# Rotor Wake Modeling of Mars Rotorcraft using the Viscous Vortex Particle Method

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**Advanced Modeling & Simulation (AMS) Seminar Series**

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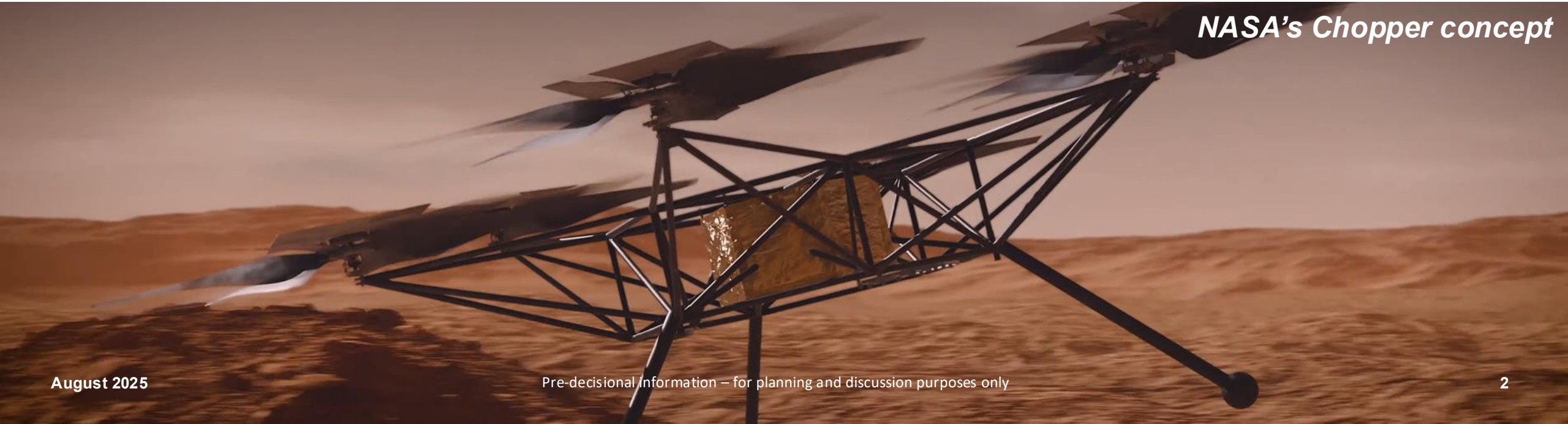




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# Expanding the Mars Rotorcraft Analysis Toolbox

- **Next-generation Mars rotorcraft are likely to be multi-rotor, large-scale configurations with expanded flight envelope**
  - Introduces complex wake dynamics, in particular rotor-on-rotor interference effects, that impact flight dynamics and control
  - Research efforts in rotor wake modeling in Mars-typical aerodynamic regime (low Reynolds number, high subsonic) is limited



*NASA's Chopper concept*

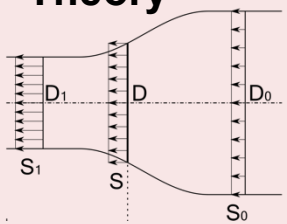

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# Range of Toolsets for Rotor Wake Modeling

