eVTOLUTION

Qualification of the Vortex Particle Method for Multi-Rotor Configurations

Public Workshop: Novel Tools for Novel Aircraft

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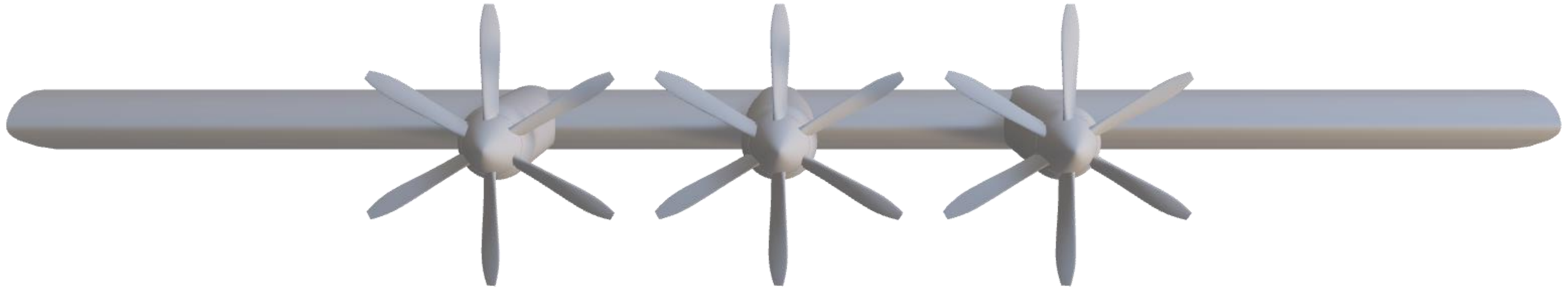
eVTOL mUlti-fideliTy hybrid desIgn and Optimization for low Noise and high aerodynamic performance - Grant Agreement 101138209

Motivation

- Distributed Propulsion: Novel possibilities & challenges
- Installation effects aerodynamically and acoustically critical
- Extensively investigated within ENODISE on low TRL (all data available at zenodo.org)
- Learnings: Tip-to-tip interaction dominant tonal noise source
- Adjacent rotors rotate through each others potential field

=> Periodic fluctuation of rotor forces => Tonal noise excitation



XPROP-S CAD data courtesy of Technische Universiteit Delft

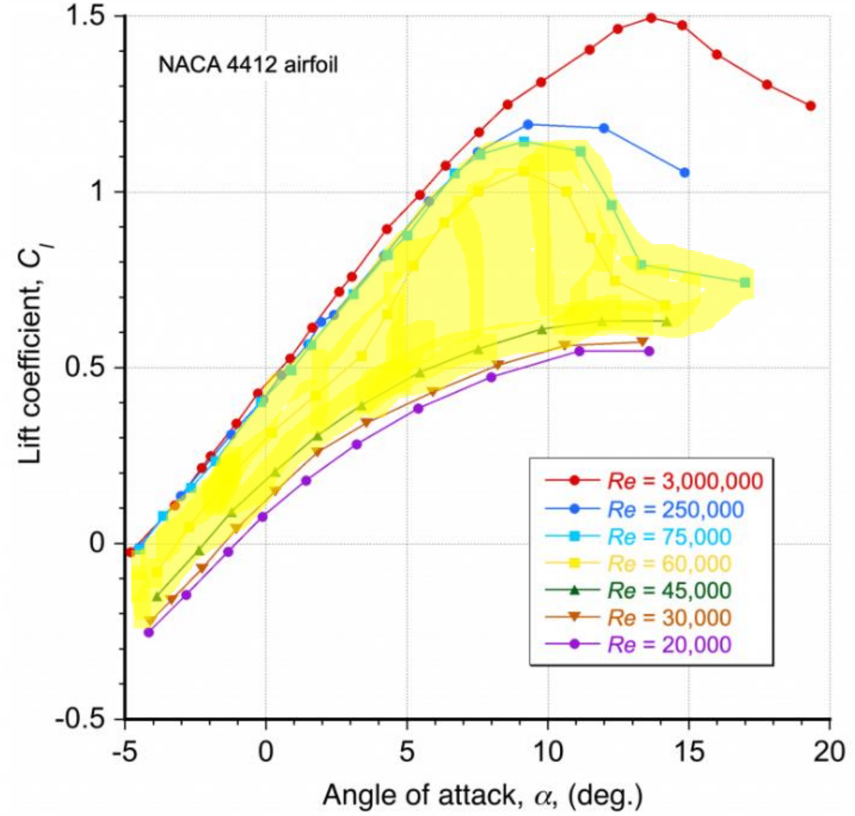
Challenges
Low Reynolds Phenomena

- ENODISE B1:

$$\mathrm{Re} < 1\mathrm{e}5, \mathrm{Ma} < 0.3$$

- Airfoil boundary layer at low Re:
  - Laminar, turbulent flow
  - Transition
  - Flow separation, reattachment

