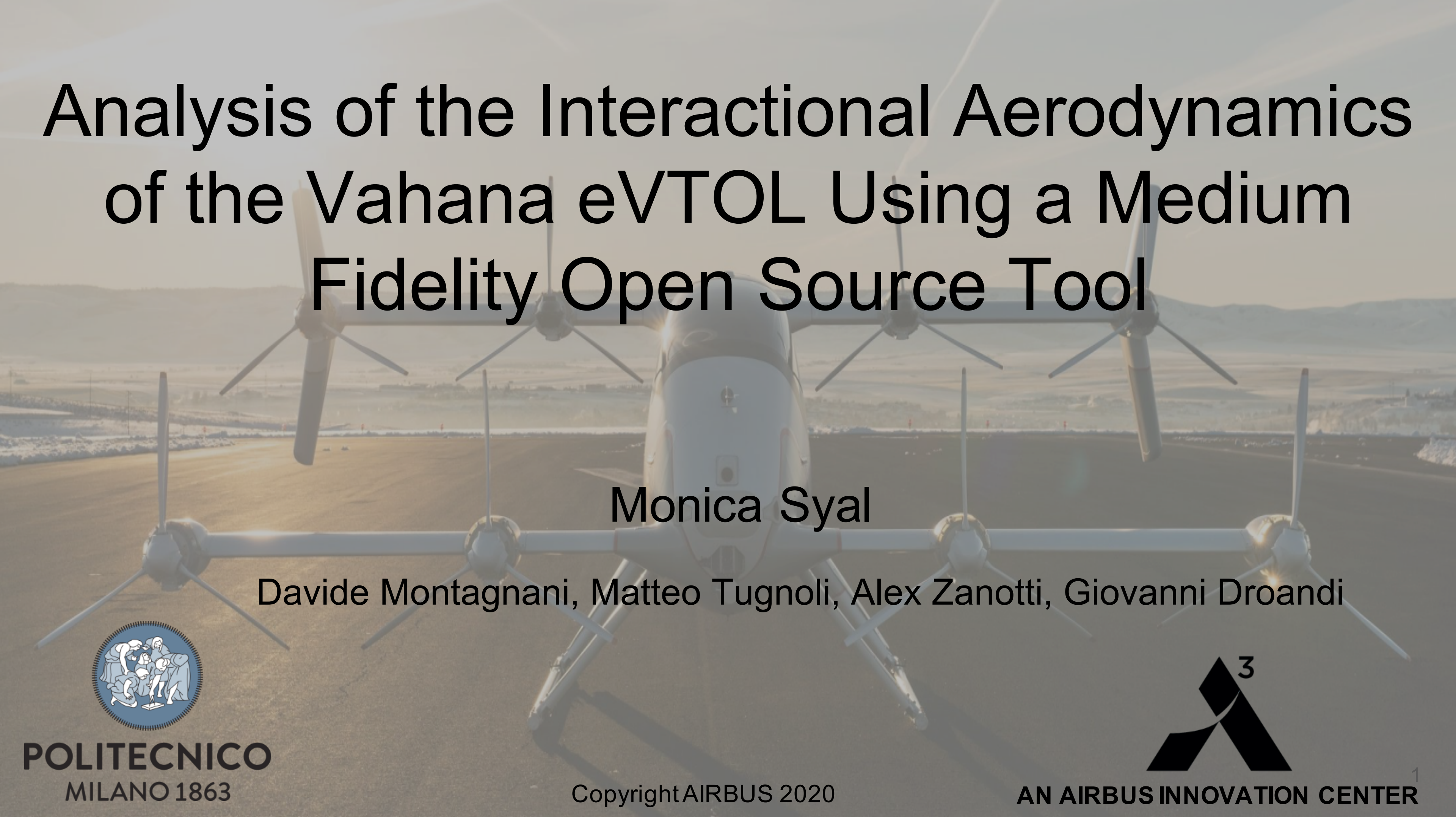

Analysis of the Interactional Aerodynamics of the Vahana eVTOL Using a Medium Fidelity Open Source Tool

Monica Syal

Davide Montagnani, Matteo Tugnoli, Alex Zanotti, Giovanni Droandi

POLITECNICO
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AN AIRBUS INNOVATION CENTER

Contributors

Davide Montagnani	*Post Doc Researcher*
Matteo Tugnoli	*Post Doc Researcher*
Alex Zanotti	*Assistant Professor*

POLITECNICO
MILANO 1863
DEPARTMENT OF AEROSPACE SCIENCE AND ENGINEERING

Monica Syal	*Senior Aerodynamics Engineer*
Giovanni Droandi	*Former Lead Engineer*

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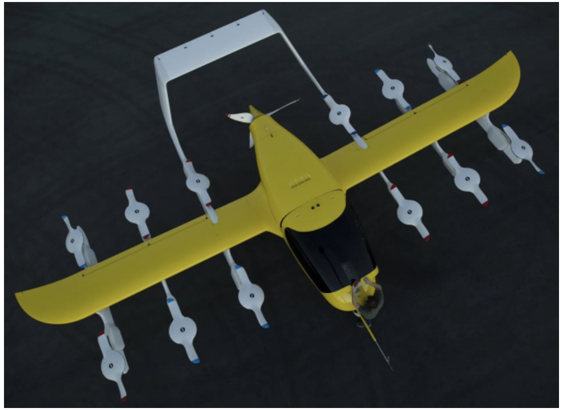
- Motivation
- Methods and Implementation
- Vahana Tests and Analysis
- Conclusions and Perspectives

Motivation

Recent interest in unconventional configurations for Urban Air Mobility (UAM)



Vahana, A^3 by Airbus: Alpha Demonstrator

- Tandem tiltwing
- Eight variable pitch fans
- Eight variable speed motors
- All-electric
- Self-piloted

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Vahana, A³ by Airbus: Alpha Demonstrator

- Tandem tiltwing
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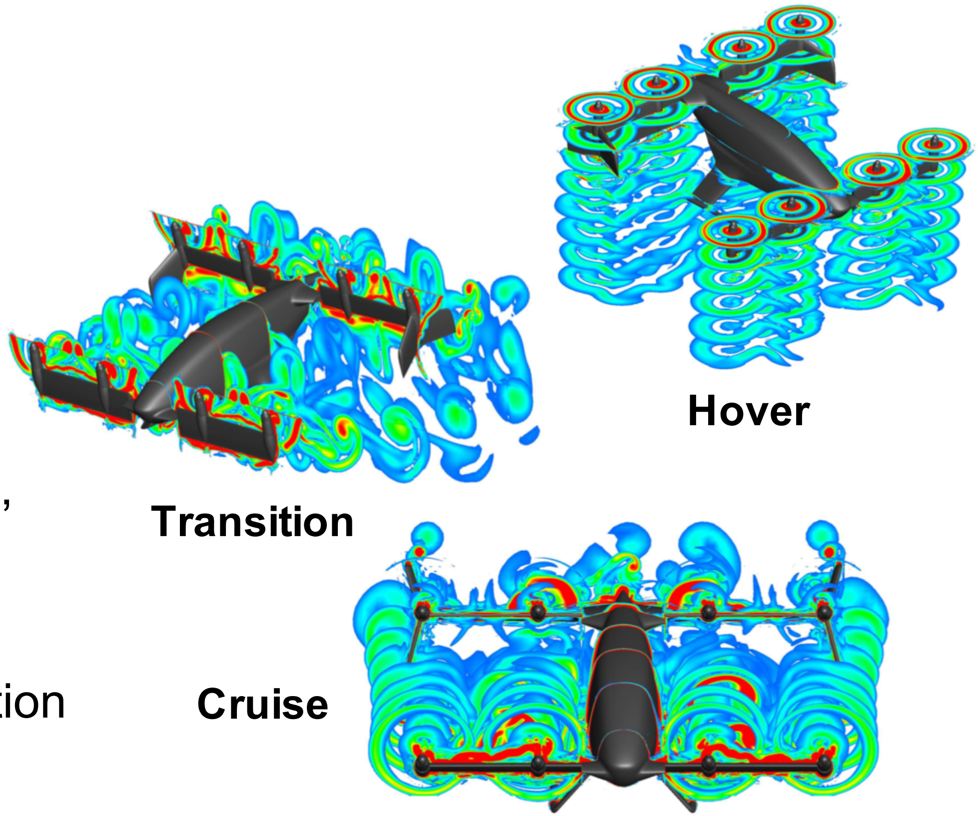
- Eight variable speed motors
- All-electric
- Self-piloted

Challenges of eVTOL Aerodynamic Modeling

- Strong aerodynamic interactions
- Multiple rotors, wings, bluff bodies
- Unsteadiness, stall, flow separation
- Large number of simulations:
  - Preliminary design
  - Detailed design: structure sizing, performance, control system design
  - Different flight conditions: transition between hover and cruise



Presented at AHS 2018

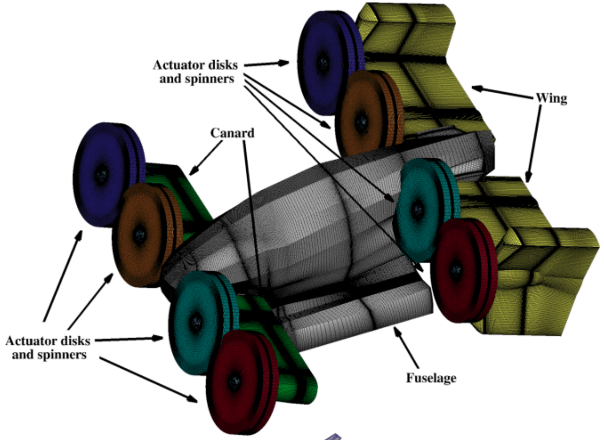
Aerodynamics Simulation Tools for eVTOLs

