ME EN 634 Project

Quasi-steady Aerodynamics Solver for a High-fidelity Controls Framework

Eduardo J. Alvarez*

Brigham Young University, Provo, Utah, 84602

1 Motivation

Technology convergence in the past ten years has opened a new design space in electric aircraft, enabling the use of distributed propulsion and electric vertical takeoff and landing (eVTOL) for urban air mobility. However, this unconventional aircraft configuration poses technical challenges that still remain to be solved. A strong noise signature and a complicated transition maneuver are examples of the challenges encountered in eVTOL aircraft, both stemming in some degree from the aerodynamic interactions between rotors and lifting surfaces. Furthermore, these interactions are common across quadrotor, tilt-rotor, tilt-wing, and distributed propulsion concepts making use of multiple rotors. As an example of eVTOL configuration, Fig. 1 shows the Vahana multirotor tilt-wing aircraft during vertical takeoff, prior to transitioning into wing-borne forward flight.

The use of multiple rotors operating in close proximity introduces strong aerodynamic interactions that are not captured through engineering models conventionally used in a controls framework. In previous work by the author, a high-fidelity unsteady aerodynamics simulation framework called FLOWUnsteady* was developed with the intent of predicting the performance of eVTOL vehicles during transition. The current version of FLOWUnsteady implements the definition of maneuvers prescribing the kinematics of the vehicle. In order to make this code fully functional for a controls framework, the kinematics engine needs to be extended into a dynamics engine, coupling the trajectory of the vehicle with the aerodynamic forces. Furthermore, in a laptop computer, the high-fidelity unsteady solver takes up to six hours of computation to resolve a typical maneuver, which limits the feasible extend of the analysis. In order to speed up the analysis and code development process, a faster solver needs to be implemented into the framework. Thus, in this project we have

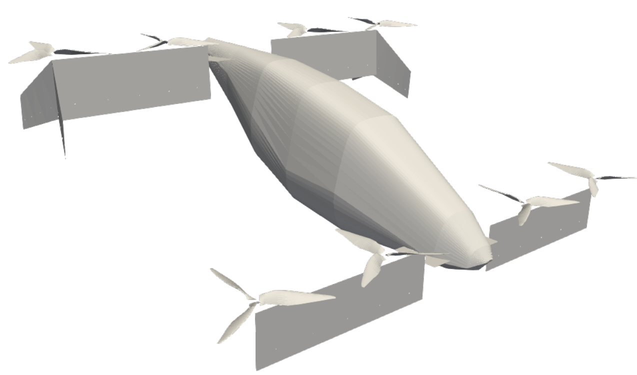

Figure 1: A^3 Vahana eVTOL aircraft modeled through FLOWUnsteady.

*Doctoral Candidate, Department of Mechanical Engineering, ealvarez@byu.edu.

*See https://github.com/byuflowlab/FLOWUnsteady and https://edoalvarezr.github.io/projects/01-aerodynamics.html