**Least Resolved** → **Most Resolved**

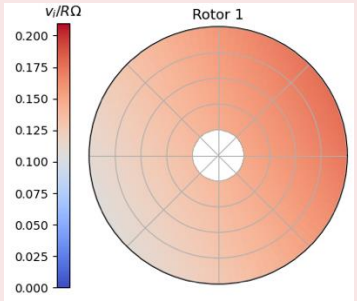
## Potential Flow

### Momentum Theory




Many Tools

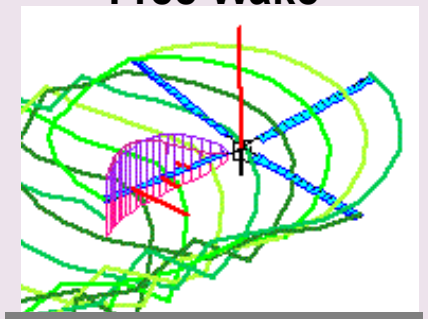
### Dynamic Inflow




CAMRAD MT

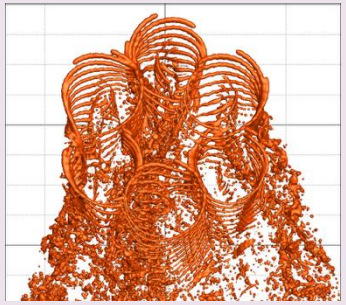
## Vortex Theory

### Free Wake



CAMRAD Free Wake

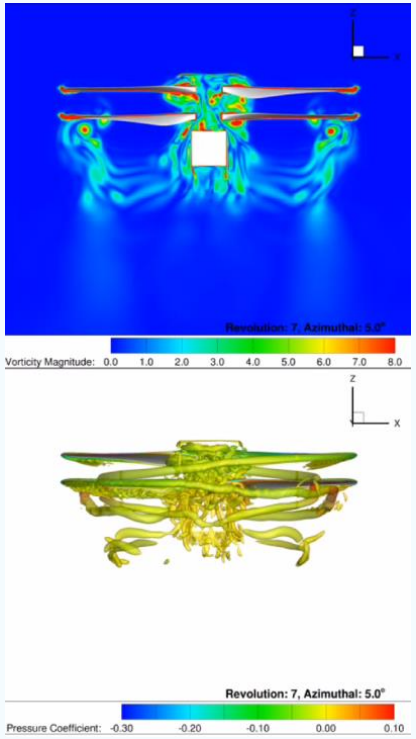