→ Influential effects on airfoil forces & noise generation



DOI:10.15394/2022.1066

Multi-fidelity Analysis
Applied Models

Low computation ⟵ Fidelity ⟶ High accuracy

Blade Element Momentum Theory:

- Analytic approach based on XFOIL generated polars
- Benefit: transitional effects depictable
- Problem: Only steady single rotor
- Lade, Tobias, „Methodenentwicklung zur Vorhersage des Propellerlärms bei Grenzschichteinsaugung im niedrigen Reynoldszahlbereich“, 2023, Master Thesis, TU Berlin

Vortex Particle Method:

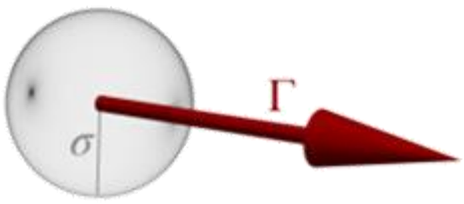
- Particle based numeric method solving Navier Stokes
- Variable Fidelity
- Benefit: Transitional effects & tip-to-tip interaction
- Alvarez, E. J., Mehr, J., and Ning, A., “FLOWUnsteady: An Interactional Aerodynamics Solver for Multirotor Aircraft and Wind Energy,” AIAA AVIATION 2022 Forum, Chicago, IL, 2022. DOI:10.2514/6.2022-3218.

Lattice-Boltzmann Method:

- Mesh based numeric method solving discrete Boltzmann equations (microscopic dynamics)
- Benefit: Tip-to-tip interaction numerically resolved
- Problem: Wall treatment fully turbulent
- Zarri, Alessandro et al. (2023), „Aeroacoustic Interaction Effects of Adjacent Propellers in Forward Flight“, AIAA

Vortex Particle Method

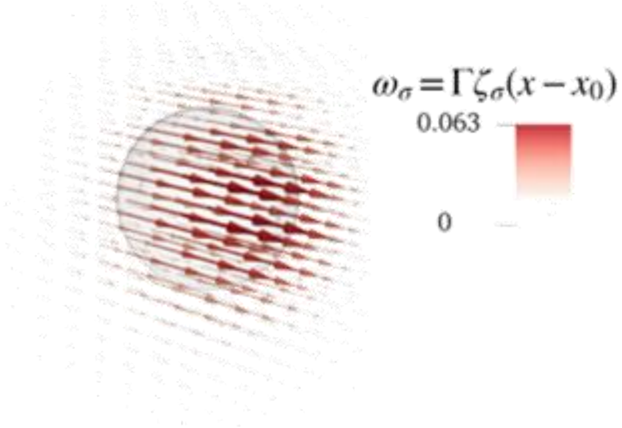
Basics



- Particle: Incompressible volume of fluid, moving with velocity u, carrying vortex strength Γ_p
- Navier-Stokes vorticity form, LES filtered

$$\frac{\mathrm{d}}{\mathrm{d}t}\overline{\boldsymbol{\omega}} = (\overline{\boldsymbol{\omega}} \cdot \nabla)\,\overline{\mathbf{u}} + \nu \nabla^2 \overline{\boldsymbol{\omega}} - \mathbf{E}_{\mathrm{adv}} - \mathbf{E}_{\mathrm{str}}$$

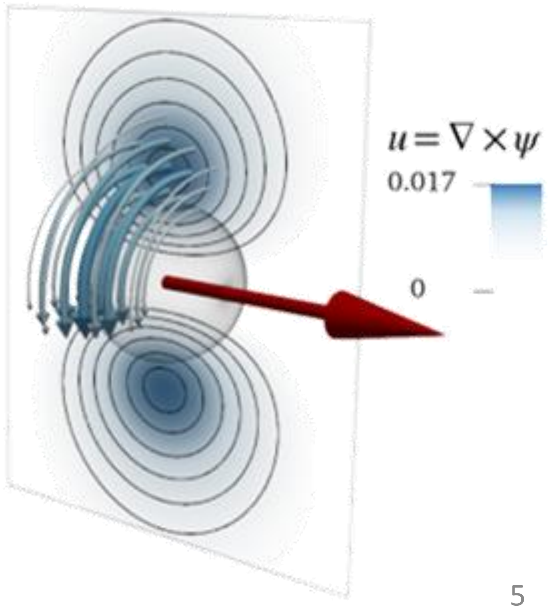
Vortex stretching | Viscous diffusion | SFS stresses T_{ij}



- Discretization with kernel function

$$\overline{\boldsymbol{\omega}}(\mathbf{x}) \approx \sum_p \boldsymbol{\Gamma}_p \zeta_\sigma(\mathbf{x} - \mathbf{x}_p)$$