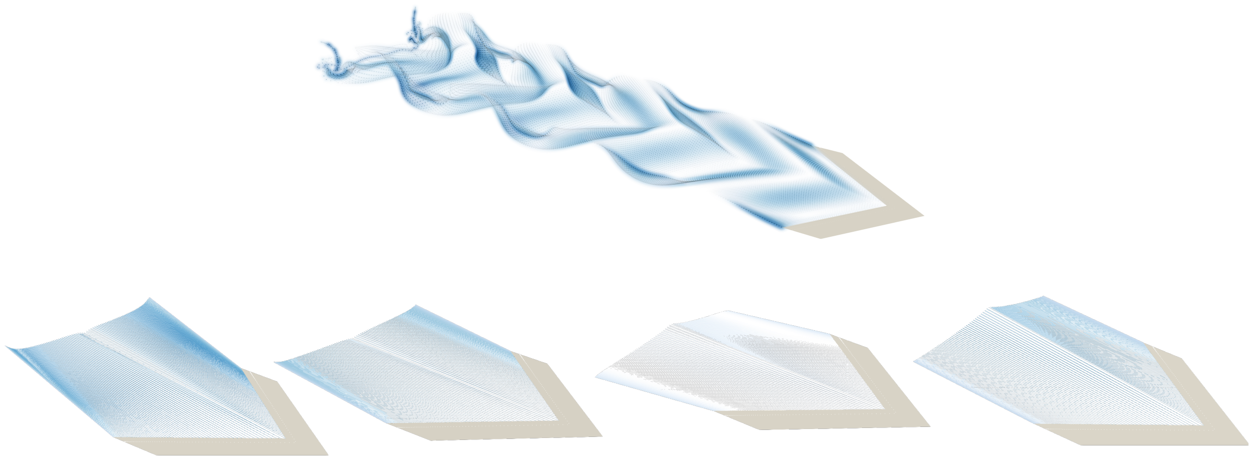

Figure 2: Heaving wing simulation with unsteady solver (top) and quasi-steady solver (bottom).

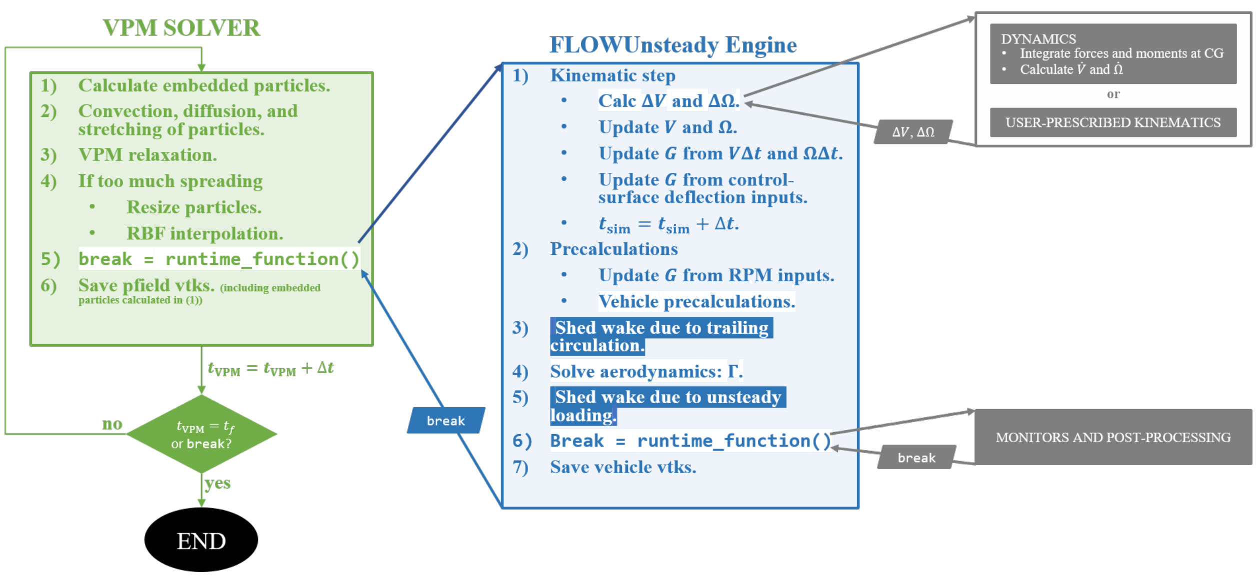

Figure 3: Flowchart of FLOWUnsteady framework.

developed a quasi-steady aerodynamics solver that speeds up the analysis process, while capturing relevant rotor-rotor and rotor-wing interactions across a prescribed kinematic maneuver. This constitutes one step forward in the development of a high-fidelity controls framework of eVTOL vehicles.

2 Methodology

Quasi-steady physical models are based in the assumption that information travels at an infinite speed across a computational domain. In the context of aerodynamics, a quasi-steady solver assumes that perturbations at the source of a wake-shedding surface immediately affect the entirety of the wake. For example, Fig. 2 shows the wake of a wing in heaving motion resolved with the unsteady solver as the wake evolves in time, contrasted to the wake of the quasi-steady solver, which is a rigid wake pointing opposite to the direction of relative motion of the wing at every instant. The quasi-steady solver implemented in our project models all lifting surfaces as a vortex-lattice system inducing velocity according to their circulation. Wings are solved with the vortex lattice method (VLM) while shedding a rigid semi-infinite wake. Rotors are solved through blade-element momentum theory (BEMT), without attempting to model the effects of wake interactions. FLOWUnsteady uses the three-dimensional geometry of the vehicle as spatial state variables (referred as G), along with the velocity of the vehicle V and angular velocity Ω. The time-dependent inputs to the framework are control-surface deflections and rotor RPMs, along with the prescribed kinematics. The workflow of the framework is summarized in Fig. 3. The quasi-steady solver is implemented in the fourth step of the FLOWUnsteady engine, as shown in Fig. 4.