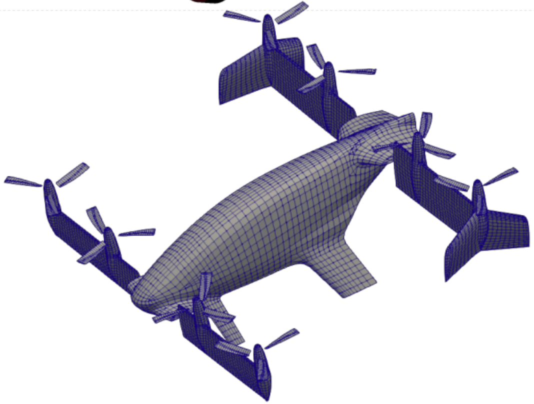
CFD computations:

+ high-fidelity
– computationally expensive
– overset grid system (Chimera) for moving surfaces

Low/Mid-fidelity tools:

+ computationally fast and cheap
– usually tailored for specific aircraft or rotorcraft application
– lack of robustness





A3 - Polimi Collaboration

Lesson learned:

- lack of **flexibility** for the new configurations
- lack of robustness of vortex filament-wake for **interactional aerodynamics**

A3 - Polimi Collaboration

Lesson learned:

- lack of **flexibility** for the new configurations
- lack of robustness of vortex filament-wake for **interactional aerodynamics**

Collaboration between A^3 and Politecnico di Milano:

- **reliable and robust** in simulating body-wake aerodynamic interactions
- **flexible** for studying any vehicle configuration
- **fast** (workstation level, not cluster level)
- **open-source** for community to use

DUST: Mid-Fidelity Aerodynamics Modeling Tool

- Written in Fortran: OO paradigms of the latest standards
- Flexibility in the definition of the model/case different aerodynamic models for the components (SP, VL, LL), hierarchical definition of their motion.
- Grid-free solver surface aerodynamic elements for the body, panel/particle wake model
- Vortex particle wake: robustness, especially for interactional aerodynamics
- Optimized for speed FMM acceleration and OMP parallelization
- Webpage: https://www.dust-project.org/
- Code: https://gitlab.com/dust_group/dust

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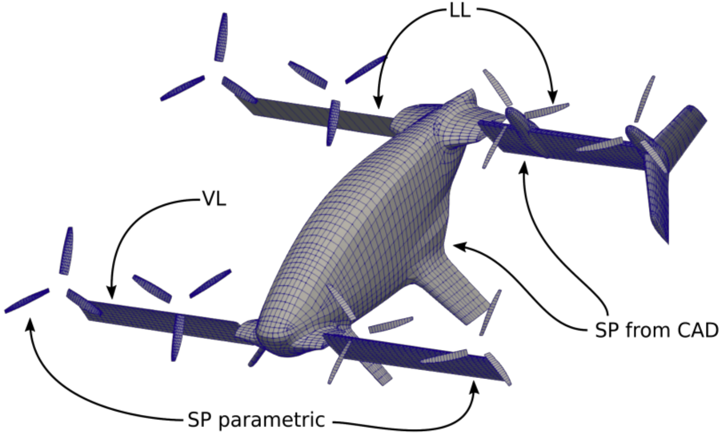
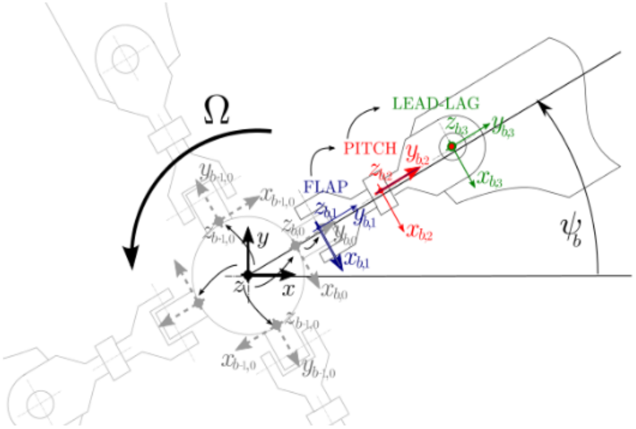
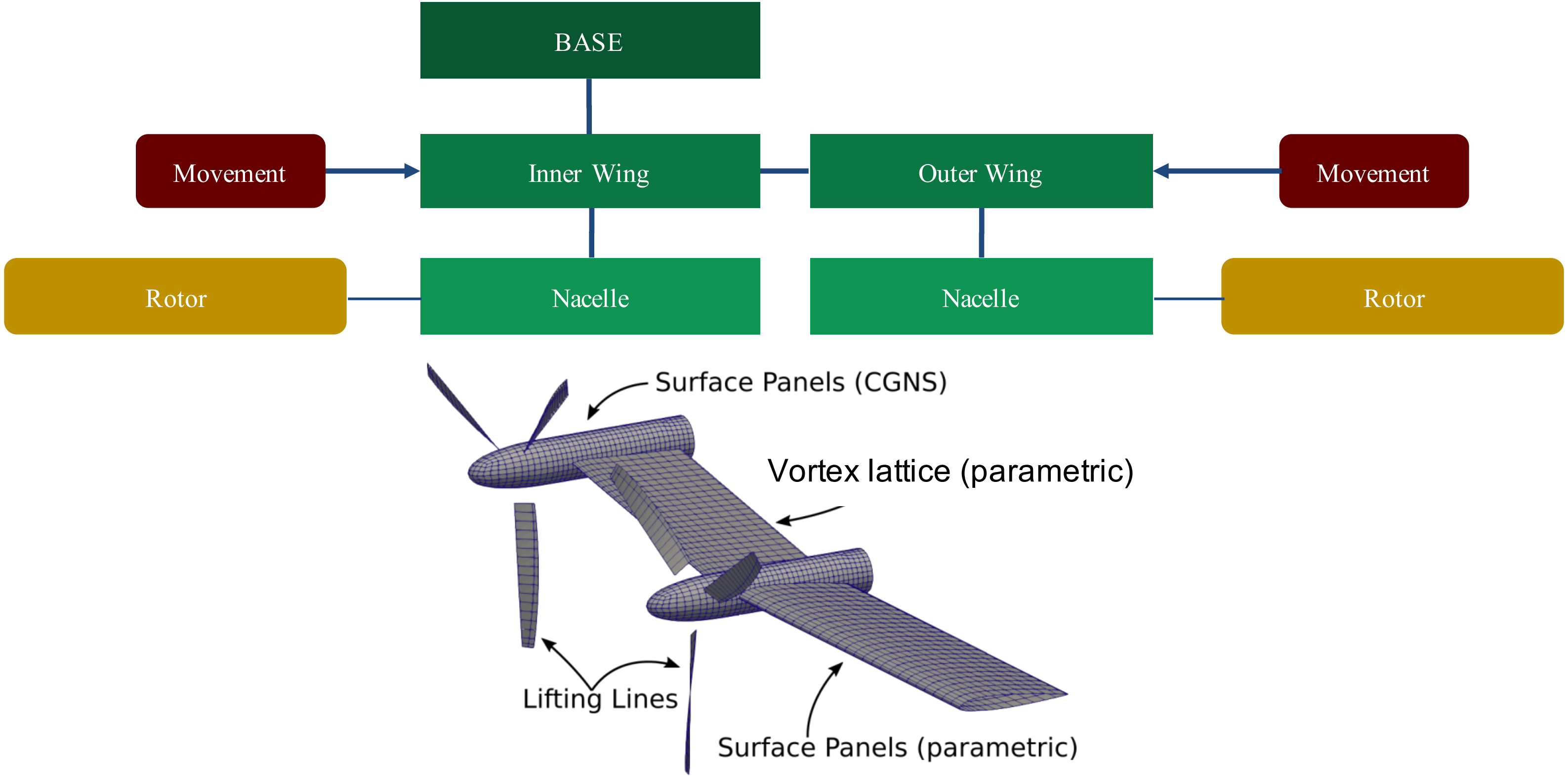
Model Generation

- Model is composed of components
- Geometry: Flexible input - CAD or parametric generation
- Different levels of fidelity of the models:
  - Surface panels (SP): for thick bodies
  - Vortex lattices (VL): for flat surfaces
  - Lifting lines (LL): for slender lifting surfaces, using lookup tables
- Flexible placing: hierarchical moving reference frames

