ZHAW - Zurich University of Applied Sciences

EASA MODEL-SI Project
D-3.2.1 Lesson Learned

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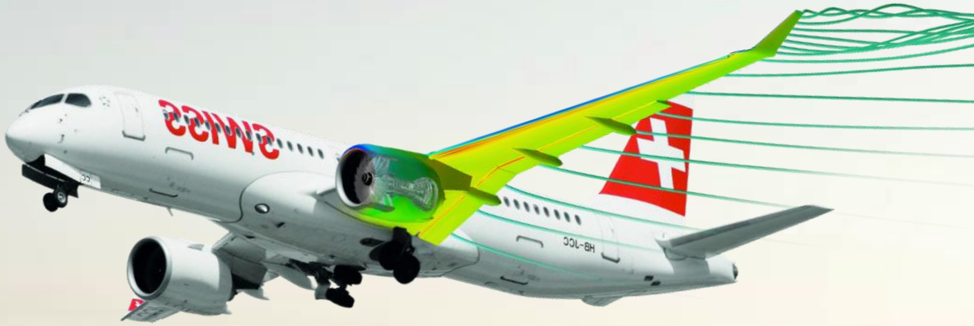


Lesson Learned

The lesson learned can be divided into these categories:

- Physics-based modeling: state-of-the-art approaches
- Experimental testing: state-of-the-art approaches
- AI/ML modeling: a new world
- Multi-fidelity implementation: the merging of data-driven and physics-based

Lesson Learned: Flight Mechanics

- Implementation

Leveraging state-of-the-art techniques, the implementation proceeded smoothly without encountering significant challenges. From a flight mechanics perspective, the implementation posed no particular difficulties, even considering the relative exotic of eVTOL aircraft

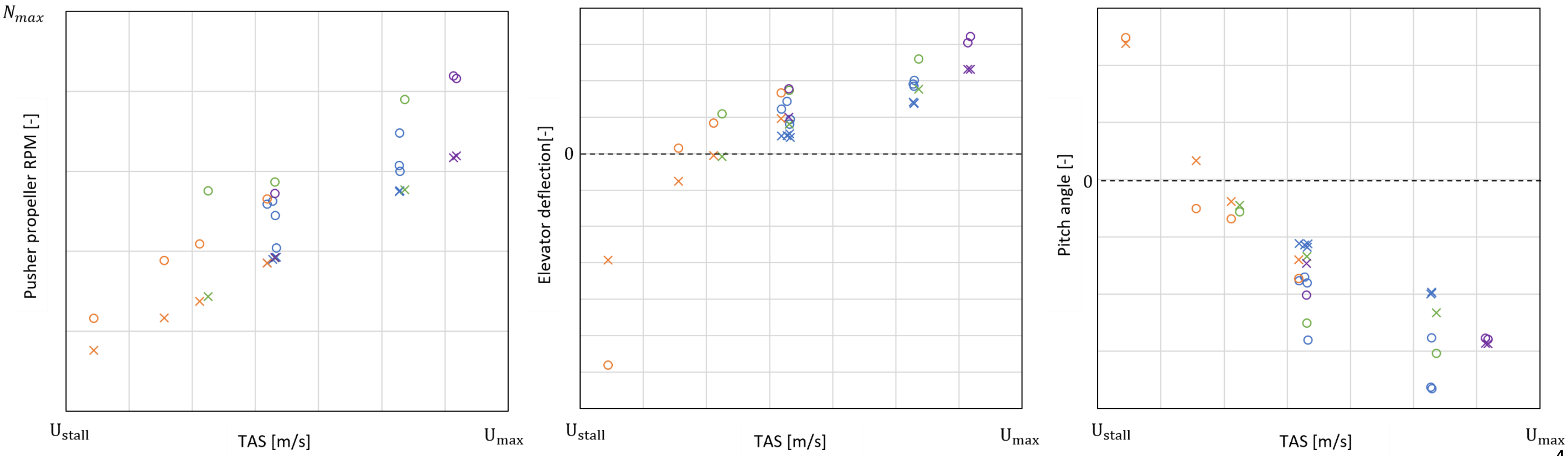
- Results

As shown from the comparison between LF model and flight tests, a good match was already achieved at low AOAs (standard conditions in airplane mode)

Flight Mechanics comparison

Trimmed conditions comparison in AP mode between:

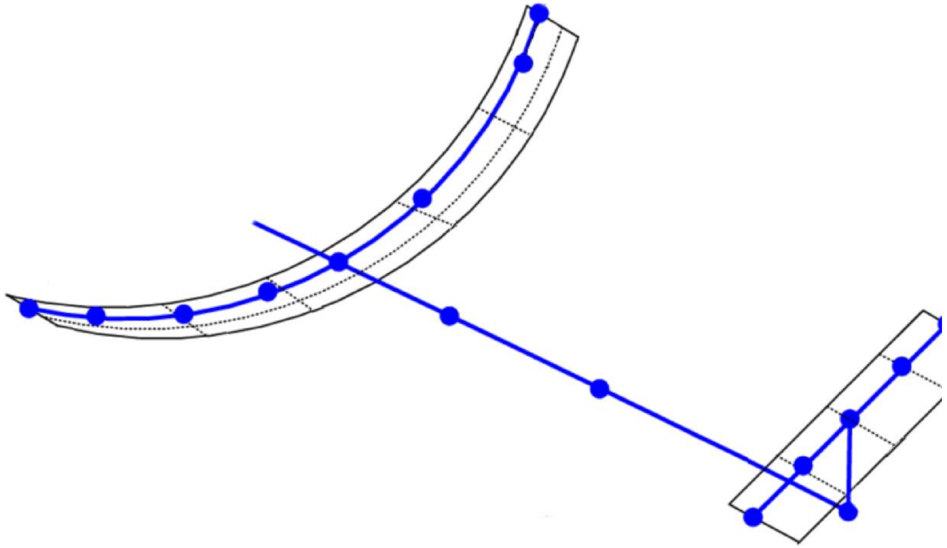
- ○ LF Flight Mechanics model
- ✖ Flight test data



Lesson Learned: Structural model

Even though, state-of-the-art techniques were used, this is what can be improved to obtain a good FEM model:

- Having the a complete a complete CAD model: a detailed representation ensures to model accurately the structure geometry
- Material Properties: knowing each component material within the structure is critical for realistic simulations
- Carbon Fiber Layup (Optional): If available, incorporating the layup configuration of carbon fiber composites



Optimizing the Model for Efficiency:

While a detailed FEM model is essential for initial analysis, computational efficiency can be improved through model order reduction techniques such as **modal condensation**. This approach simplifies the model by focusing on the most significant vibration modes, drastically reducing computational costs for subsequent analyses.