### Vortex Particle Methods



Flightlab VVPM

## Grid-based CFD

### Blade-resolved 3D CFD

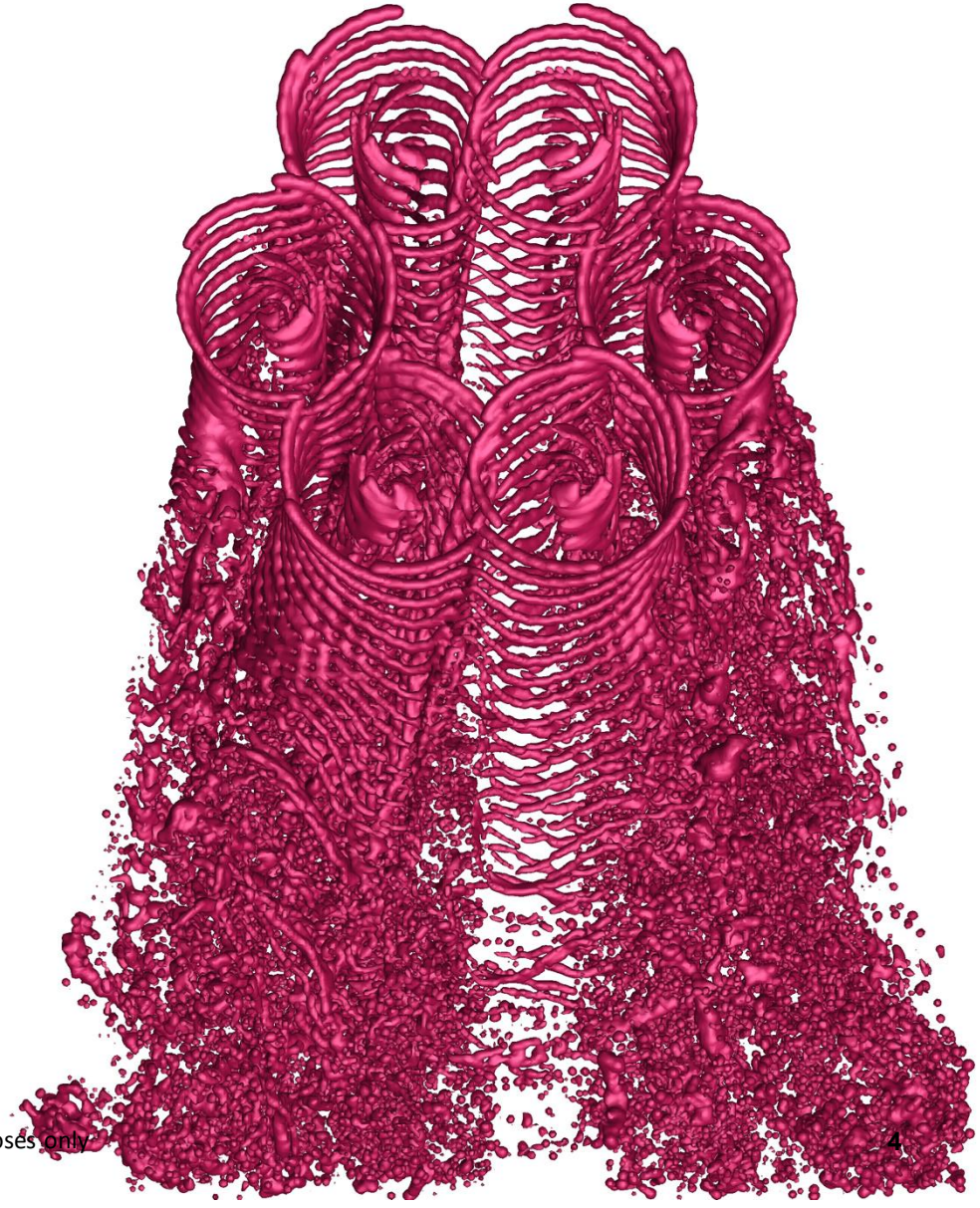



OVERFLOW

August 2025

# The Need for a Mid-fidelity Approach

- **Objective: Evaluate the utility of a Viscous Vortex Particle Method (VVPM) for Mars rotorcraft wake predictions**