- Variable fidelity through particle size σ



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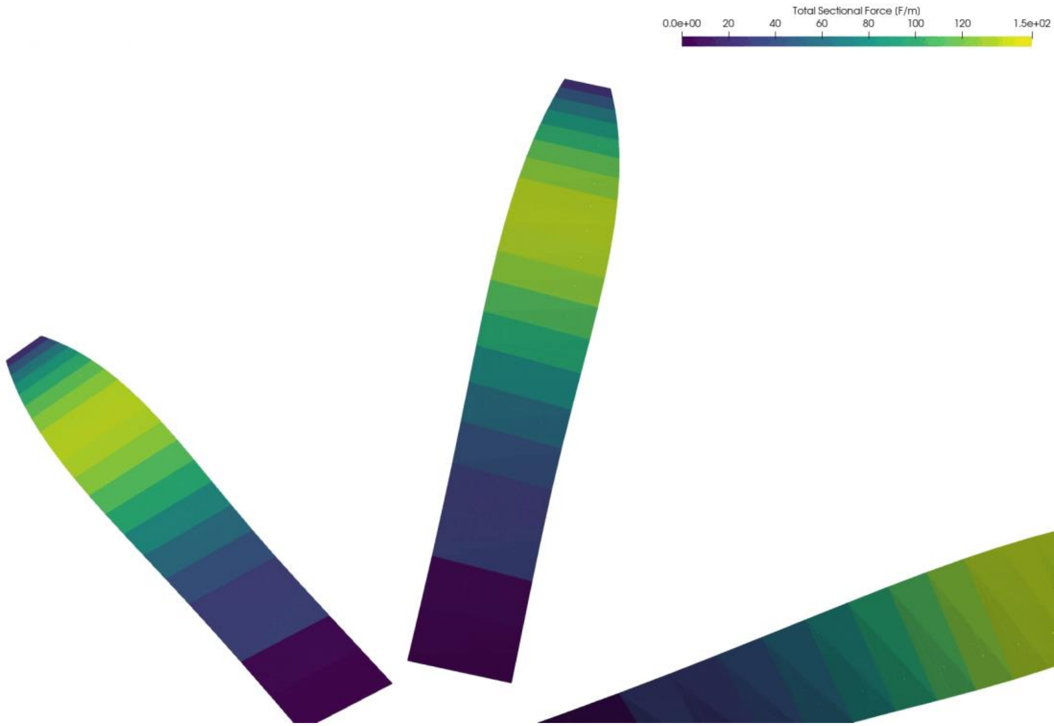
Vortex Particle Method
Rotor Modelling

- Lifting surfaces discretized as thin plate asserting force based on XFOIL polars
- Procedure:
  1. Discretization in N 2D cuts
  2. Lift, drag forces corrected by tip loss-, 3D stall delay-model
  3. AoA calculated every timestep
  4. Particles carrying lift-/drag-induced vorticity placed into free field
- Restrictions: no depiction of boundary layer profile, wake deficit



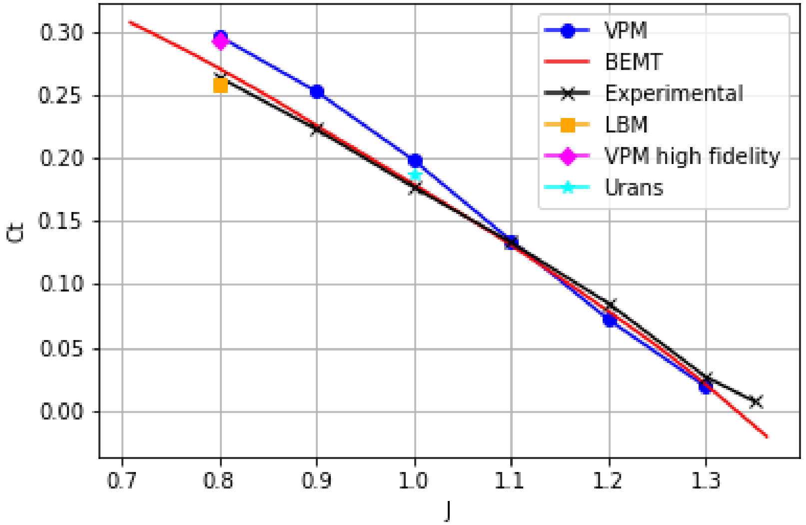
Vector orientation/scaling: Circulation
(only tip vortex depcted)

