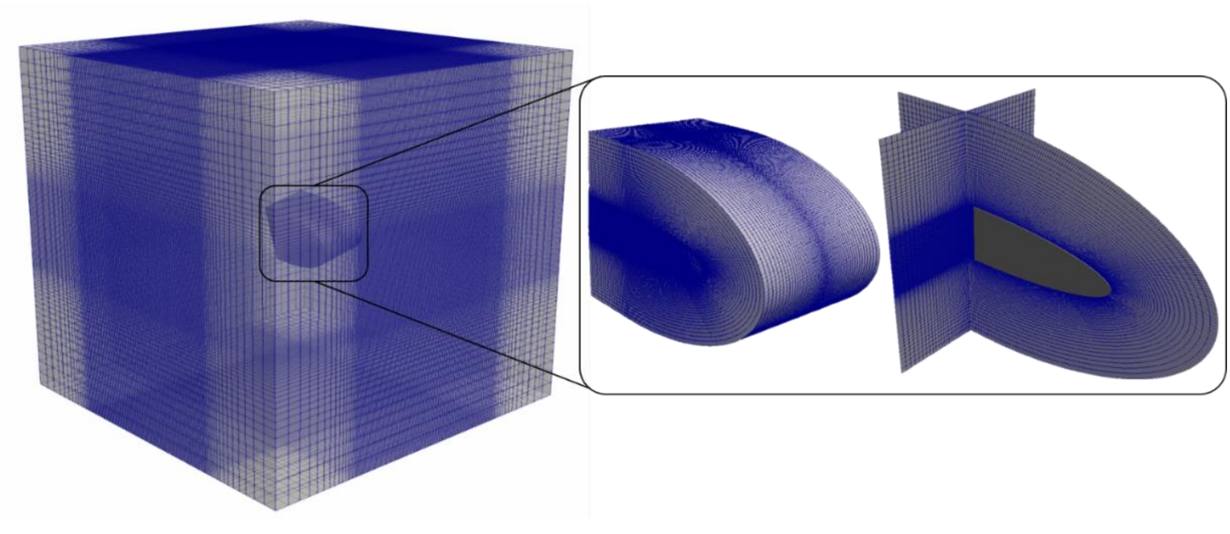

Figure 4: Overset grid for the flapping simulation

Figure 4 shows one typical domain defined for the flapping simulations. A C-grid expands for 2 chords around the semi-elliptical wing and is then nested inside a cubic background grid of 10 times the wing span. The component grid is moving with the wing while the background grid is static. The grids are coupled thanks to the interpolation of flow variables. A role is assigned to each cell, at each time step. Activated cells solve the classical flow equations, holes are inactive cells that lay inside the wing geometry and, interpolated cells receive information from neighbor cells of the other grid system. The accuracy of this procedure is analyzed thanks to 2D test cases shown on figure 5. The first two cases consider a standing flat plate which experiences an incoming flow at velocity U_x. The first case has a uniform grid while the second case employs the described overset approach. Regarding the third case, the flat plate moves in still air from left to right at the same velocity U_x. For the three cases, all the other numerical and physical parameters are identical. The dimensionless drag for $Re =$ 500 is shown on figure 6. After a transitory phase, the three drags fit quantitatively well and two main outcomes are learned. For a well-designed grid with sufficiently small time steps, the diffusion error due to the inter-grid interpolation doesn't affect significantly the drag and the influence of (de)activation of cells during a body motion is also negligible.