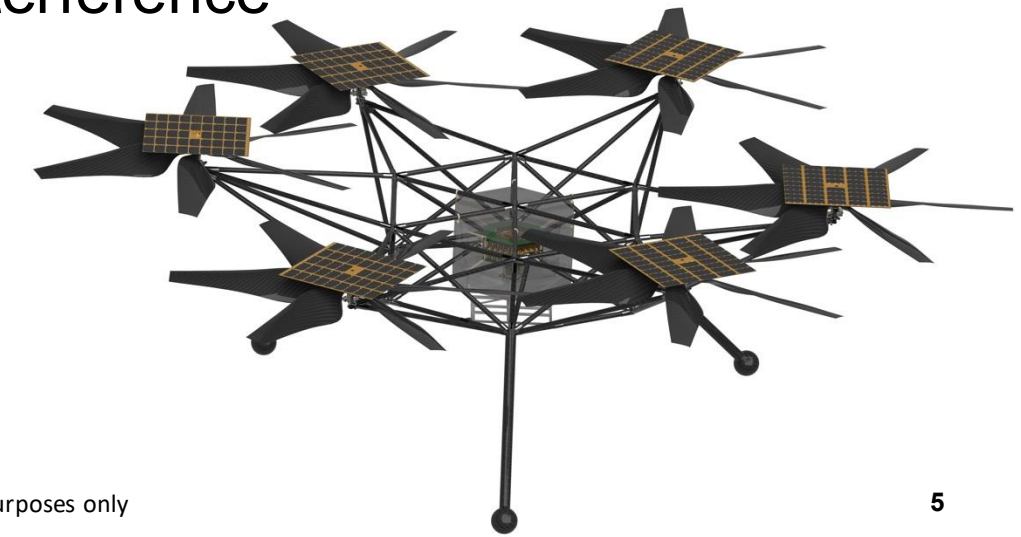



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# Outline

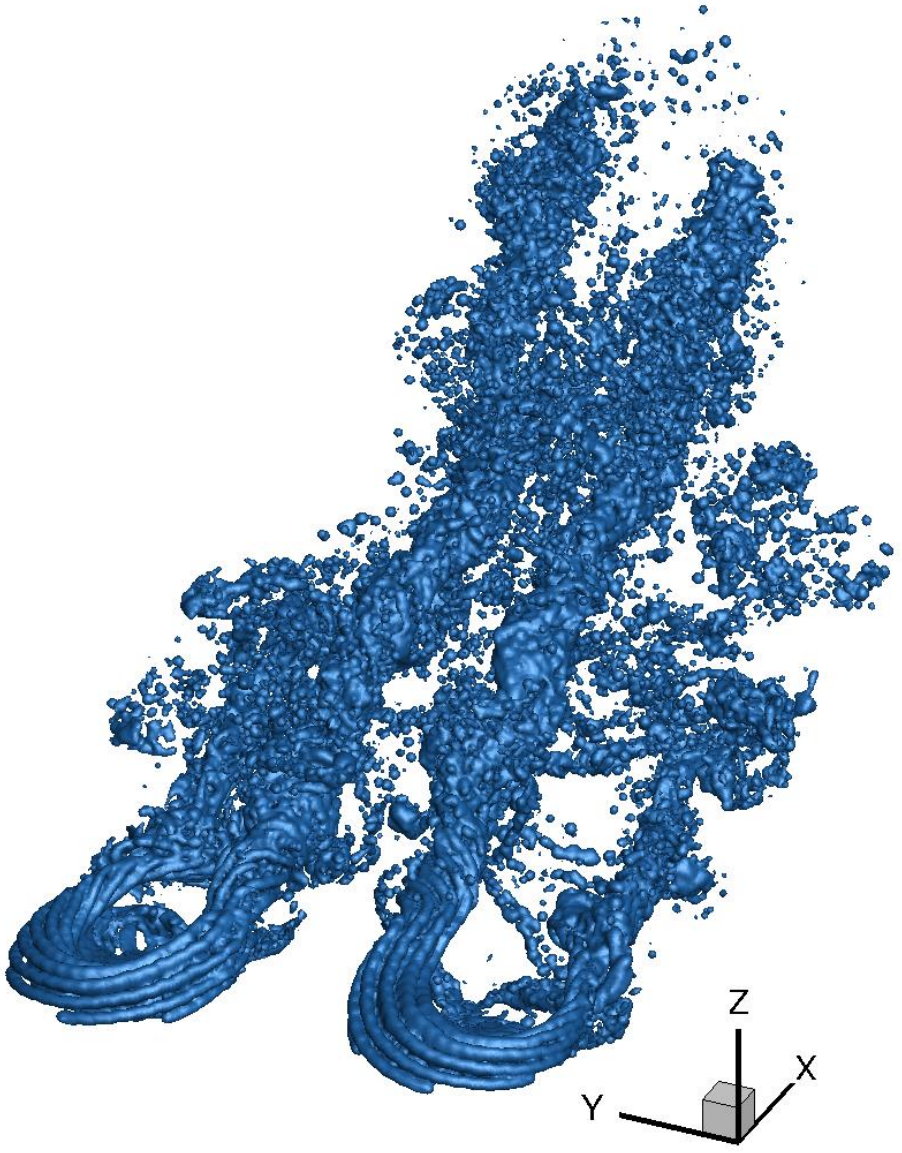
- **The Viscous Vortex Particle Method**
- **Validation against the Ingenuity Mars Helicopter**
  - Coaxial performance predictions in hover
  - Forward flight data from Mars
- **Analysis of a next-generation Mars rotorcraft concept**
  - Multi-rotor wake dynamic predictions
  - A VVPM derived reduced-order rotor-rotor interference model for real-time flight dynamics analysis
- **Conclusions**