Isolated Rotor
Performance

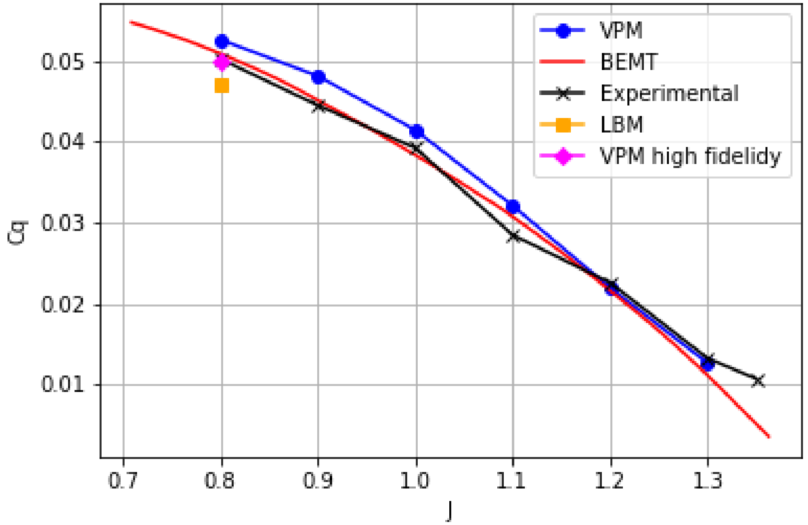
Variation of rpm, $v_\infty = 30\ \mathrm{m}/s$:

- VPM (low fidelity) overestimates rotor forces
- Overestimation increases with higher rpm
- Windmilling occurs too early