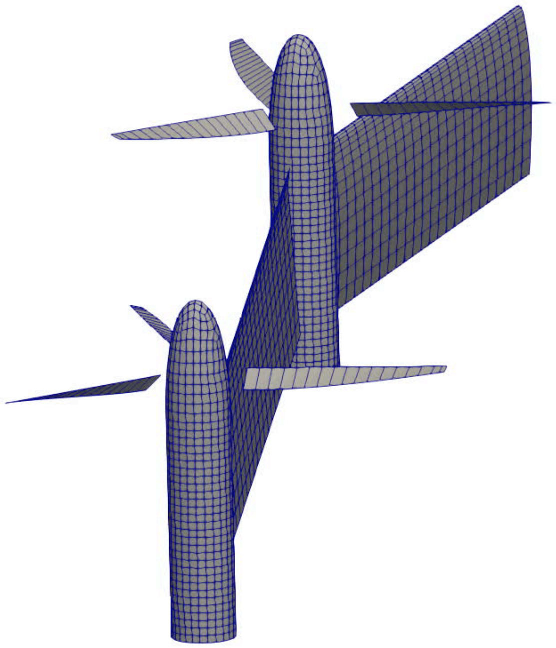




Model Generation - Example

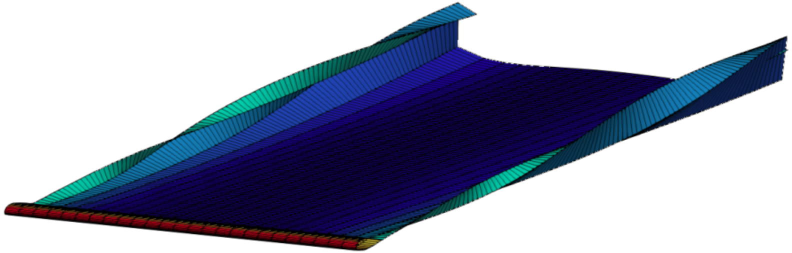


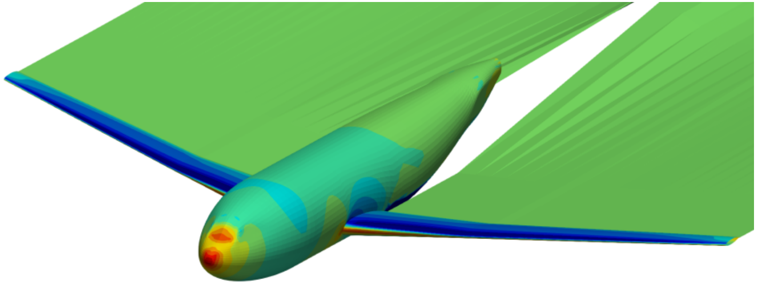
Model Generation - Example



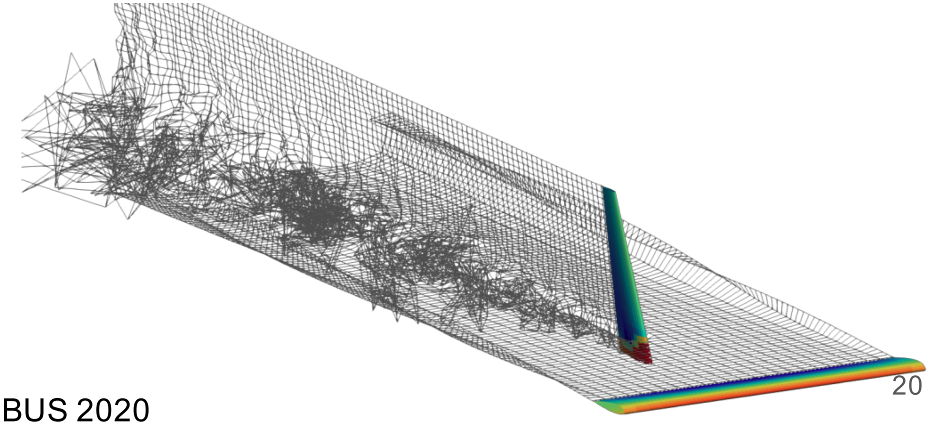
Wake - Panels

- Panel wake, rigid or free: cheap, effective in case of classical configurations



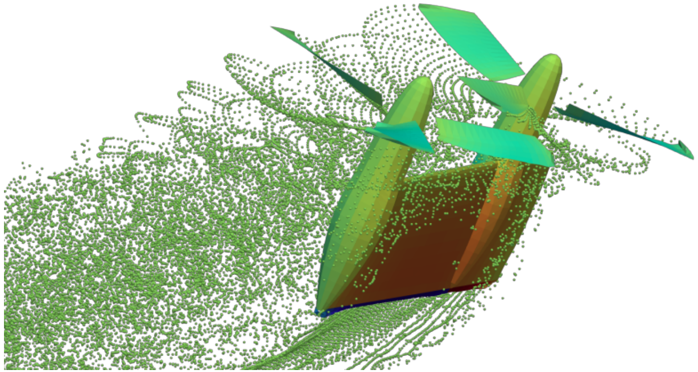


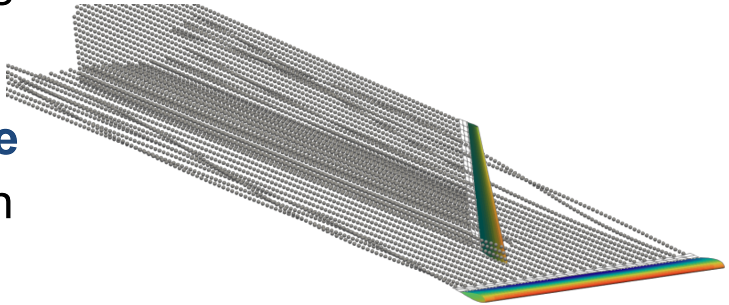
However it might lead to instabilities when wakes interact with solid bodies or other wakes



Wake - Vortex Particles Method

- Lagrangian grid-free method to solve the vorticity equation and describe the evolution of the free vorticity
- Panels are transformed into particles in a mixed panel/particle model of the free vorticity
- Dramatic reduction of numerical instabilities when wakes interact with bodies or other wakes
- Accelerated with **Cartesian fast multipole** algorithm (linear cost of computation with number of particles)



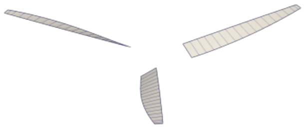


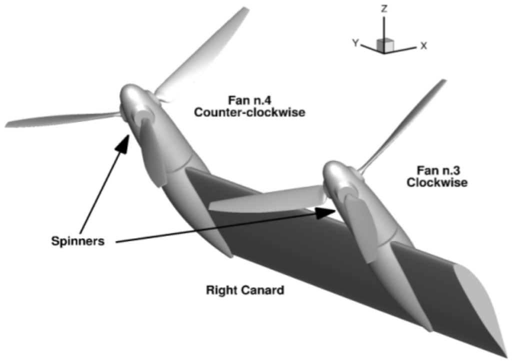
Contents

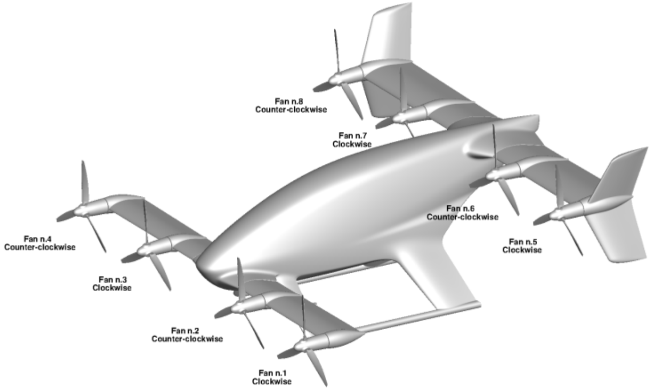
Configurations Tested

From sub-components to the full vehicle:

- **Isolated fan:**
    - Hover and forward flight
    - Compared with experiments and CFD
- **Canard with two fans:**
    - Transition flight
    - Compared with CFD
- **Complete Vahana vehicle:**
    - Vertical and forward flight
    - Compared with flight data and CFD





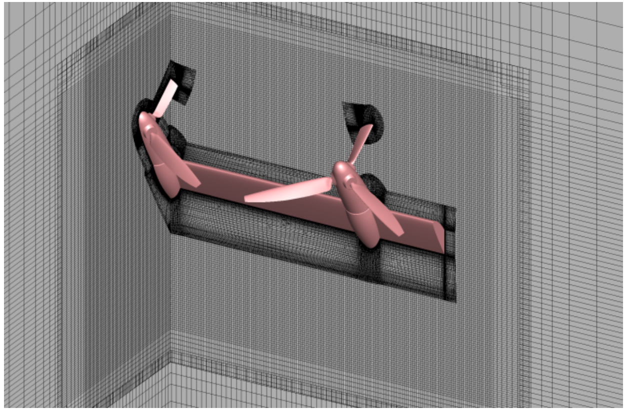


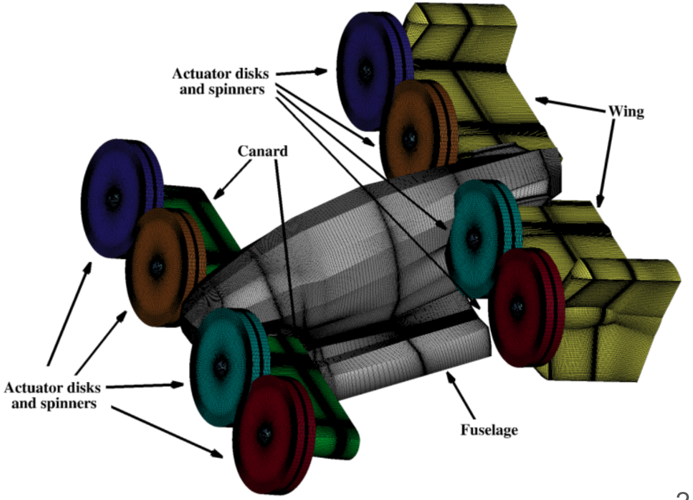
CFD Comparisons

CFD comparisons with ROSITA (ROtorcraft Software ITAly)