# The Viscous Vortex Particle Method: Overview

- **First principles approach to rotor wake and interference problems**
- **Grid-free, computationally tractable for complex multi-rotor configurations**
- **Relevance for Mars rotorcraft wake analysis:**
  - Retains effect of air viscosity on vorticity diffusion, important for Mars typical Reynolds numbers
  - No empirical tuning parameters
- **Allows for (loose) trim coupling**



# The Viscous Vortex Particle Method: Governing Equations

**Incompressible NS, constant viscosity**

Eulerian frame

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla u} = -\frac{\boldsymbol{\nabla} p}{\rho} + \boldsymbol{\nu \nabla^2 u}$$

$\nabla \times ()$

**Vortex Transport Equation**

Lagrangian frame

$$\frac{\boldsymbol{d\omega}}{dt} = \boldsymbol{\omega} \cdot \boldsymbol{\nabla u} + \boldsymbol{\nu \nabla^2 \omega}$$

- Solve for vorticity field $\omega = \nabla \times u$
- Pressure field $p$ decoupled from governing equations
- No explicit convection term- mitigates numerical dissipation

# The Viscous Vortex Particle Method: Discretization and Solution

$$\frac{d\boldsymbol{\omega}}{dt} = \underbrace{\boldsymbol{\omega}\cdot\nabla\boldsymbol{u}}_{\text{Vortex stretching}} + \underbrace{\nu\nabla^2\boldsymbol{\omega}}_{\text{Viscous diffusion}}$$

- **Vortex particle representation of vorticity field**
  - For N particles each with position and vorticity $\boldsymbol{x_i}, \boldsymbol{\alpha_i}$, vorticity field represented as $\boldsymbol{\omega}(\boldsymbol{x},\boldsymbol{t}) = \sum_i^N \boldsymbol{\xi_\sigma}(\boldsymbol{x} - \boldsymbol{x_i})$, where $\boldsymbol{\xi_\sigma}$ is (commonly Gaussian) distribution function
- **Biot-Savart, kernel $K(\cdot)$, gives a convection-diffusion problem such that for each particle:**

$$1)\ \frac{d\boldsymbol{x_i}}{d\boldsymbol{t}} = \boldsymbol{u_i} = -\sum_j \frac{\mathbf{1}}{\boldsymbol{\sigma_{ij}}}\boldsymbol{K}\left(\frac{|\boldsymbol{x_i}-\boldsymbol{x_j}|}{\boldsymbol{\sigma_{ij}}}\right)\left(\boldsymbol{x_i} - \boldsymbol{x_j}\right)\times\boldsymbol{\alpha_j}$$

$$2)\ \frac{d\boldsymbol{\alpha_i}}{d\boldsymbol{t}} = \boldsymbol{\alpha_i}\cdot\nabla\boldsymbol{u_i} + \nu\nabla^2\boldsymbol{\alpha_i}$$

Contributions from all particles: Direct summation is $O(N^2)$ – need fast summation method