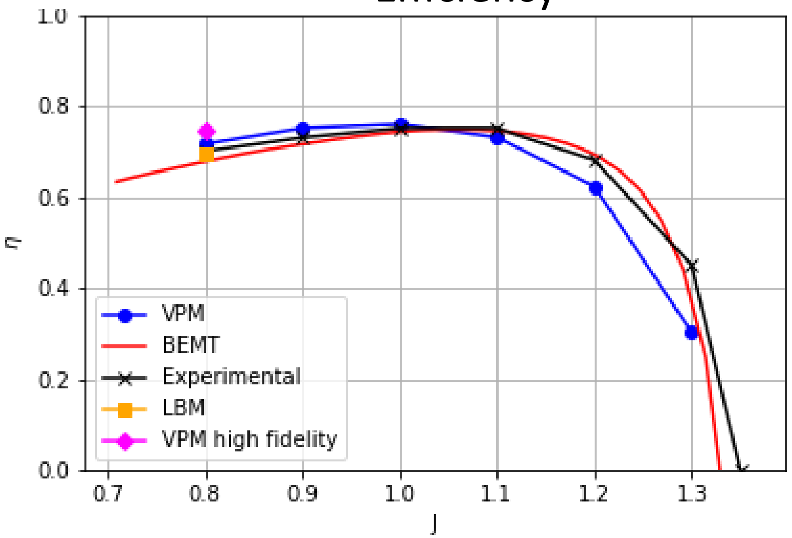
Thrust



Torque



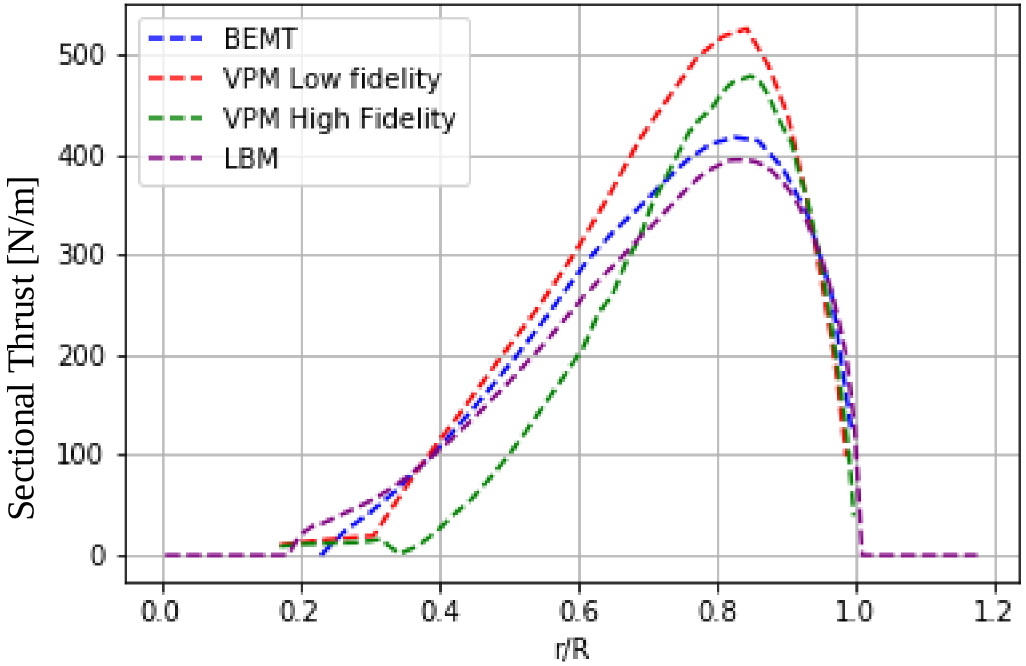
Efficiency

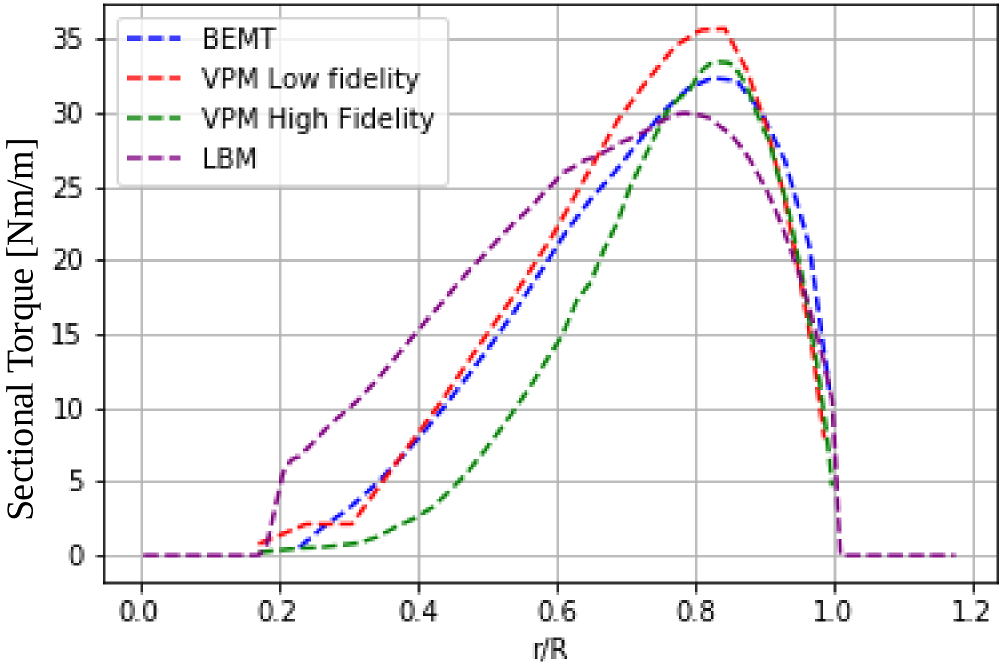


Isolated Rotor
Aerodynamics

Radial distribution of rotor forces

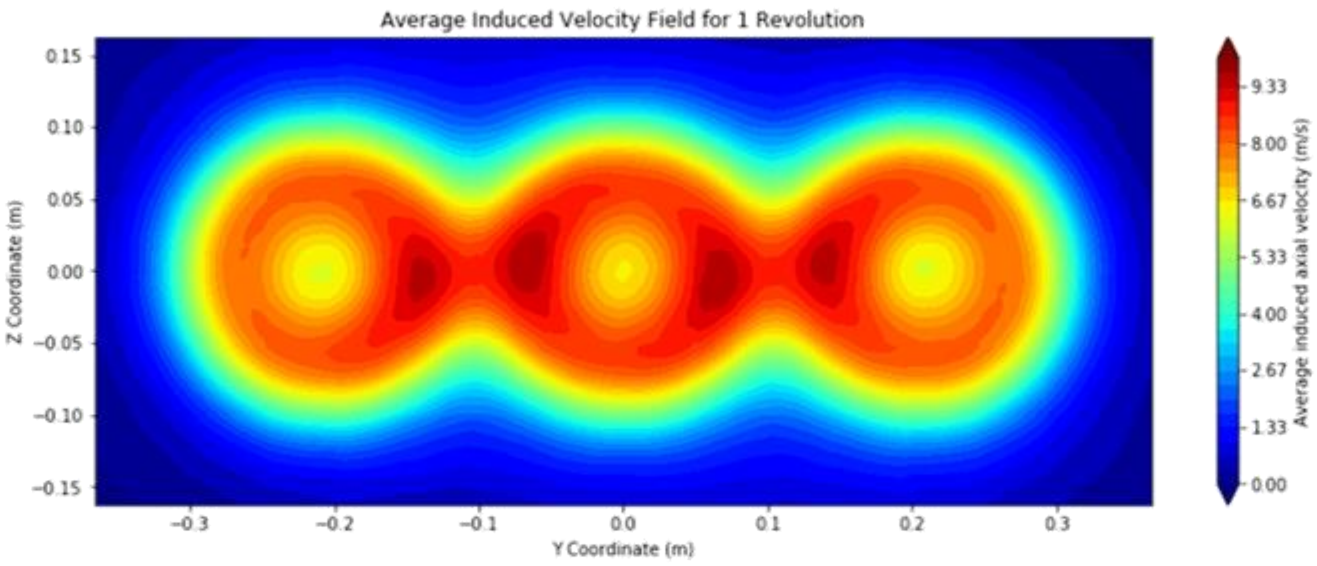
- Qualitative agreement
- VPM higher then LBM, BEMT => deviation shrinks with higher fidelity