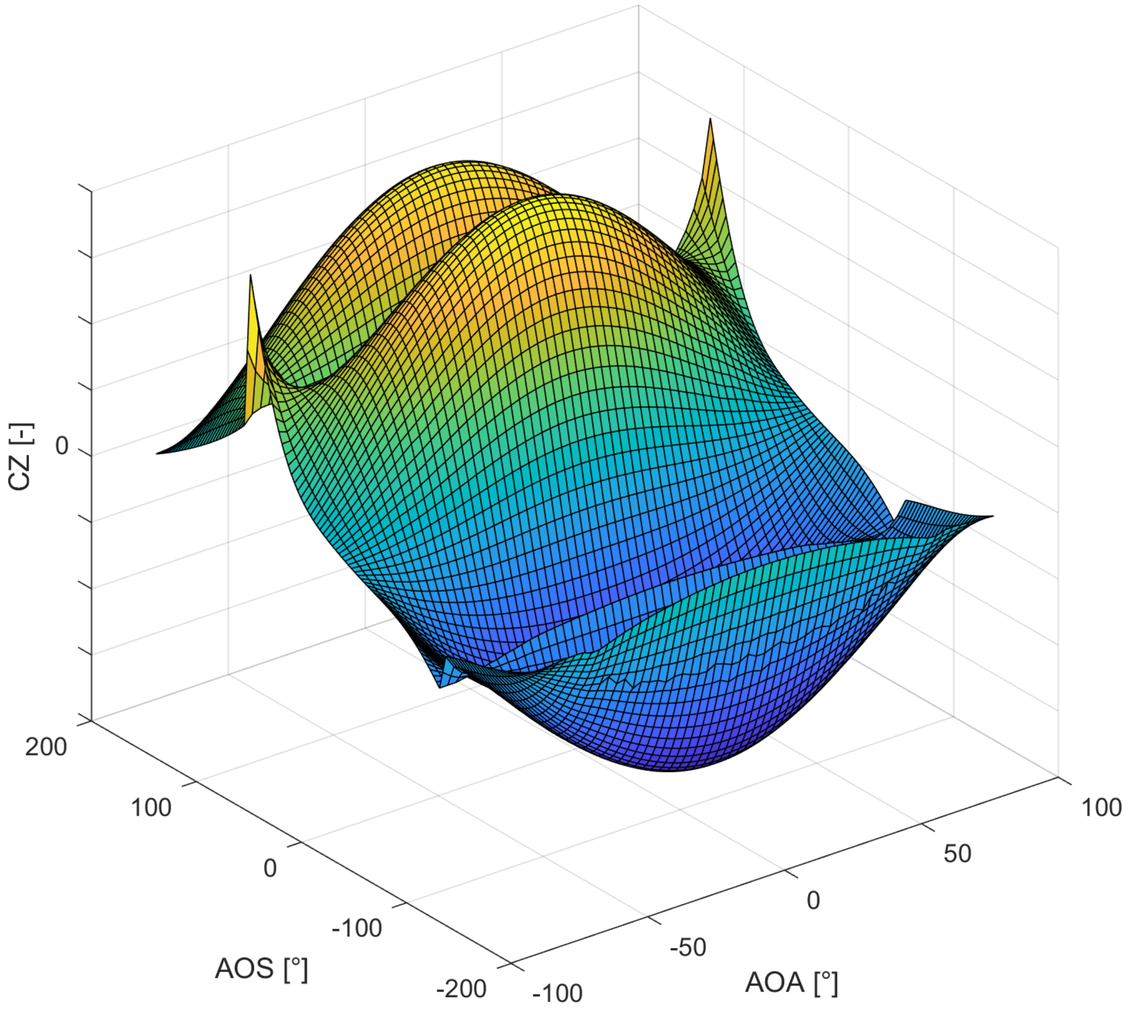
However it’s important to minimize potential **error accumulation**, it's crucial to begin with a good structural model built with the considerations outlined above.

Lesson Learned: Low-fidelity Aerodynamics

LF aerodynamics is simulated with Vortex Lattice Method (VLM). A simpler and quick approach which have some limitations.

The aerodynamic modeling of some eVTOL flight conditions is challening:

- in particular in Helicopter mode and/or during transition, the VLM, not capturing separation effects, is overpredicting the forces and moments
- only in the «linear region», where the flow remains attached, the LF is reliable (between AOA = [-10,10]°)

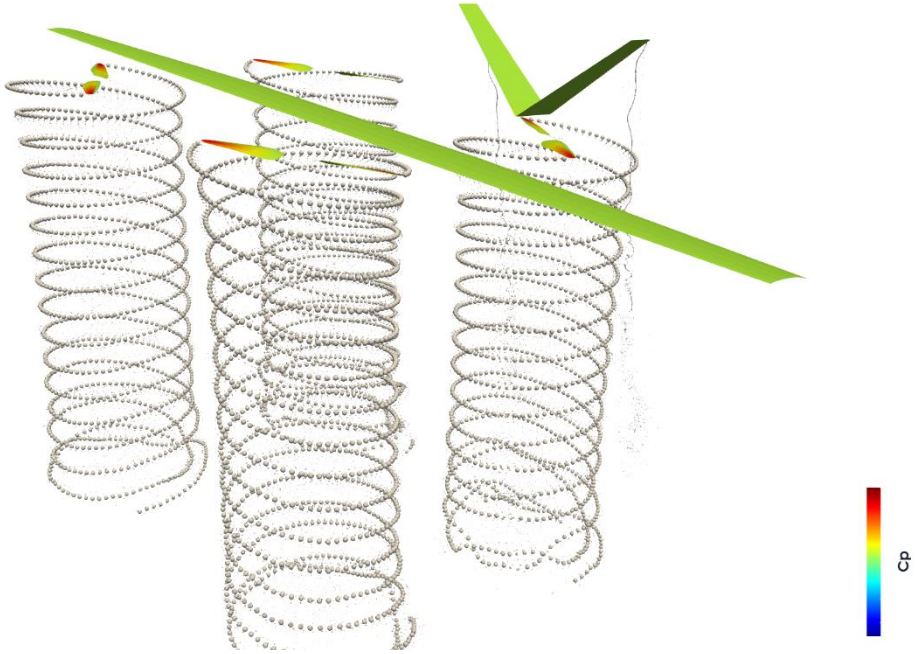


Lesson Learned: Mid-fidelity Aerodynamics

The Vortex Particle Method (VPM) gained popularity thanks to some recent open-source releases. Depending on what is the objective, they can be extremely useful.