Finite volume compressible RANS, chimera grid

- Full rotating fan
- Canard with full rotating fan
- Full vehicle with actuator disks (Droandi et al. 2018)



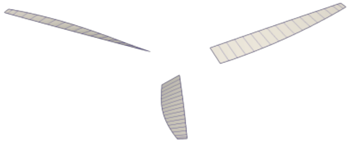


Isolated Fan Testing

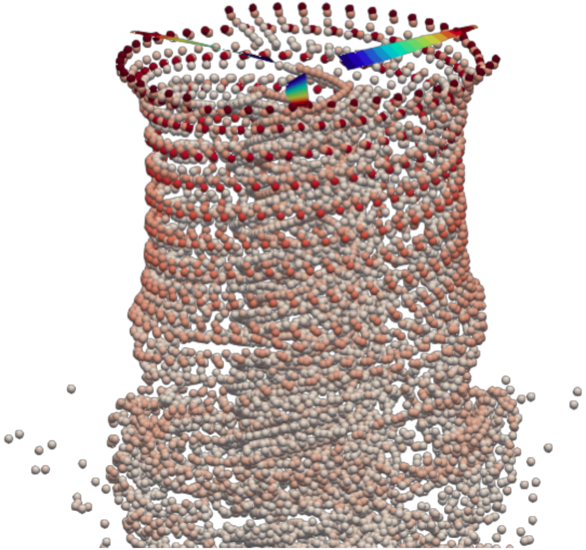
- Vahana fan: 3-bladed, 0.75 m radius, variable pitch, and driven by electric motor
- **Static testing in hover:**
  - Loads measured by 6-component load cell
  - Performance measured at a range of collective and RPM settings
- **Dynamic testing in edgewise flight:**
  - Designed truck test stand
  - Tests conducted at Pendleton UAS range
  - Performance measured at different advance ratios and fan tilt angles

Isolated Fan in Hover

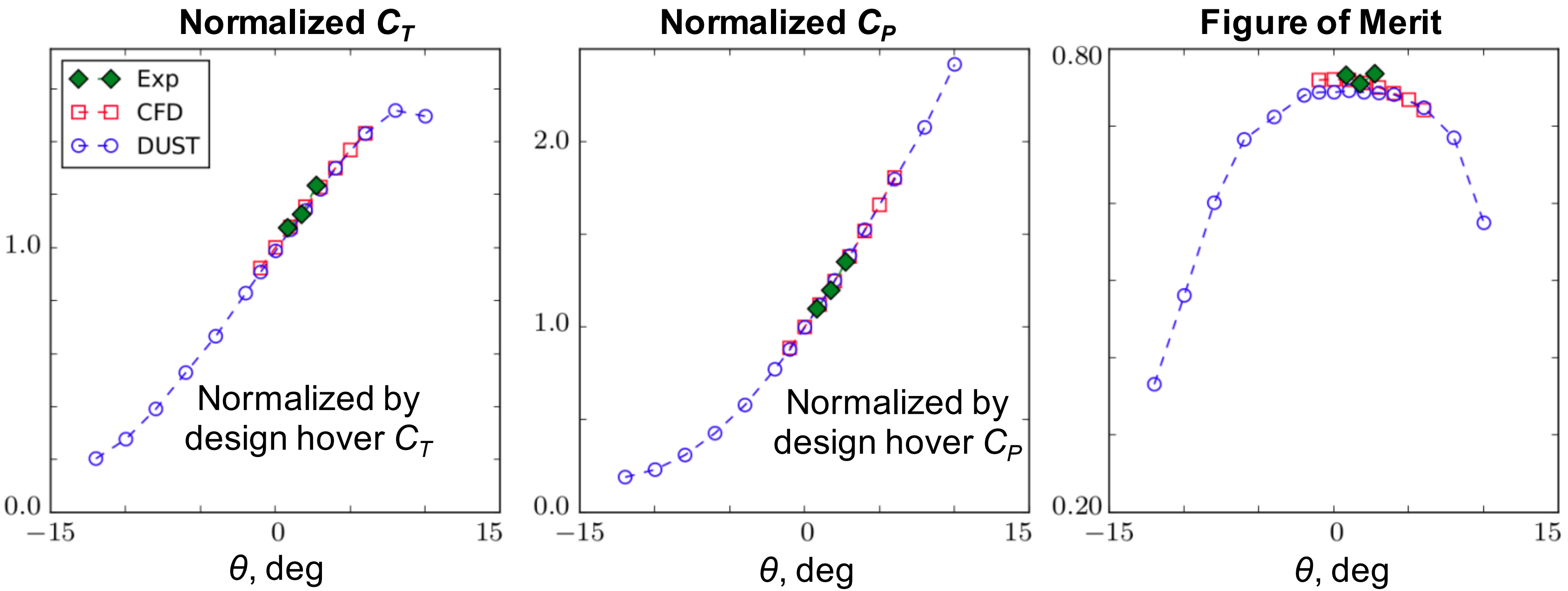
- Blades modeled using lifting lines in DUST
- Wake modeled using vortex particles
- Simulation time step = 7.5^{o}
- Simulation time = 16 revolutions
- Number of particles ~ 40,000



Lifting line model



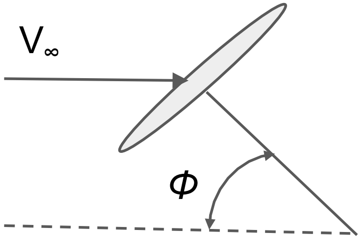
Isolated Fan in Hover



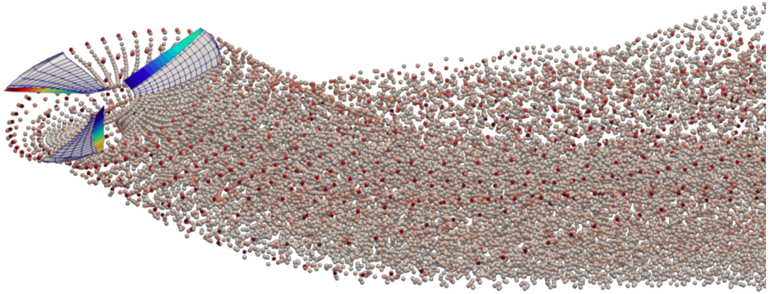
- Good comparison with both experiments and CFD

Isolated Fan in Forward Flight

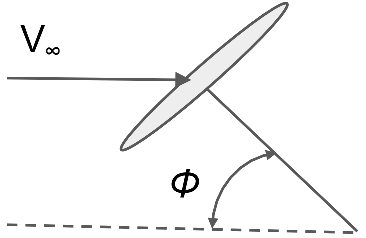
- Airspeed, shaft tilt, blade collective and RPM prescribed from truck test data
- Test points are not necessarily along the trimline
- Blades modeled using lifting lines in DUST
- Wake modeled using vortex particles
- Simulation time step = 7.5°
- Simulation time = 16 revolutions
- Number of particles ~ 40,000

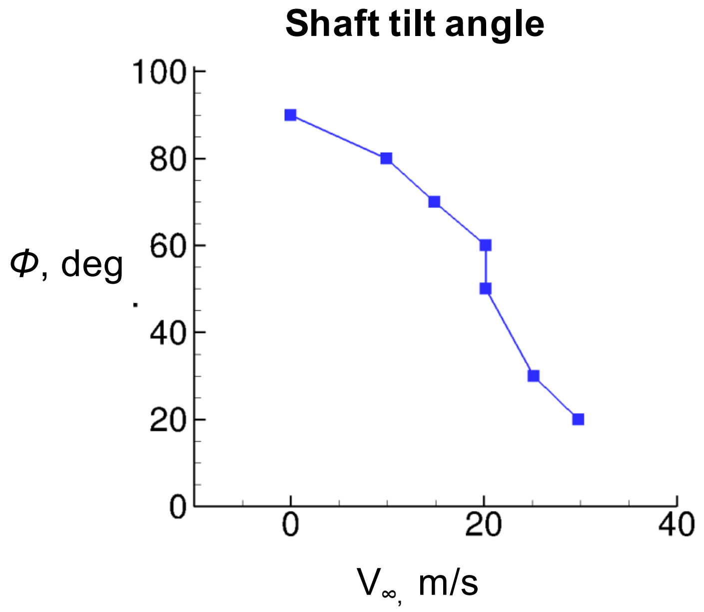


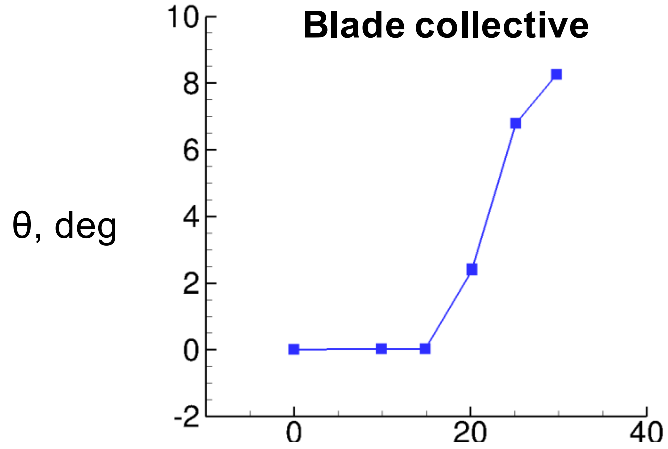
Φ: Shaft tilt angle
Φ = 90° → hover
Φ = 0° → cruise