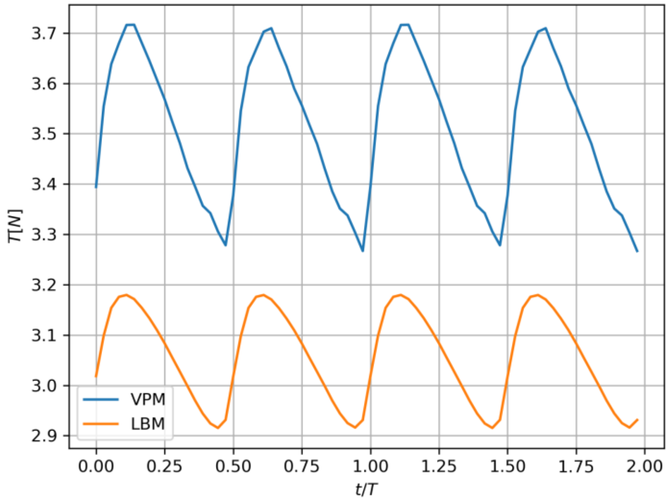


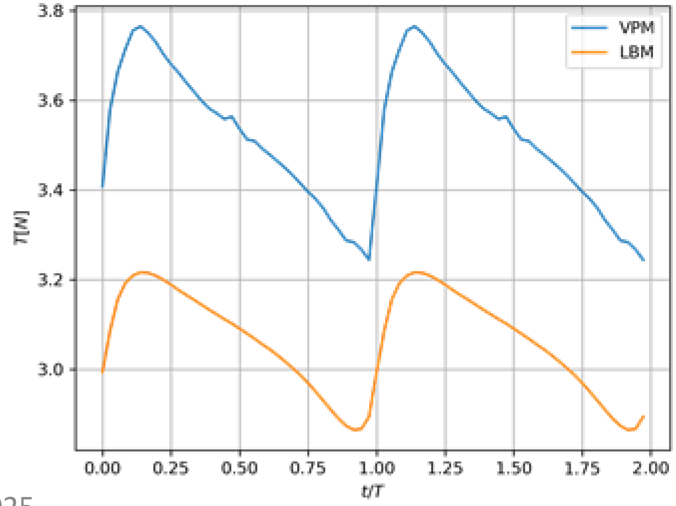


Multi Rotor
Aerodynamics

- Peaks in mean induced velocity field
- Total Thrust fluctuation:
  - Noise generating mechanism
  - Fluctuation qualitatively well captured
  - Mean thrust and amplitude overestimated