Challenges:

- Familiarization with VPM **not trivial**
- A VPM simulation of an entire aircraft can be run on a local machine in about one day. An HPC infrastructure is anyway recommended
- Wing aerodynamics are captured correctly **only** at low AOA
- Very promising methods but not a silver bullet.



Lesson Learned: Mid-fidelity Aerodynamics

Advantages

- Costs: compared to standard CFD, the computational costs of VPM can be one order of magnitude lower
- Vorticity captured: VPM captures and resolves vortex structures thanks to its Lagrangian meshless approach. This makes them well-suited for problems dominated by vortex shedding
- Pre-processing: being a meshless method, an important time can be saved. VPM can be easily adapted to complex geometries
- Community building: thanks to this “new” approach, our team had the chance to know many experts in this fields, such aerodynamicists and code developers

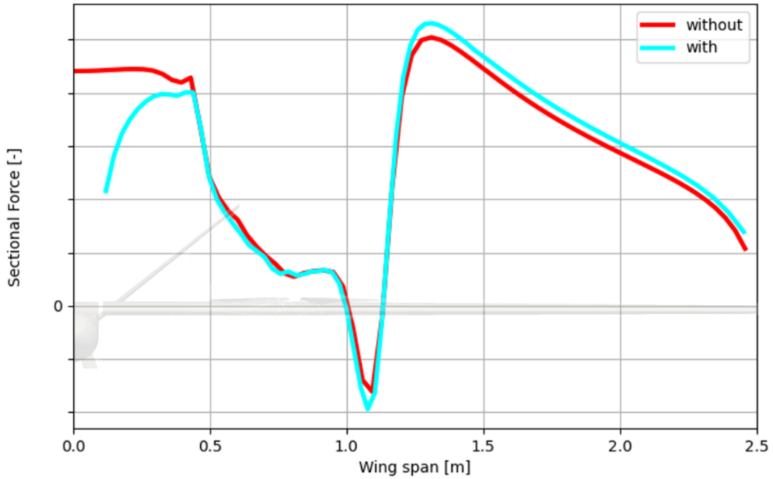
Disadvantages

- Accuracy: Forces and moments on aerodynamic surfaces can be correctly calculated only partially
- Separation: since the method relies on potential flow theory, it does not account for flow separation. Therefore the flowfield where particles move is badly influenced. This is particularly important for tails (or other aerodynamic surfaces) which are immersed in the rotors/propellers wake. The local angle of attack could not be correctly calculated
- Bluff bodies (e.g. fuselage) interaction: despite one can perform a simulation with bluff bodies, the interaction with wings or tails is still missing

DUST Wing force distribution comparison

Comparison between a simulation with and without the fuselage:

- The small fuselage is partly influencing the wing aerodynamics.
- The wake shedding over the wing is similar for both cases

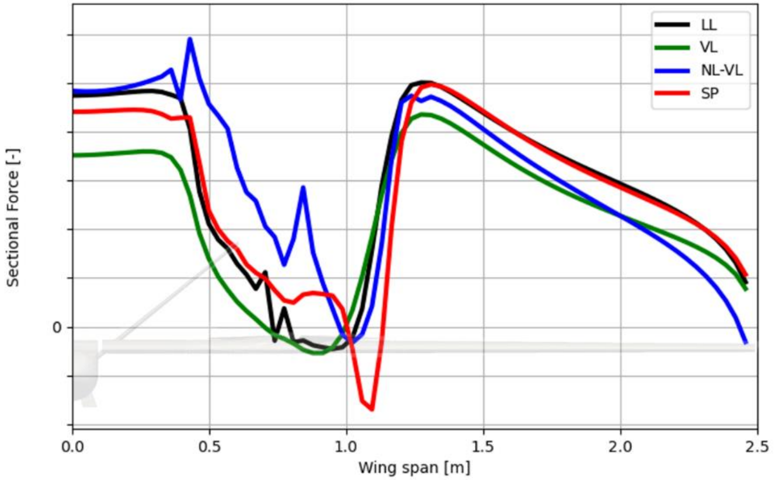


CASE	FRONT PROPELLER THRUST	REAR PROPELLER THRUST	WING LIFT FORCE
% DIFFERENCE WITH/WO FUSELAGE	+0.1	-0.2	-7.03

Comparison of the wing aerodynamic modeling:

- Lifting Line (LL)
- Vortex Lattice Method (VL)
- Non-Linear Vortex Lattice Method (NL-VL)
- Surface Panels (SP)

No particular difference is noticed at low AOA



% DIFF BETWEEN METHODS	FRONT PROPELLER THRUST	REAR PROPELLER THRUST	WING LIFT FORCE
SP	-	-	-
NL-VL	+2.1	+0.3	+6.1
VL	-0.4	+3.0	-19.2
LL	+1.2	+7.0	+3.8

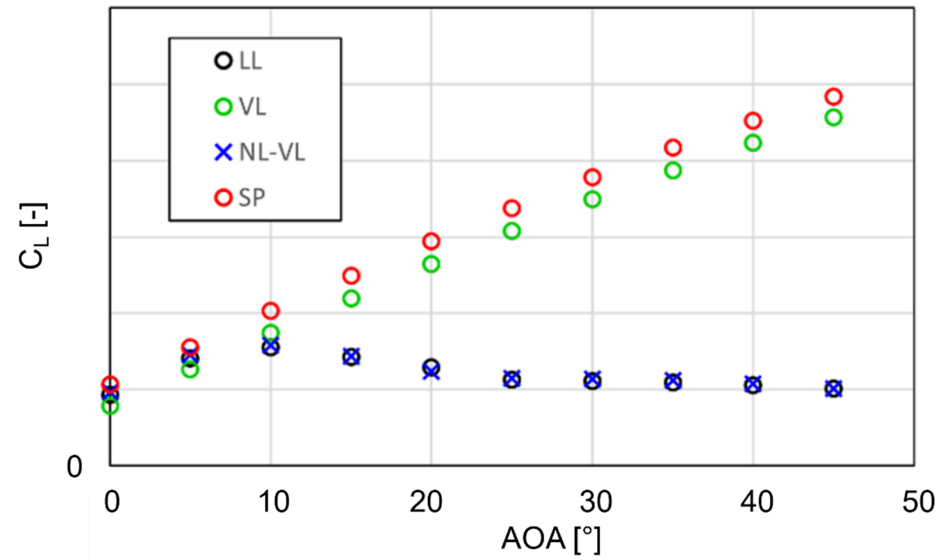
Mid-Fidelity Simulations: DUST

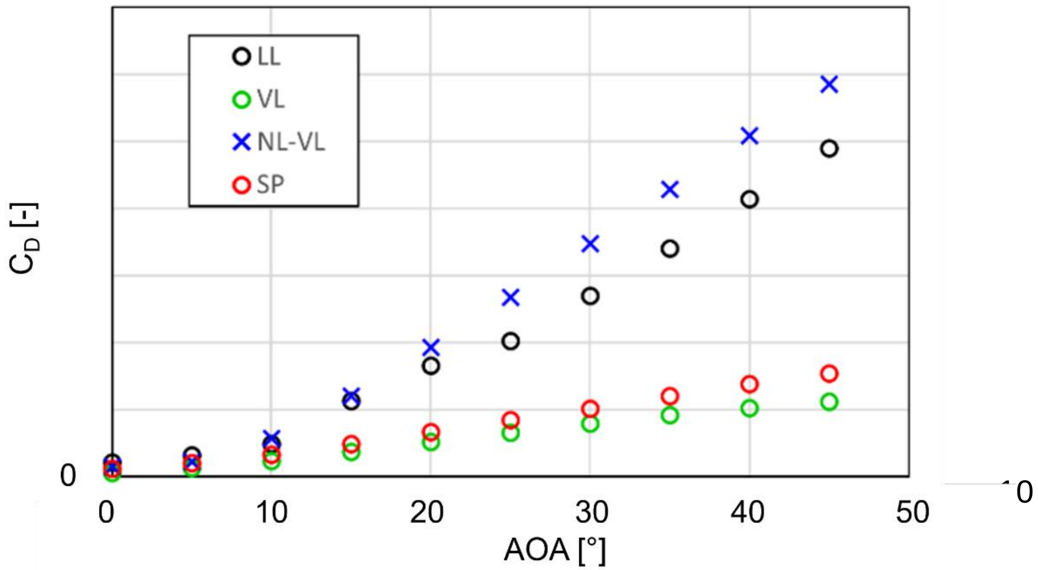
Comparison of the wing aerodynamic modeling:

- Lifting Line (LL)
- Vortex Lattice Method (VL)
- Non-Linear Vortex Lattice Method (NL-VL)
- Surface Panels (SP)

Here are our take-home messages:

- Classical VL and SP methods, not relying on aerodynamic tables, overpredict the lift at high AOA
- LL method is quicker than NL-VL but suffers of numerical instabilities
- NL-VL is so far the best compromise

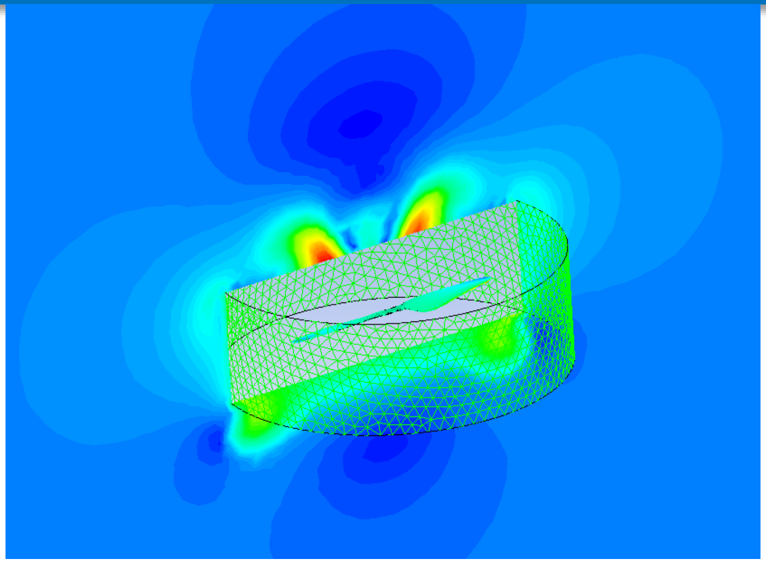


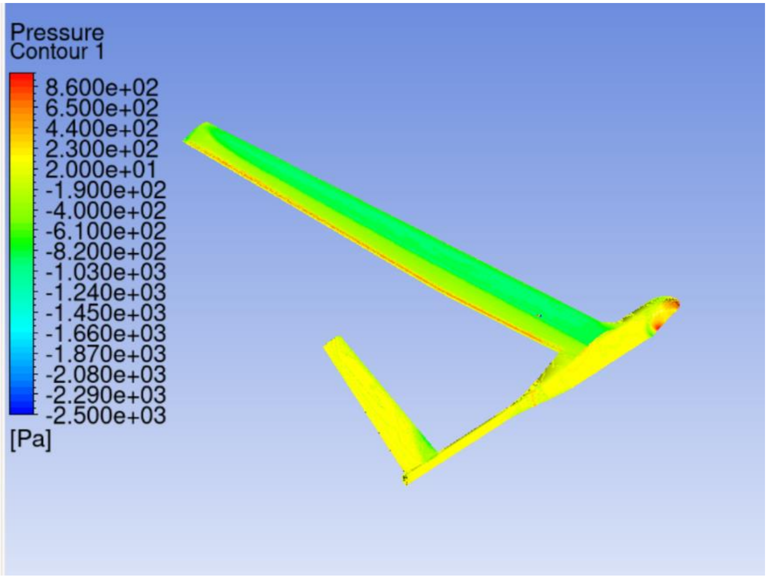


Lesson Learned: High-fidelity Aerodynamics

High-fidelity simulations are performed with standard CFD methods. Despite it is already known that RANS struggle to capture correctly vorticity, these are our main take-home messages:

- Simulation of a single component (e.g isolate rotor) is trivial, still more time-consuming than LF and MF but more accurate
- The main challenges are not associated with the methods itself but rather with the size of the problem. An eVTOL aircraft usually have multiple rotors / propellers which increase the computational costs.
- The actuator disk (AD) method is not suited for this kind of aircraft: AD works well only when the flow is parallel with the rotor thrust axis. Since in eVTOLs the flow angle varies greatly over the flight envelope, this method is not recommended
- Since unsteady simulations are needed, the computational cost in terms of memory and processors is great. GPU could partly relieve this situation