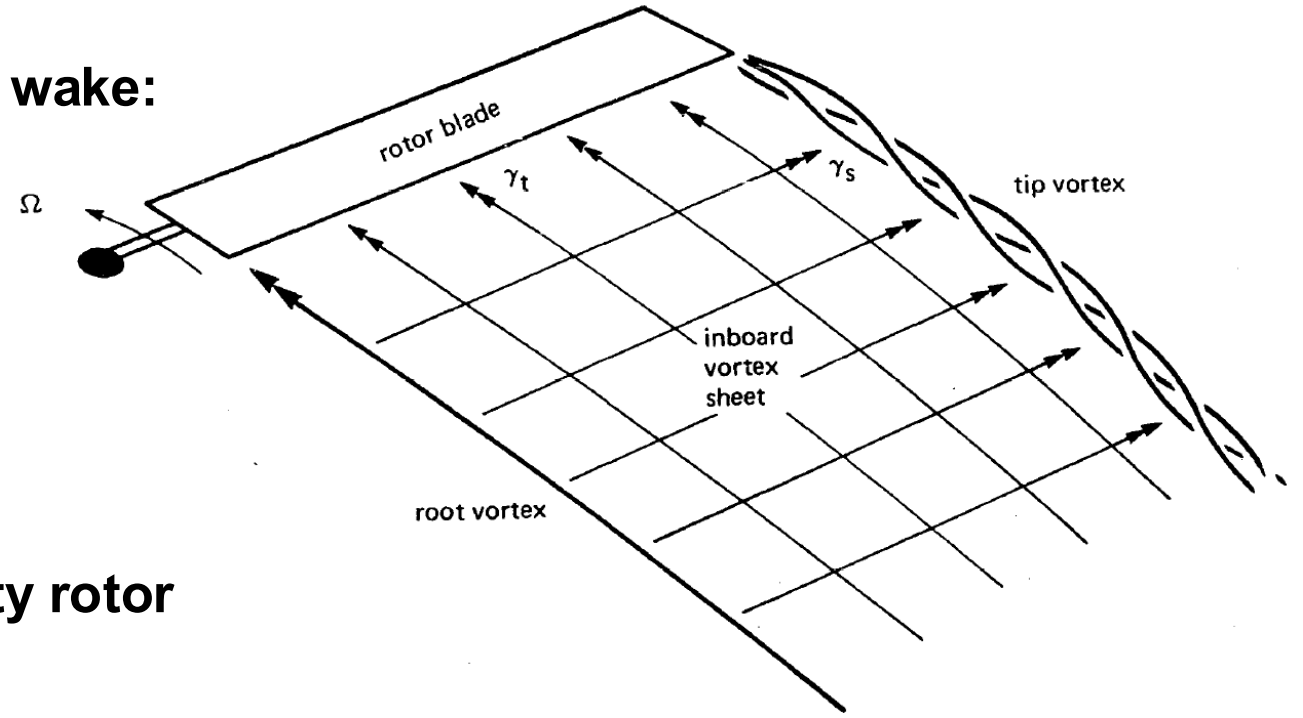
Laplace operator approximated through particle-strength-exchange (PSE) to avoid differentiation

# The Viscous Vortex Particle Method: Coupling with a Rotor Model

- Aerodynamic surfaces act as vorticity sources, releasing new particles to the vorticity field
- In lifting line theory, each blade segment is associated with a blade bound circulation vector $\Gamma_b$
- Conservation of vorticity gives net flux into wake:

$$\gamma_w = -\frac{d\Gamma_b}{dt} + v_b \nabla \cdot \Gamma_b$$

Shed vorticity  Trailed vorticity




- Note: Allows for coupling with higher-fidelity rotor aerodynamics model

# Aero- and Flight Dynamics on Mars: The Mars Environment

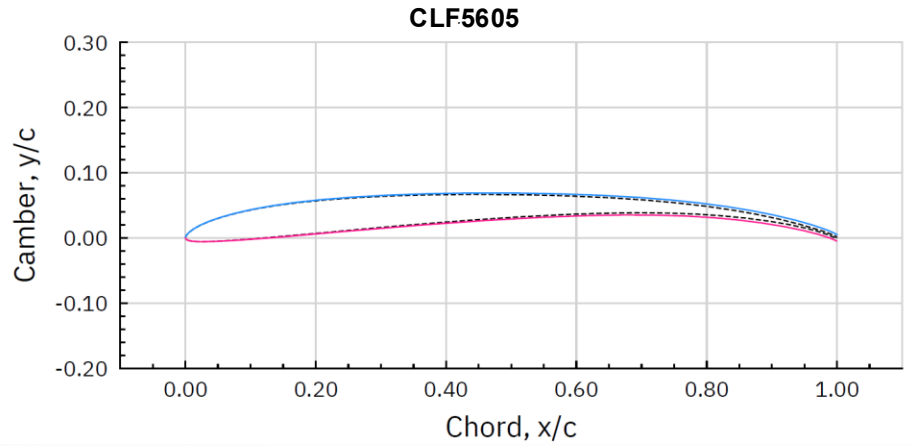
- **Reduced atmospheric density (~1-3% Earth)**
  - Low Re (~10K) : Adverse effect on aerodynamic performance
  - Minimal aerodynamic flap damping
- **Reduced gravity (~38% Earth)**