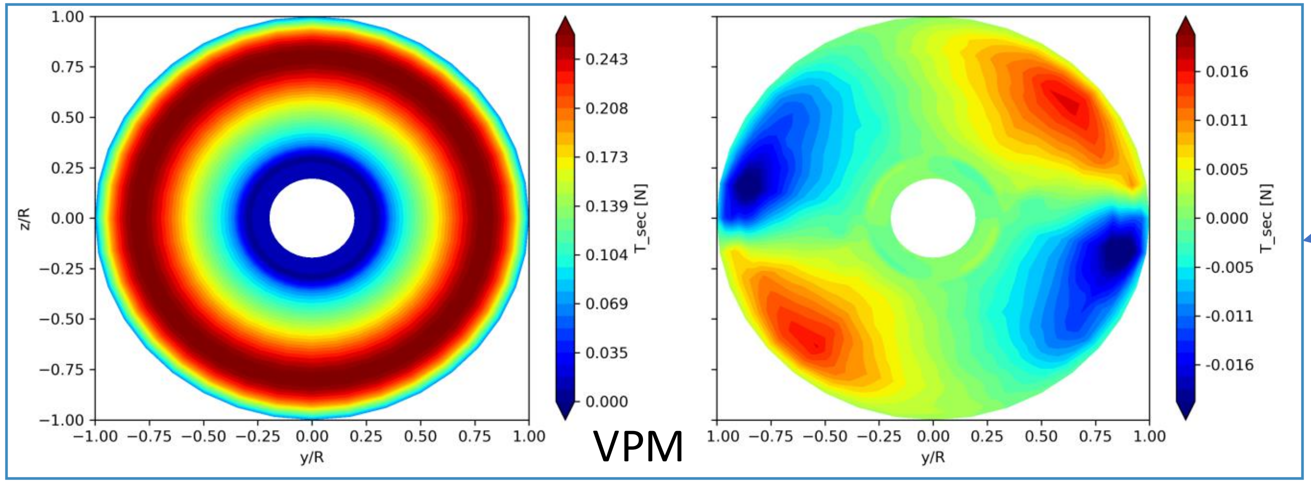


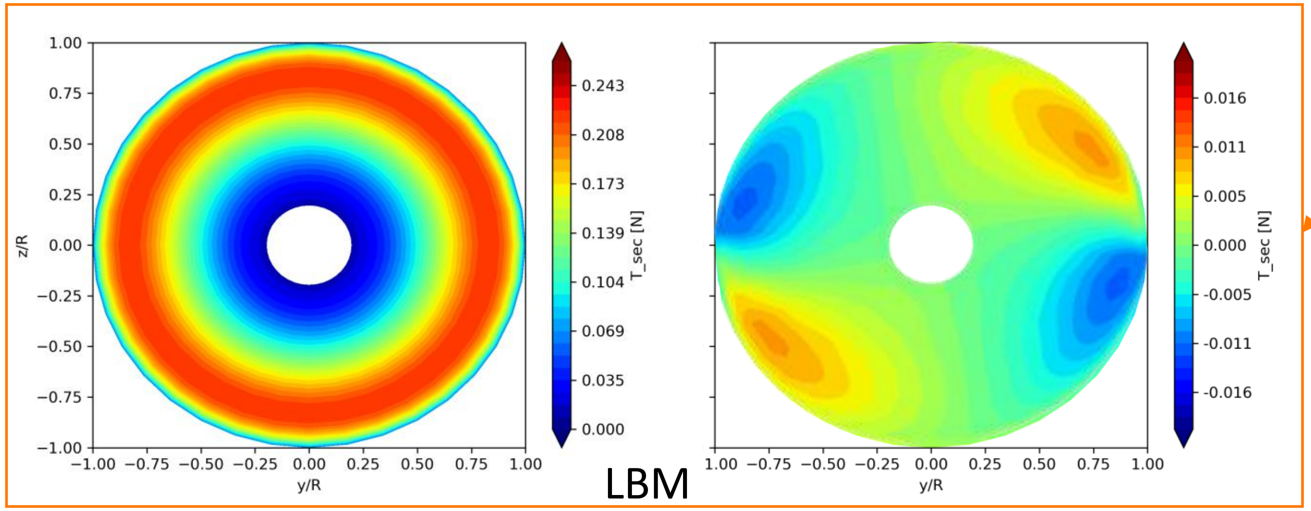


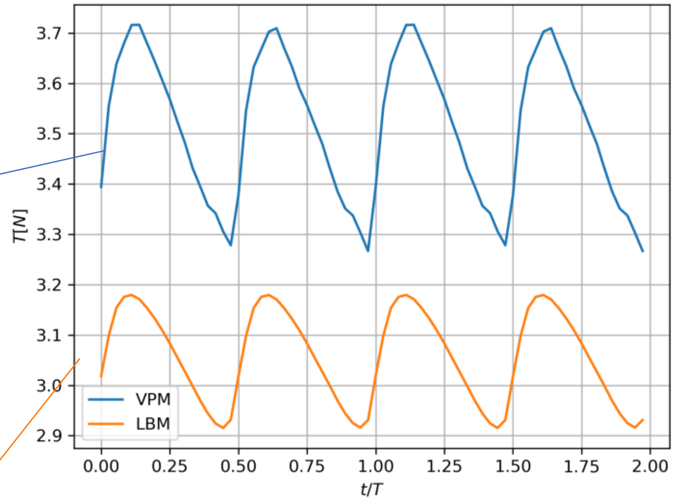


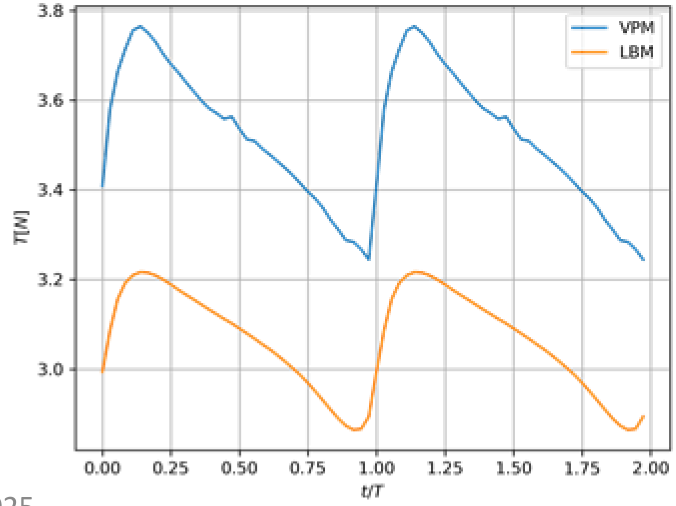
Multi Rotor
Aerodynamics

Mean Thrust $\bar{T}$ | Thrust Fluctuation T'