3 Results

In order to test the interactional aerodynamics predicted by the quasi-steady solver, we defined a test case with a swept-back wing with two propellers as shown Fig. 5. The wing loading distribution (left plot) shows negligible fluctuations due to rotor-on-wing interactions, as well as the lift coefficient C_L (right plot). This is due to only accounting for the influence of the rotors through their blade-induced velocity, while neglecting the effects of the wake. In contrast, the rotors show significant fluctuations in thrust, which are due to the effects of the velocity induced by the wing. This evidences that the quasi-steady solver successfully captures wing-on-rotor interactions, while

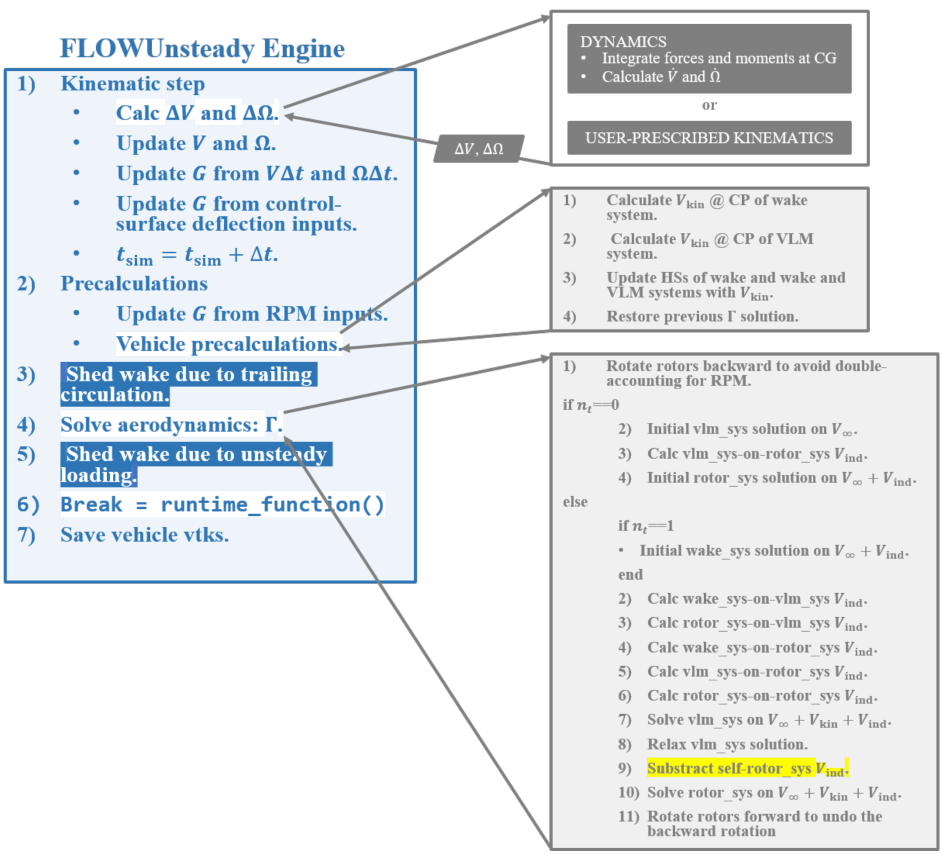

Figure 4: Flowchart of FLOWUnsteady framework.