Lesson Learned: High-fidelity Aerodynamics

- Flow solvers
  - Navier-Stokes: solving flow characteristics at the macroscopic level, objective in the current study
  - Boltzmann Approach: The Lattice Boltzmann Method solves the flow characteristics at the microscopic level, focusing on the particle distribution and collisions.
- Comparison with MF and LF-methods (Cons/ Pros)
  - (+) physics: robust to blade geometry to predicting tip vortex core structure and the viscous growth of the vortex core.
  - (-): Still time-consuming; not suitable for eVTOL preliminary design phases where various configurations need to be tested within a limited time
- Advancements of NS-approach
  - Turbulence enclosure: The scale-resolving simulation (SRS) turbulence models are being widely used, like DES, SAS and other RAN-LES hybrid models.
  - High-order numerical schemes: MUSCL for Finite-Volume and WENO for Finite-Difference (FD) are typically used in both in-house and commercial codes.
  - Vorticity confinement method: Adding a designed anti-diffusion term into the standard NS equations for vorticity preservation.
  - Combination with middle-fidelity methods aimed at reducing computational time, e.g., computing the flow field around bodies including rotor wake-induced effects.
  - Computational time: Commercial solvers incorporate GPU techniques to accelerate high-fidelity simulations. For example, Siemens, Ansys and Dassault have been converting their CPU-based CFD solvers to GPU-based ones, such as Ansys Fluent GPU. Since these solvers are newly implemented, the validation process of the solvers, particularly for rotor aerodynamics and wake modeling applications, is still ongoing.

Wing aerodynamics comparison

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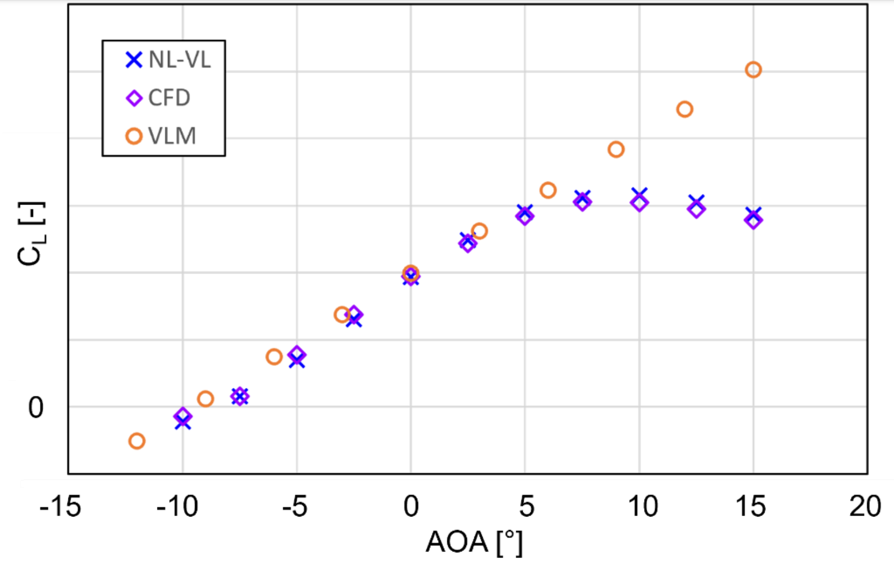
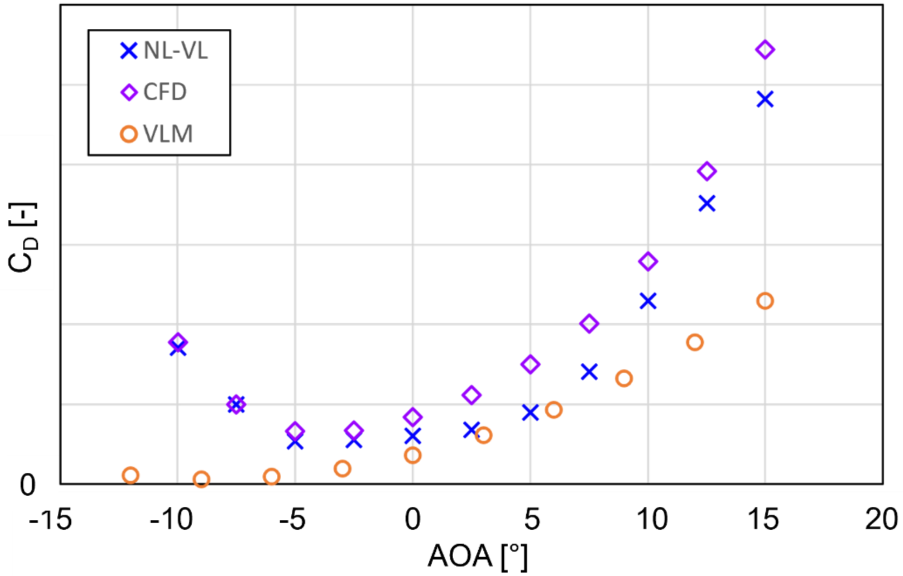
Comparison between different models fidelity:

- Low-fidelity: Vortex Lattice Method (Tornado)
- Mid-fidelity: Vortex Particle Method (DUST)
- High-fidelity: CFD steady RANS

Here are our take-home messages:

- Classical VLM is good for the initial model implementation and model architecture testing
- NL-VL is so far the best compromise





Flight Tests

The eVTOL is equipped with standard sensors and additionally:

- ● accelerometrs
- ▬ strain gauges

Key notes:

- Several flights were accomplished in the entire flight envelope in both Helicopter and Airplane mode
- Structural modes were identified
- Flight test data is compared with simulation data

Lesson Learned: Flight Tests

The following challenges were identified related to the aircraft structure identification:

- To identify effectively the structure eigenfrequencies, strain gauges and accelerometers data need to be as less noisy as possible: all the propeller vibrations are already contributing to worsening flight data quality
- An accurate calibration is crucial: The position of all sensors and applied loads should be measured correctly
- When no exact aircraft geometry nor material properties are available, good-quality measurements can be used to retrieve a FEM model from the data. The following could be used:
  - Take advantage of good quality measurements to identify structure eigenfrequencies (minimum the first five)
  - Knowing the wing geometry would allow us to solve an optimization problem to match material properties(used as design variables) with the identified eigenfrequencies.

Lesson Learned: Flight Tests

The following challenges were identified related to the aircraft flight dynamics identification:

- Flight test data quality needs to be good for system identification, both static and dynamic. Here what coud be improved:
  - Flying with as little as possible wind to reduce unknown wind and turbulence
  - Flying simple maneuvers need to be possible (e.g.: straight and level flight)
  - Angle of attack and angle of sideslip measurements would have helped to reduce environment unknown
  - Complete manual control surface inputs would allow to perform specific manuevers to excite the aircraft modes
- If stability analysis of the whole system is desired, more information on all system components (sensors, FCC, actuators) should be available

Lesson Learned: Data-driven

Challenges associated with the implementation of a data-driven model:

- Machine Learning model choice: co-kriging would be the easiest approach but since our system is so complex, a Neural Network (NN) was needed
- Data generation:
  - Thousand of Low-Filidety (LF) data points are generated with Latin Hypercube Sampling: it gives a good representation of the flight envelope
  - Mid- (MF) and High-Filidety (HF) partial availability can cause unreliable predictions: some effects could be badly represented
  - «Non-uniform» data: some flight envelope areas in MF or HF have more data points than other (imbalances / unrepresented): e.g. if in some parts of the flight envelope, there are not enough data points
- Overfitting problems
- Uncertainty quantification: to assess the epistemic uncertainty, a Bayesian approach is needed (BNN)
- «Physical» check: assess the NN against some operational tests to check its reliability
- The modeling implementation is iterative: set-up a number of tests to check the NN reliability. It could be needed to create additional data points
- Integration with physics-based model: classical trim problems are solved with a method where the calculations need to be deterministic. A change of strategy could be needed
- Compared to LF simulations, the introduction of the BNN increased the simulation time greatly. Real-time simulation were not possible anymore

Lesson Learned: Summary

The lesson learned can be divided into these categories:

- Physics-based modeling:
  - following the state-of-the-art approaches, any particular challenge was observed in the implementation part
  - Capturing correctly the physics over the flight envelope was a difficult task: especially in Helicopter mode and Transition
- Experimental testing: following the state-of-the-art approaches, any particular challenge was observed. Ensure good quality data and a large flight time over all weather conditions
- NN modeling: not a trivial task, many challenges
- Multi-fidelity implementation: the merging of data-driven and physics-based presented several challenges, in particular, related to the non-deterministic nature of the BNN

Thank you!
Questions?

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