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Multi Rotor

Aeroacoustics

PropNoise:

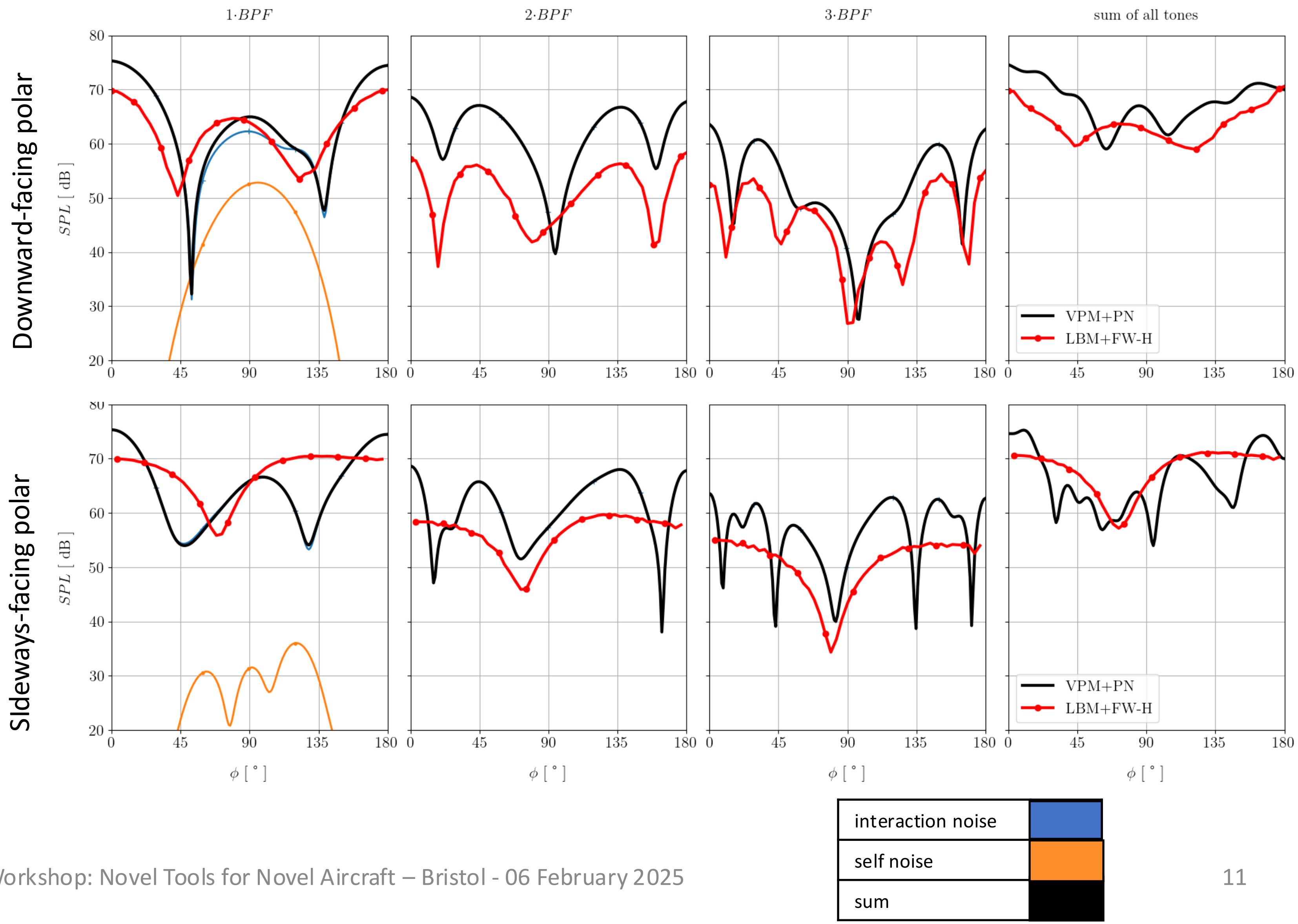
- Analytic approach based on acoustic analogy
- Sum of different noise generating mechanisms: self noise, tip-to-tip interaction
- Aeroacoustic interference model

FW-H: Numeric approach

Tonal noise directivity:

- Good agreement in directivity pattern
- Same trends in frequencies
- Overestimation of propeller forces
  => Overestimation SPL

Tonal noise directivity



Discussion & Next Steps

Benefits:

- Easy setup, no meshing
- Sufficient results in little computational time
- Acoustic and aerodynamic trends well depicted
- No instability issues encountered

Restrictions:

- Low mach (& fidelity) propeller model
- Results highly resolution dependend (convergency studies ongoing)
- Rising physical time, increasing particle numbers => more expensive

Next Step:
Apply method to eVTOLUTION baseline configuration & further validation