*The Perseverance Mars rover captured by Ingenuity*

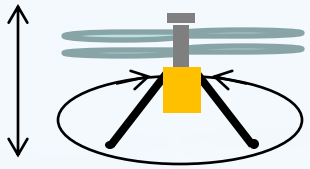
# The Ingenuity Mars Helicopter: Vehicle Overview

| | |
|---|---|
| R | 0.605 m |
| m | 1.8 kg (~ 6.7 N) |
| $\Omega$ | $\leq$ 2800 RPM |
| $M_{tip}$ | 0.6–0.7 |
| $Re_c$ | ~10k |






**Symmetric/Antisymmetric Collective**

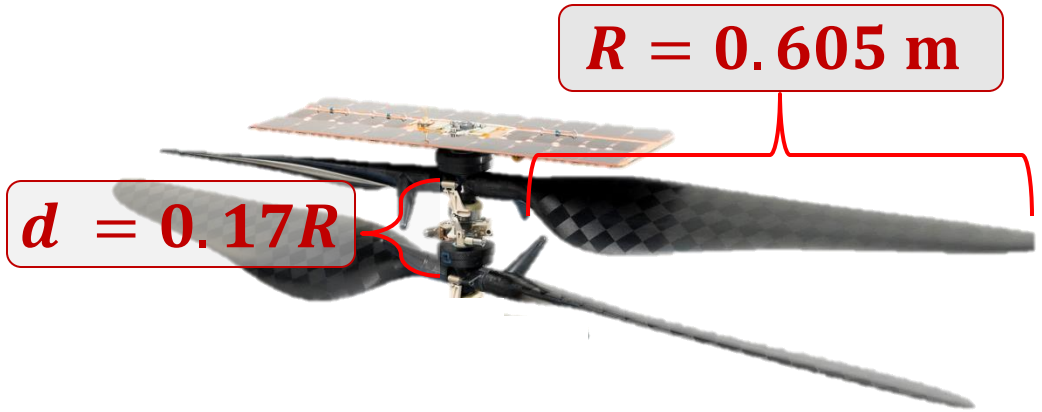


**Longitudinal/Lateral Cyclic**

# Experimental Validation in Hover - Overview

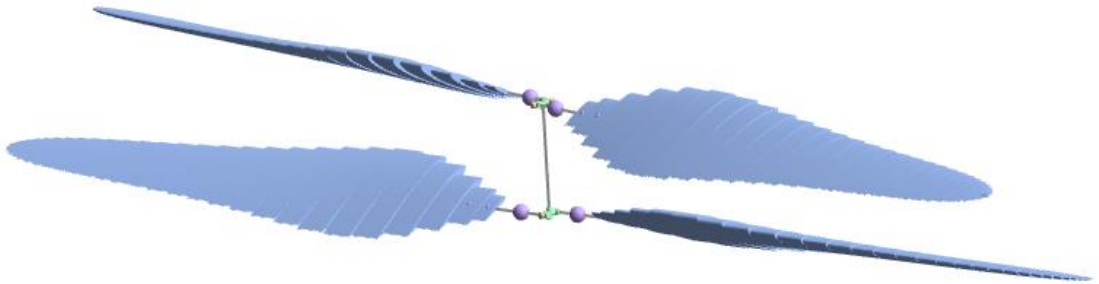
## Experimental Data

- **Ingenuity test campaign in NASA JPL 25ft Space Simulator, 2022**
  - Coaxial hover performance for Engineering Development Model 1 (EDM1)
- **Investigated increased blade loading and stall characteristics**