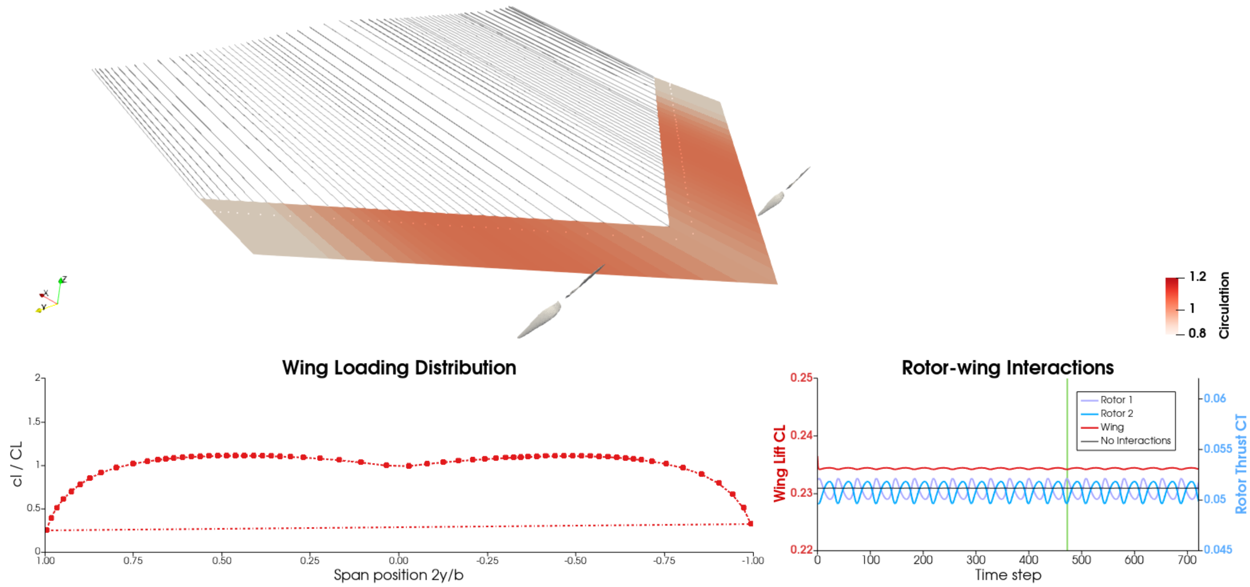

Figure 5: Simulation of swept-back wing with two propellers. Fluctuation of the rotor thrust coefficients evidences that the quasi-steady solver successfully captures wing-on-rotor interactions.

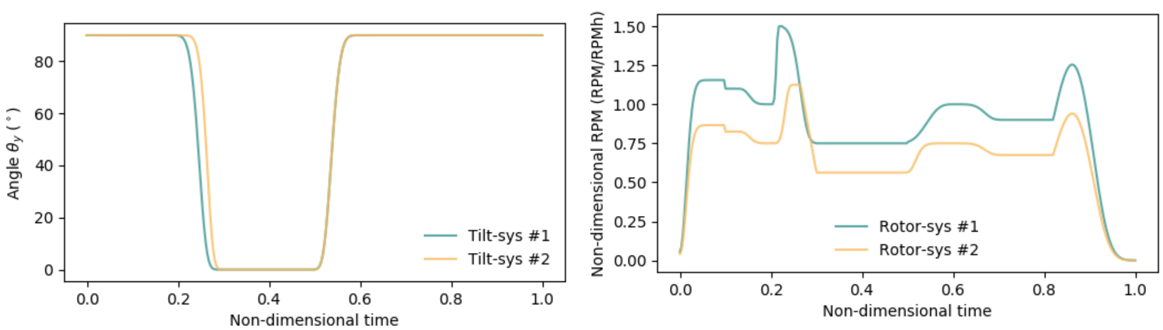

Figure 6: Control inputs for Vahana VTOL simulation.

capturing only minimal rotor-on-wing interactions.

Next, the quasi-steady solver was tested on the Vahana eVTOL vehicle shown in Fig. 1. The vehicle has two tilting wings used as control surfaces, and the rotors in each wing are controlled as one system, having two rotor systems (one for each wing). The control inputs used in the simulation are shown in Fig. 6, with the vehicle taking off in $0 < t < 0.2$, transitioning into forward flight in $0.2 < t < 0.3$, cruising in $0.3 < t < 0.6$, and landing in $0.6 < t < 1.0$. The kinematics prescribed for this maneuver are shown in Fig. 7, with the dashed vertical lines indicating the different VTOL stages of the maneuver. A time-lapse of the Vahana vehicle under this maneuver is shown in Fig. 8, portraying the results of such prescribed kinematics and control inputs. In the current state of the test, we have only tested the lifting surfaces, and inclusion of rotors is left for future work. The resulting lift produced by each wing throughout the maneuver is shown in Fig. 9, evidencing the ability of the quasi-steady solver to resolve the VTOL maneuver.