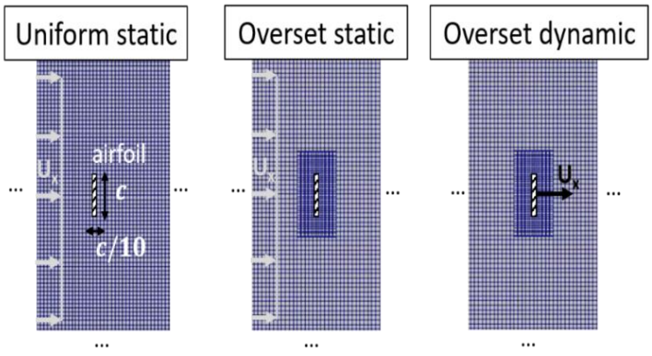

Figure 5: Layout of three 2D test cases

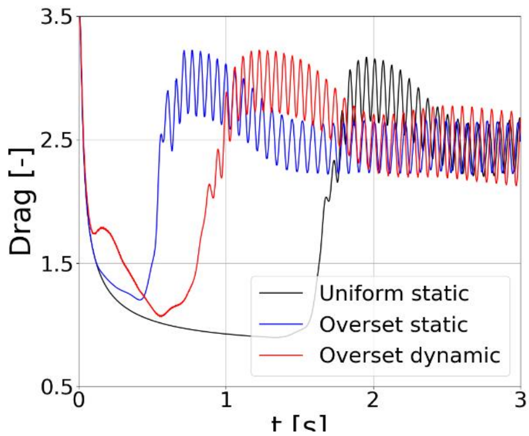

Figure 6: Drag comparison for the 3 simulations

For the baseline simulation of the flapping wing, small cells capture the boundary layer near the wing wall and expand towards the overset interface (figure 4). The background grid keeps the maximum cell size of the component grid and expands it towards the domain boundaries. This reduces interpolation diffusion while keeping a reasonable number of cells (around 3M). Near the wing, the fluid is dragged at very low Reynolds number, laying in the early turbulent regime (but assumed laminar as verified in [1]). The flow is unsteady and solved with the overPimpleDyMFoam of OpenFOAM v2012.

Figure 7 and 8 show good agreement between the surrogate model and the CFD forces for 2 flapping cycles. Both lifts follow a similar sinusoidal motion and have a mean difference below 5 percent. The CFD's lift peaks slightly later than the surrogate model. During the first half of the downstroke, the lift rises while both $|\dot{\phi}|$ and α increases (α peaks at 45°). This motion favors the formation of a strong and stable LEV on the wing top surface supported by a low-pressure bubble. The Q criterion and streamlines confirm this trend on figure 9. $|\dot{\phi}|$ and α follow the opposite tendency during the second quarter. The wing slows down, goes vertical again (α peaks at 0°) and the LEV detaches near the end of the period. The upstroke phase is symmetric to the downstroke such that the lift trace is similar for the two strokes.

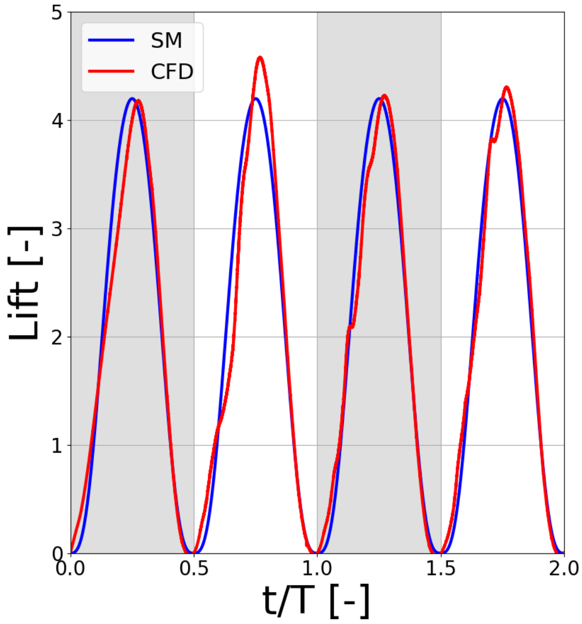

Figure 7: Lift coefficient estimated by the surrogate model (SM) and the CFD simulation (CFD)

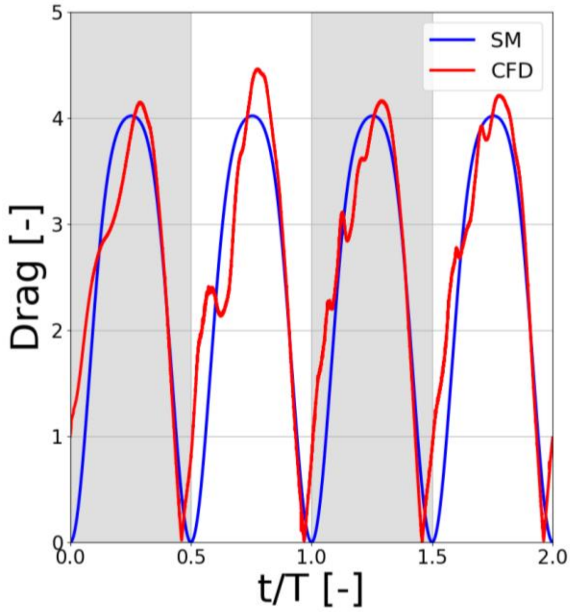

Figure 8: Drag coefficient estimated by the surrogate model (SM) and the CFD simulation (CFD)