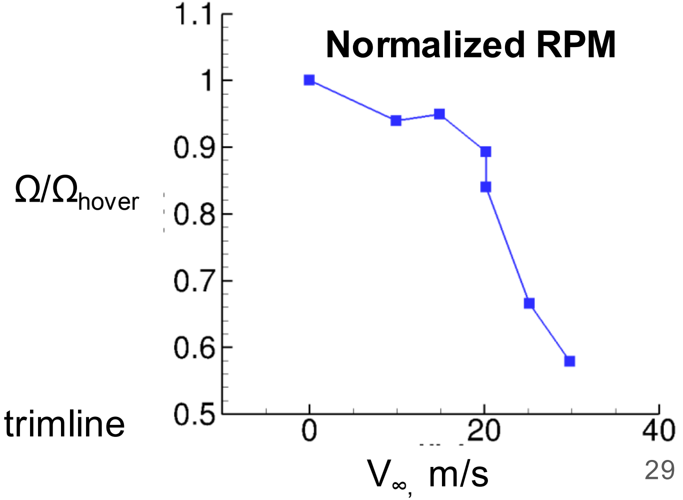


Isolated Fan in Forward Flight





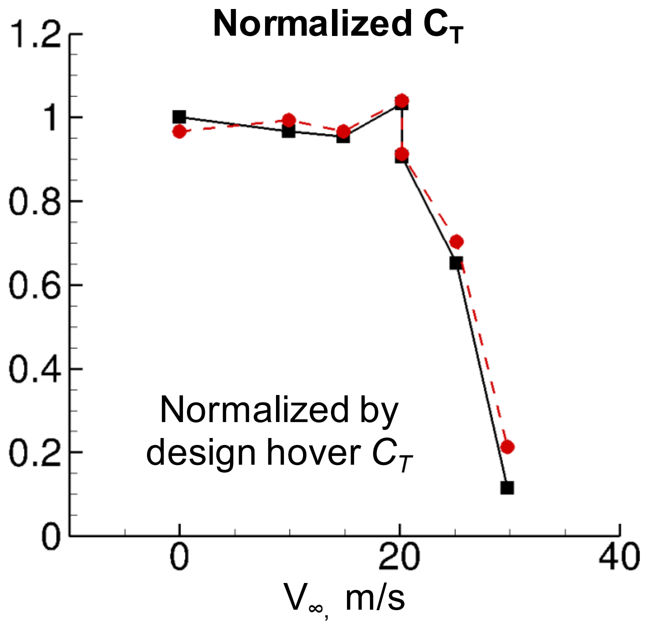


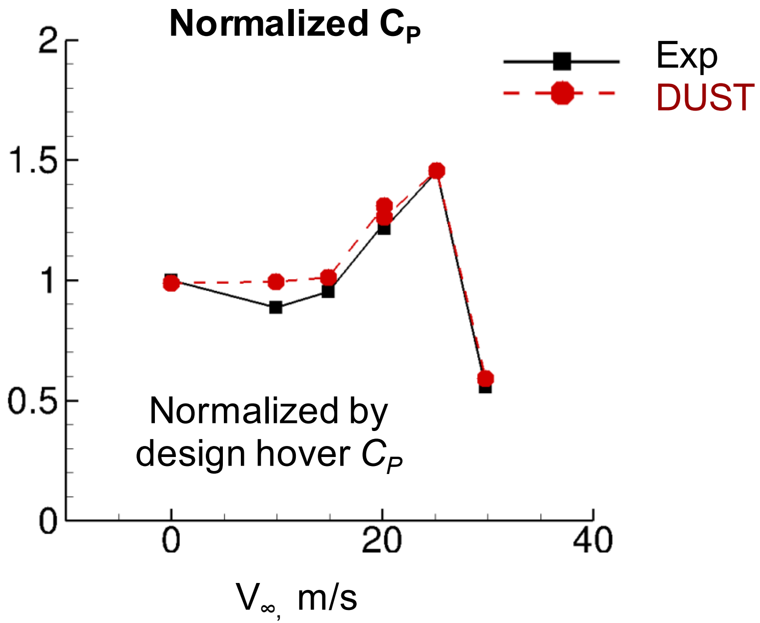


Φ: Shaft tilt angle
Φ = 90° → hover
Φ = 0° → cruise

Note: Experimental test points are not necessarily along the trimline

Isolated Fan in Forward Flight

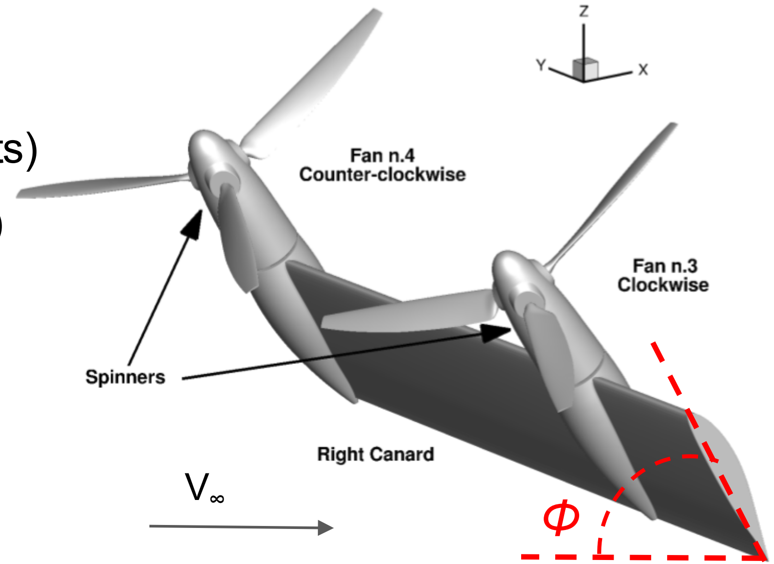




Overall good comparison with experiments

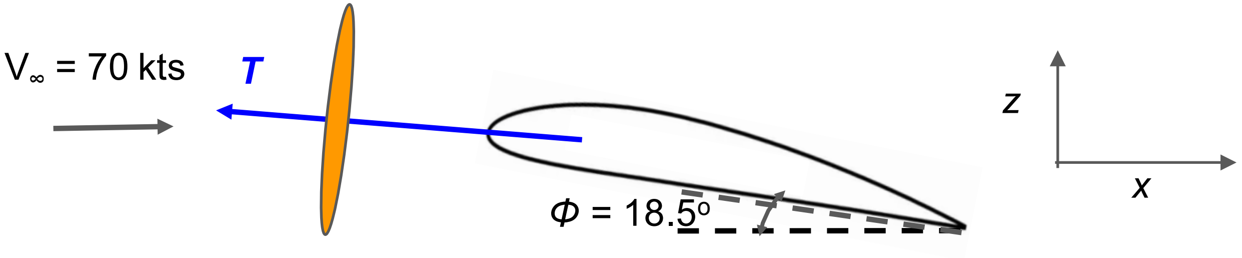
Isolated Canard with Two Fans

- Canard with two fans
- Transition flight configurations:
  - Tilt = 18.5°, Airspeed = 36.3 m/s (70 knots)
  - Tilt = 60.0°, Airspeed = 20 m/s (40 knots)
- RPM and collective prescribed from trimline
- DUST model:
  - Fans modeled using lifting lines
  - Canard modeled with:
    - Surface panels (SP) with/without nacelles
    - Vortex lattice (VL)
    - Lifting lines (LL)



Isolated Canard with Two Fans: Late-Transition

- Freestream = 70 knots, Shaft tilt angle $\Phi = 18.5^o$

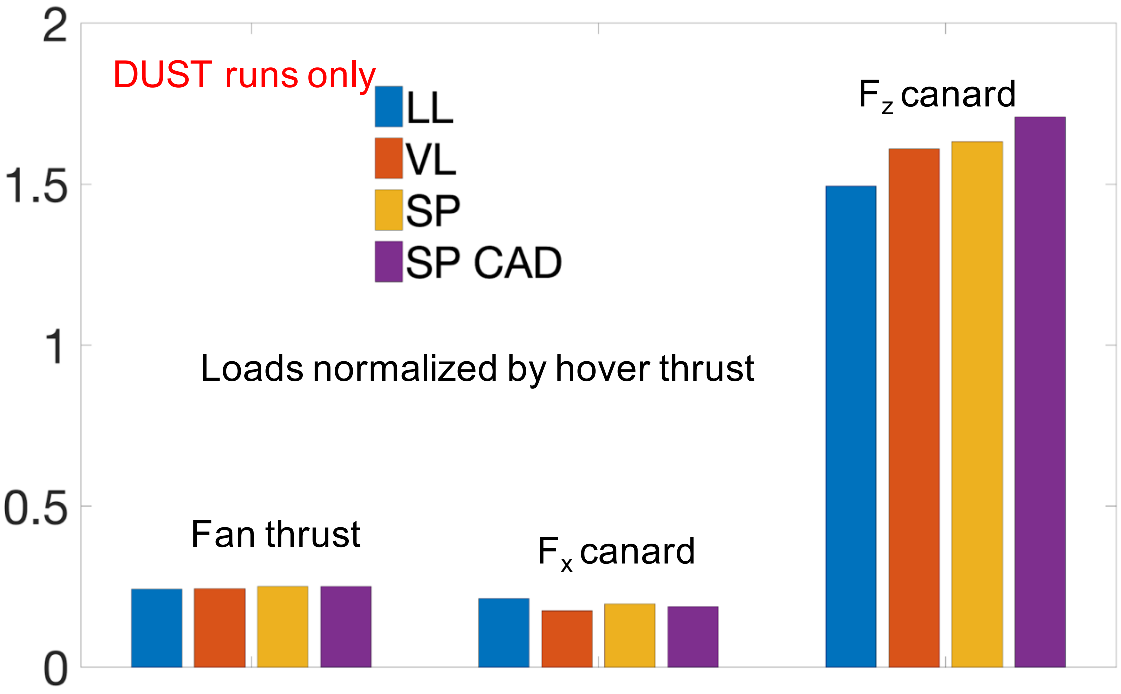


- Simulation time step = 5^o
- Simulation time = 20 revolutions
- Number of particles ~ 155,000