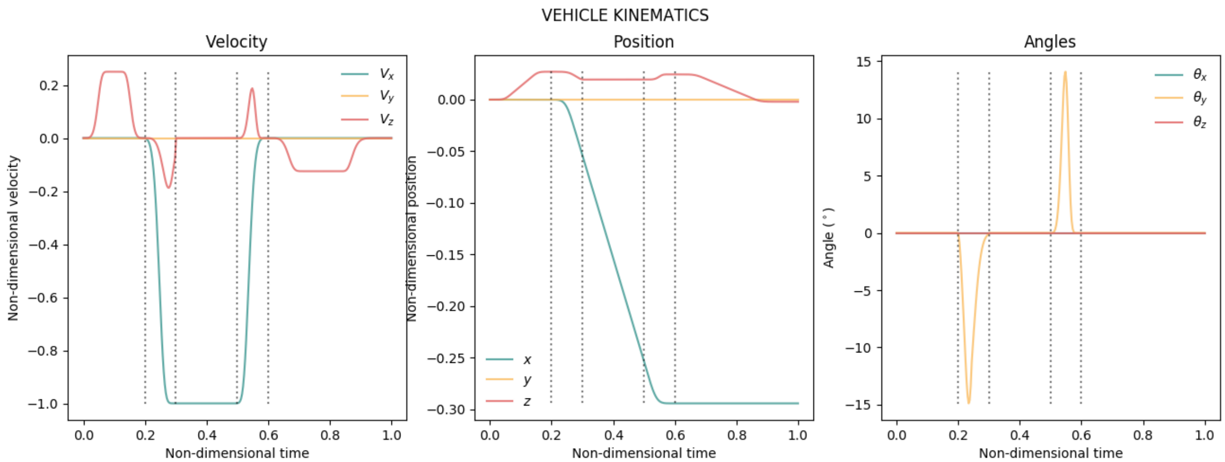

Figure 7: Prescribed kinematics of the Vahana VTOL maneuver.

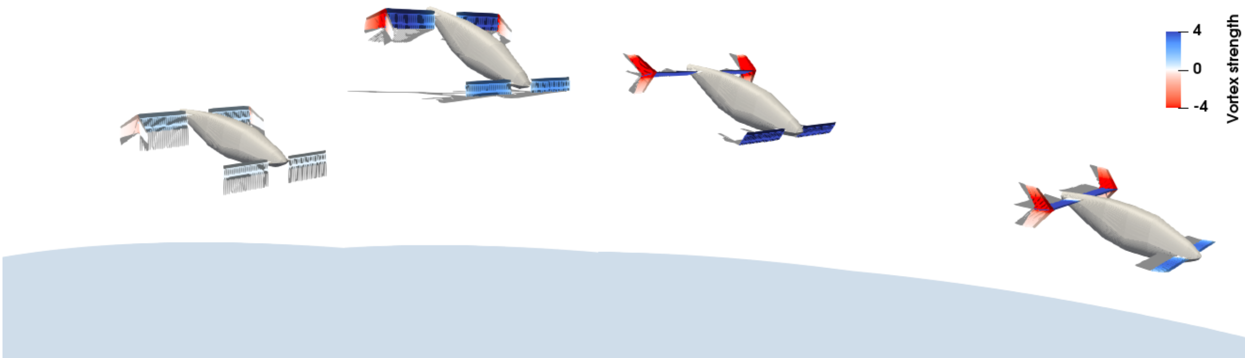

Figure 8: Time-lapse of Vahana VTOL simulation.

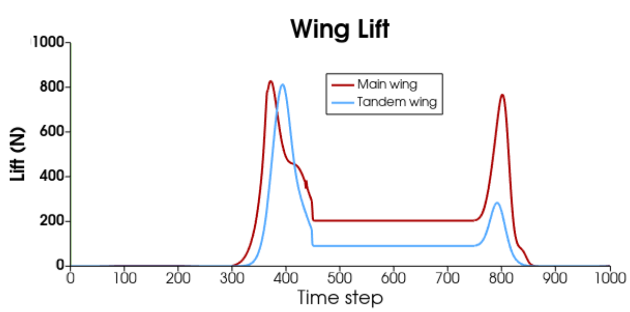

Figure 9: Lift produced by each wing through the VTOL maneuver.