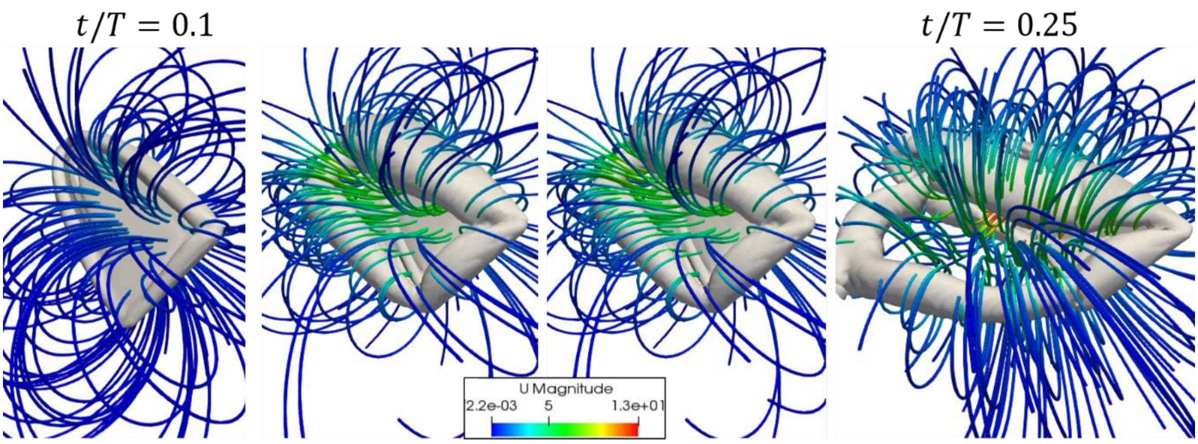

Figure 9: Formation of the LEV during downstroke visualized by the Q-criterion and streamlines

The surrogate model and CFD drag also fit qualitatively well even if the CFD drag oscillates more at the beginning of the strokes. The wing-wake interaction justifies this behavior. At the beginning of a stroke, the wing moves back in the vortices that were shed during the wing flipping at end of the previous stroke (figure 10). Overall, the wing-wake interaction lightly influences the forces since vorticity is progressively shed during the entire second half of the stroke. When the pitch motion is more dynamic, the shed LEV can be used by the wing to significantly enhance lift at the beginning of the strokes.

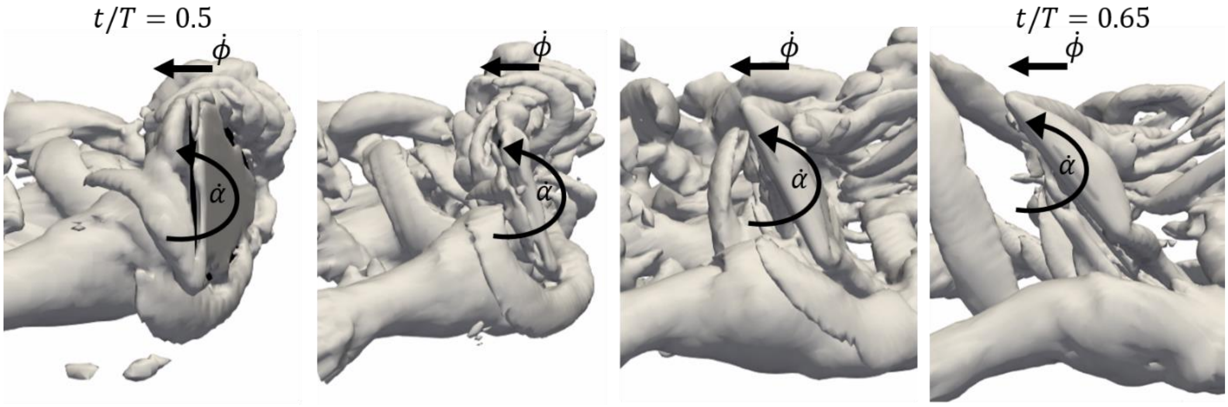

Figure 10: Wing-wake interaction during the early phase of the upstroke visualized by the Q-criterion

For simple harmonic motions executed by standard wing geometries, the surrogate models predict similar aerodynamic performances than laminar, overset, CFD simulations. However, further analysis have shown that the results differ more for dynamic flapping motions that correspond to realistic hovering maneuvers. The strong hypotheses of the surrogate models partially explain this discrepancy. The model is fully analytical, relies on quasi-steady assumptions and few empirical constants. Unsteady terms will then improve the model accuracy and CFD regression will calibrate its empirical constants. This will be carefully undertaken ensuring that the model remains valid for other flight regimes.

Regarding CFD, the fidelity level will also increase thanks to LES modelling. Next, the CFD environment will take into account wing deformation during the flapping motion. Indeed, insects and hummingbirds highly twist their wings to efficiently manipulate the flow structures during hovering [6]**.** The deformable overset method will be implemented in OpenFOAM and will rely on the existing morphing mesh and overset method. This simulation framework, mixing surrogate models and high fidelity simulations, will then be the base of an optimizer that explores efficiently optimal flapping strategies in different conditions.

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