Isolated Canard with Two Fans: Late-Transition

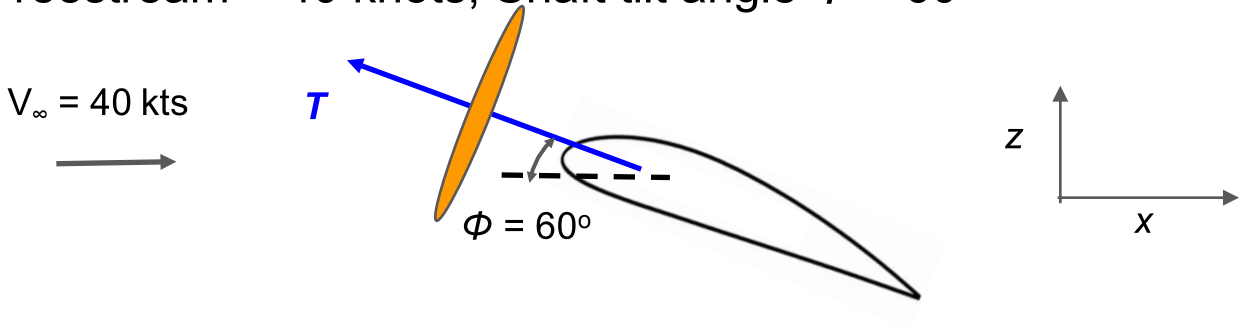
- Freestream = 70 knots, Shaft tilt angle Φ = 18.5°

- Fans produce ~ 25% of hover thrust
- Fan loads not affected by canard model choice
- Lifting line predicts higher canard drag
- Vortex lattice predicts minimum drag

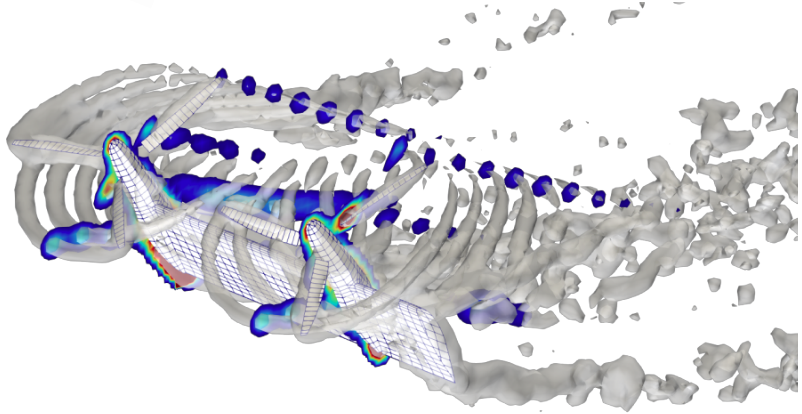


Isolated Canard with Two Fans: Mid-Transition

- Freestream = 40 knots, Shaft tilt angle $\Phi = 60^o$



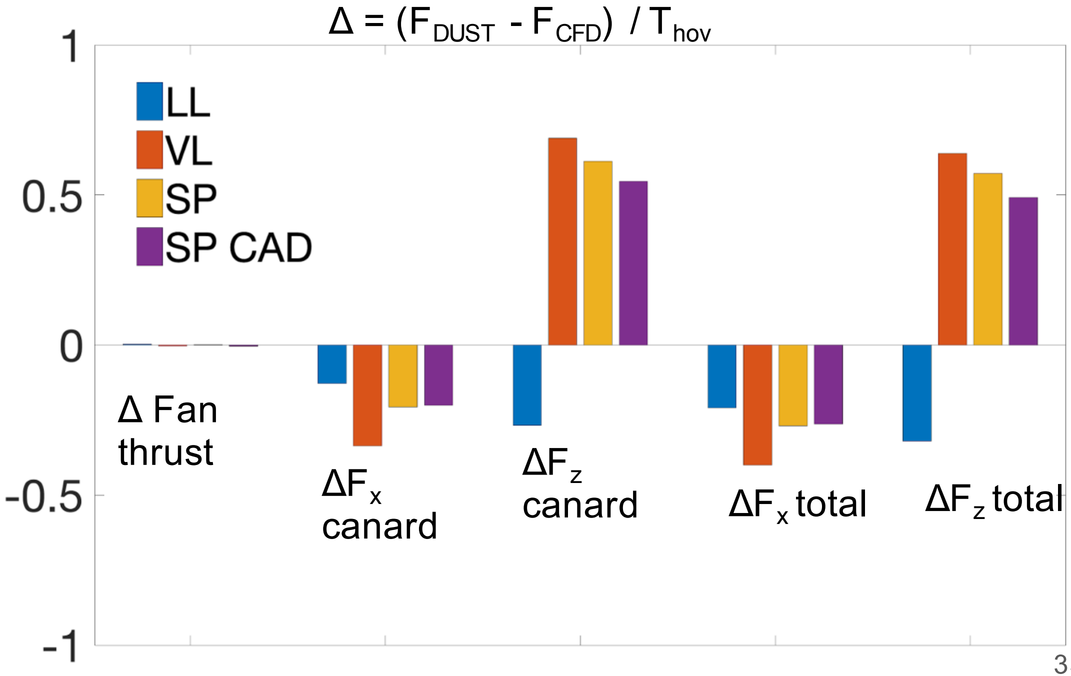
- Simulation time step = 5^o
- Simulation time = 20 revolutions
- Number of particles ~ 75,000



Isolated Canard with Two Fans: Mid-Transition

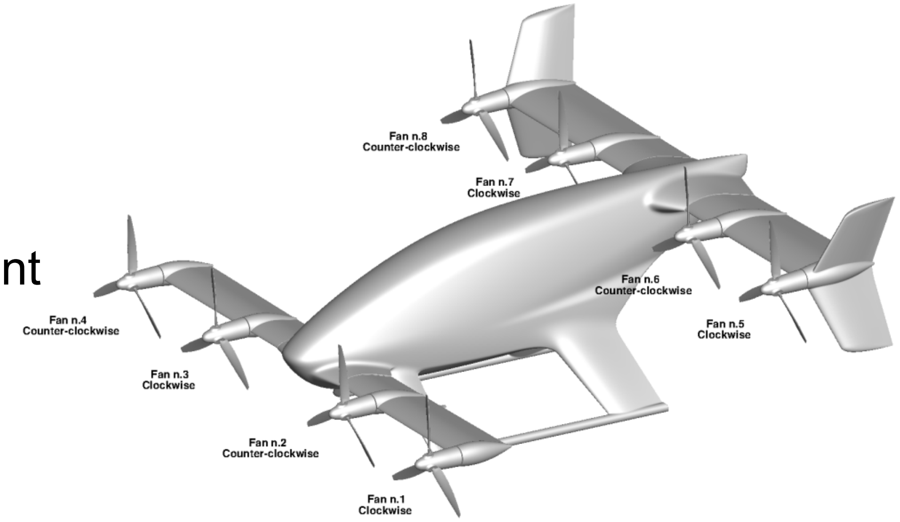
- Freestream = 40 knots, Shaft tilt angle $\Phi = 60^o$

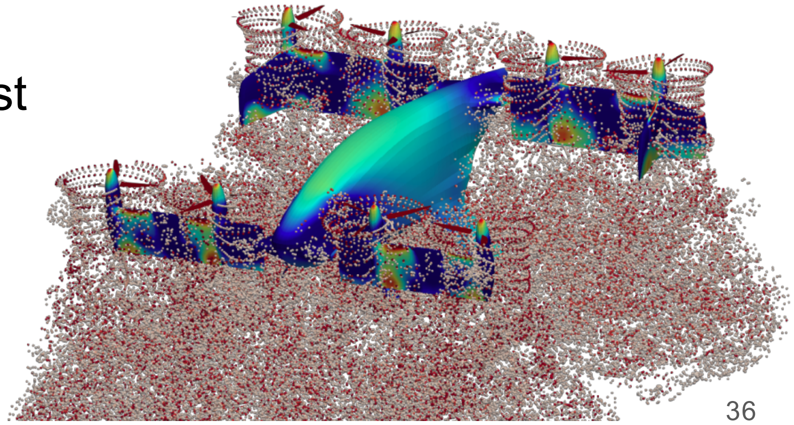
- Fans produce ~ 85% of hover thrust
- Good agreement of fan loads
- All methods underestimate drag
- LL underestimate lift: crude model
- VL and SP over predicts lift: no separation



Full Vahana Simulations

- Flight conditions:
  - Vertical mode: hover, ascent, descent
  - Mid-transition at 40 knots
  - Late-transition at 70 knots
- Vehicle states:
  - Trim vehicle states specified from flight test
  - Vehicle not re-trimmed in simulations
- Compared DUST with CFD and flight test data

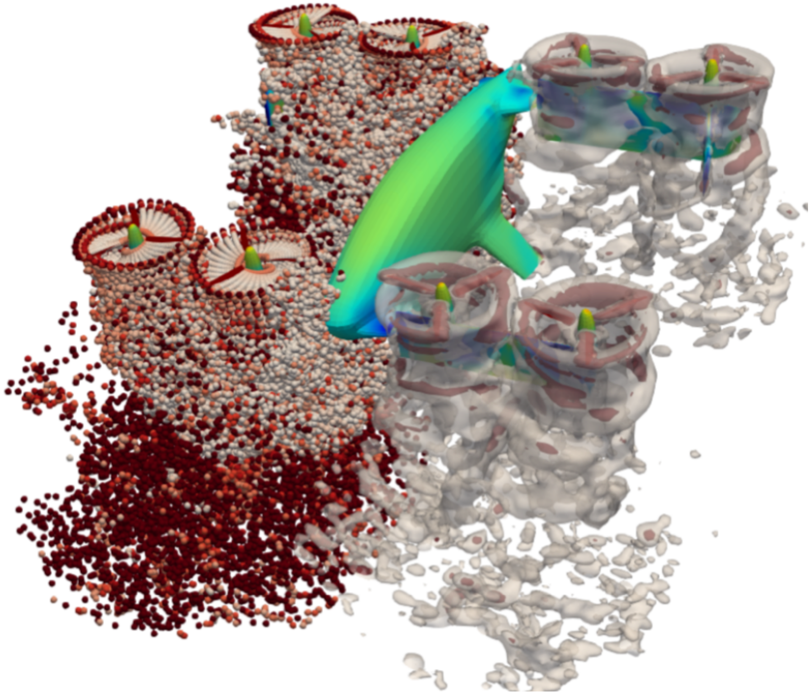




Full Vahana - Helicopter Mode

- Surface panels:
  - Wings with motor fairings and spinners
  - Fuselage
- Fans modeled using lifting line
- Simulation time step = 7.5^{o}
- Simulation time = 20 revolutions
- Number of particles ~ 550,000

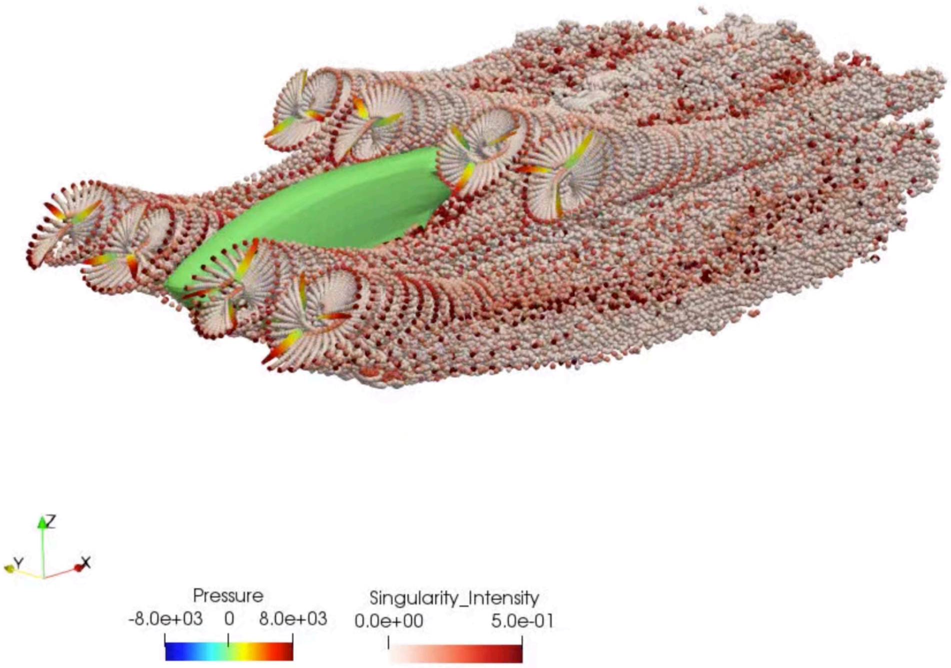
DUST



Wake in hover with pressure contours on body (Ref: Montagnani et al. 2019)

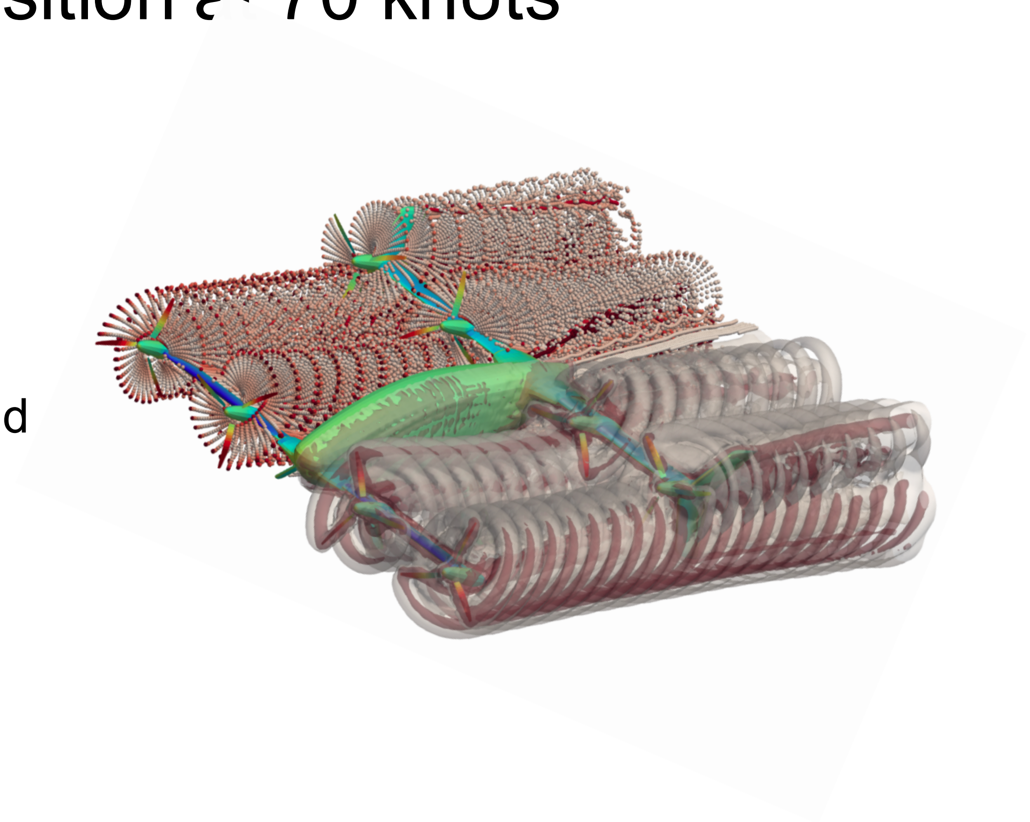
Full Vahana - Mid-Transition at 40 knots

- Airspeed = 40 knots
- Shaft angle = 60^o
- DUST model:
  - Wings: SP, LL
  - Motor fairings and spinners and fuselage: SP
  - Fans: LL
- Simulation time step = 7.5^o
- Simulation time = 20 revolutions
- Number of particles ~ 250,000

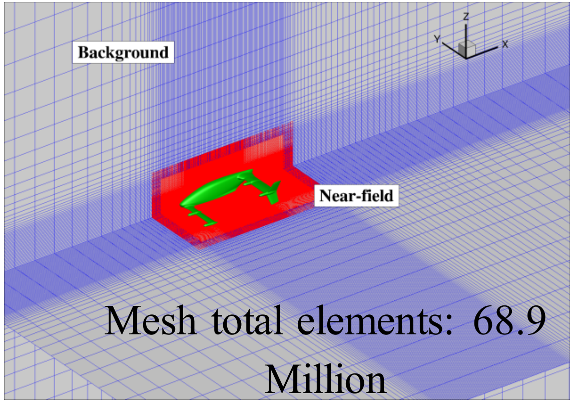


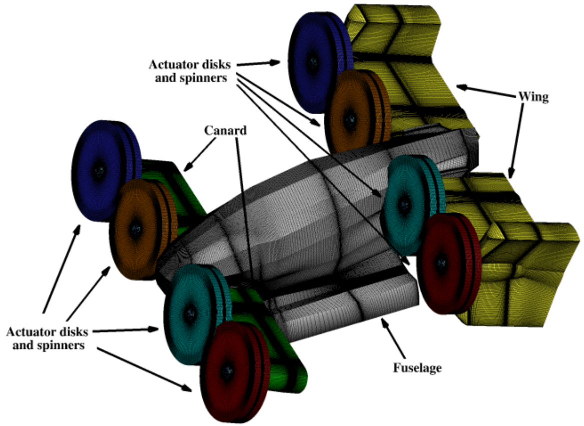
Full Vahana - Late-Transition at 70 knots

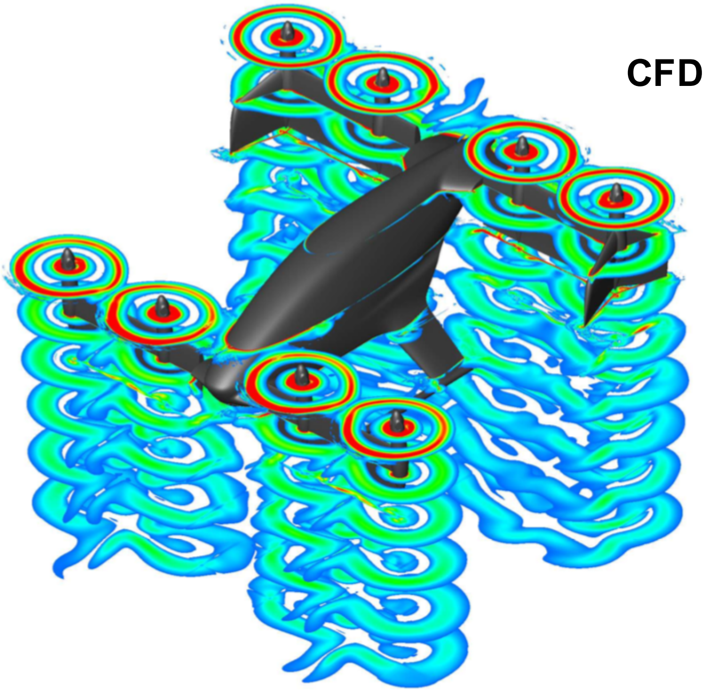
- Airspeed = 70 knots
- Shaft angle = 18.4^o
- DUST model:
  - Wings: SP, LL
  - Motor fairings and spinners and fuselage: SP
  - Fans: LL
- Simulation time step = 7.5^o
- Simulation time = 20 revolutions
- Number of particles ~ 250,000



Full Vahana CFD Model



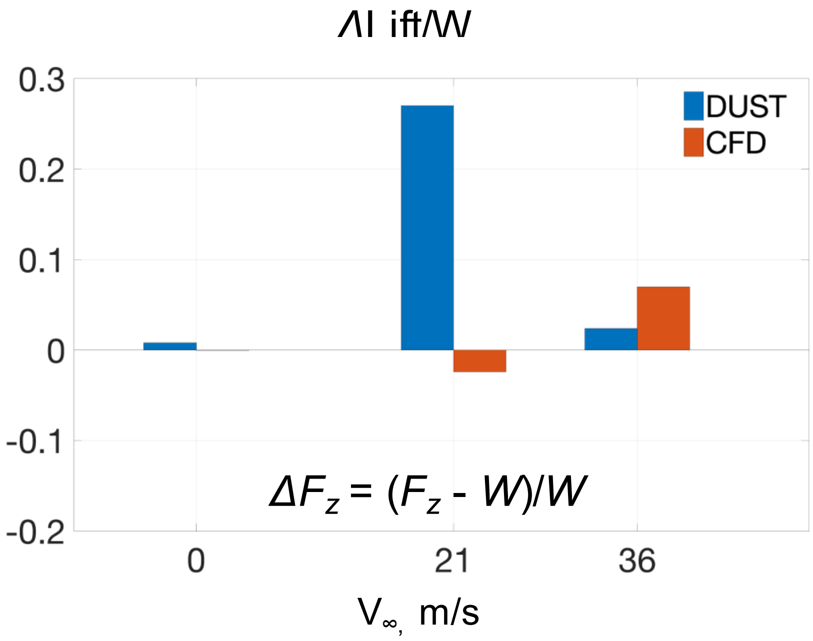




Vorticity contours on a series of Z-constant planes in hover (Ref: Droandi et al. 2018)

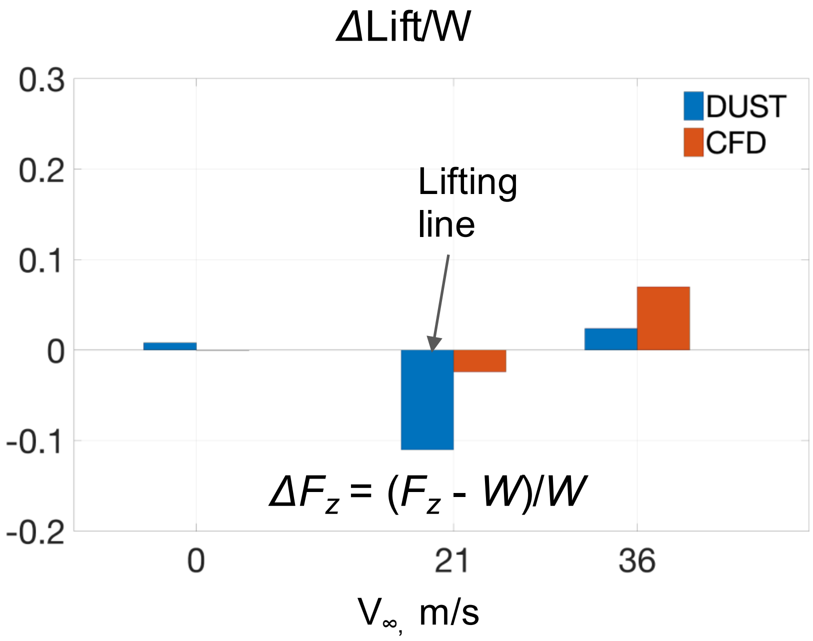
Full Vahana DUST Simulation Comparison

- Difference in normalized lift is maximum at 21 m/s (40 kts) using surface panels



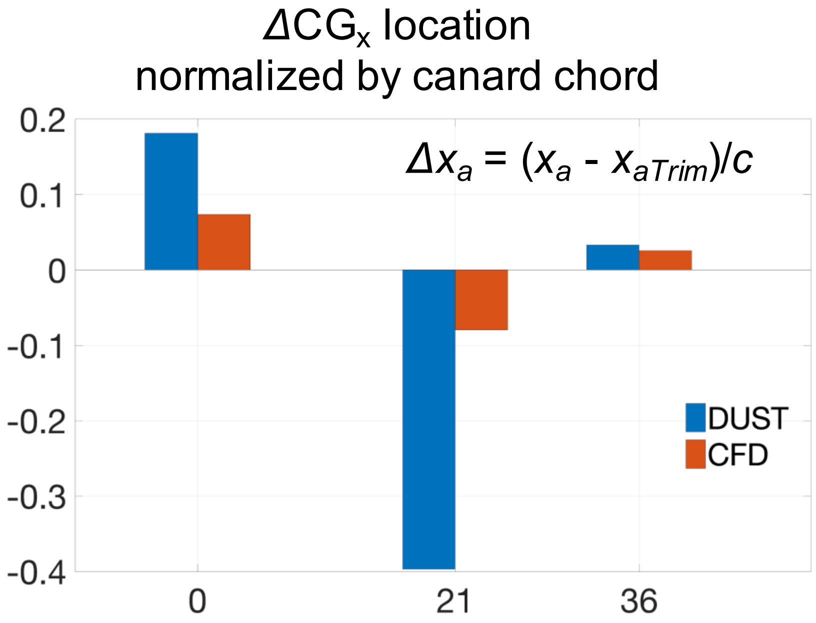
Full Vahana DUST Simulation Comparison

- Difference in normalized lift is maximum at 21 m/s (40 kts) using surface panels
- DUST under predicts lift using lifting line



Full Vahana DUST Simulation Comparison

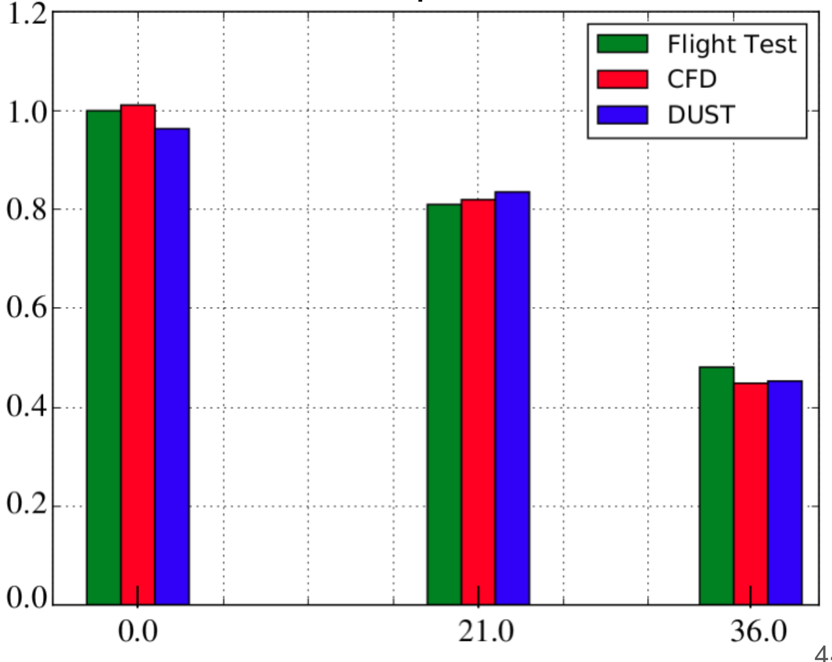
- Difference in normalized lift is maximum at 21 m/s (40 kts) using surface panels
- DUST under predicts lift using lifting line
- Mid-transition is a difficult condition to model



Full Vahana DUST Simulation Comparison

- Difference in normalized lift is maximum at 21 m/s (40 kts) using surface panels
- DUST under predicts lift using lifting line
- Mid-transition is a difficult condition to model
- Good agreement of power predictions from DUST with flight test and CFD

Total shaft power normalized by hover power



Contents

Conclusions

- Mid-fidelity aerodynamic codes are necessary for eVTOL development
- DUST is a flexible, open-source solution
- Good results in most of the Vahana test cases
- Able to represent the physics underlying
- Limits with stalled surfaces
- Need to take into account separations

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