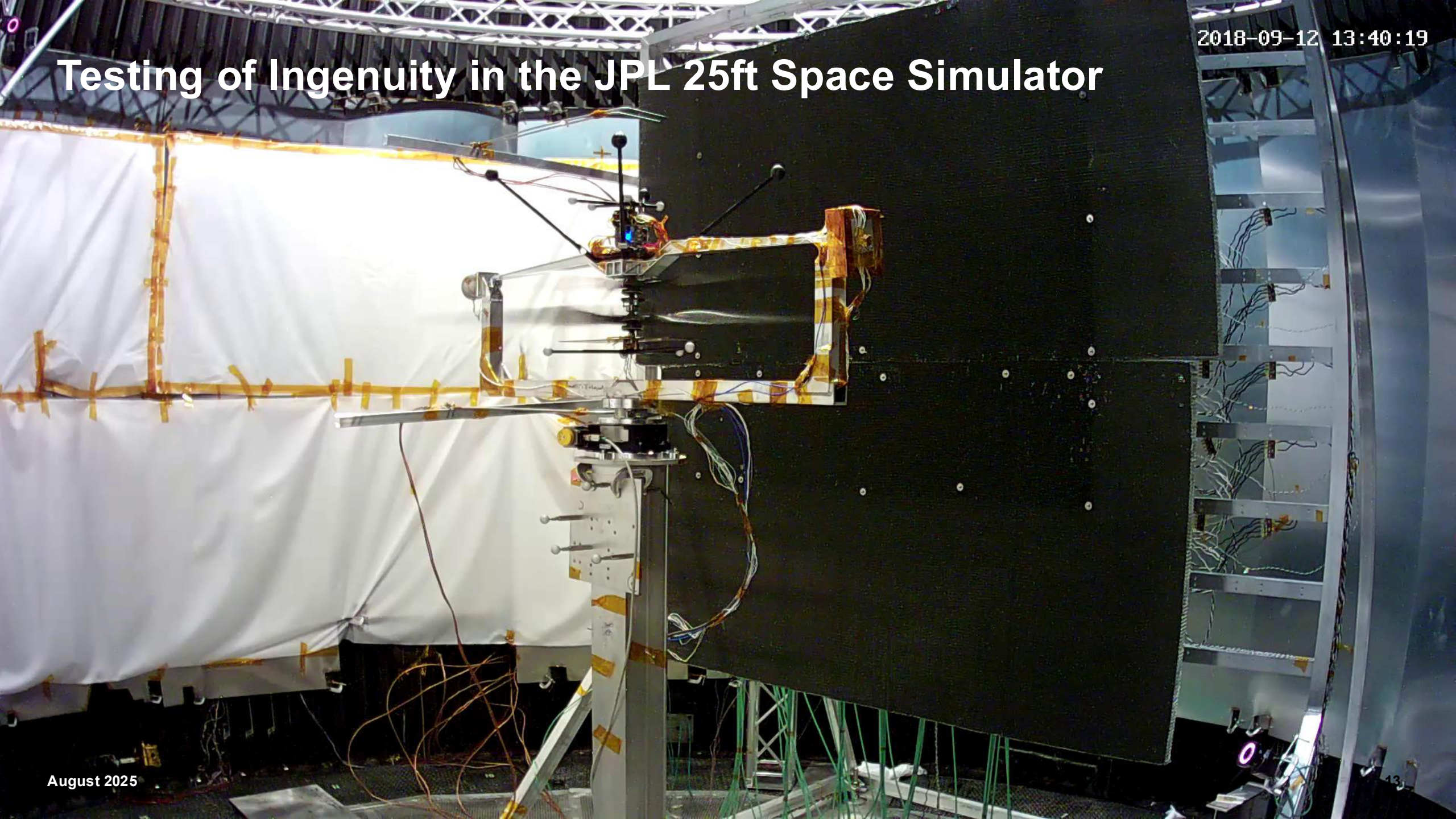



## Simulation Model

- **Aerodynamic rotor model**
  - Lifting line theory with Weissinger-L 3D correction
  - Airfoil performance look-up tables from 2D CFD using OVERFLOW
  - No unsteady models for attached flow or dynamic stall

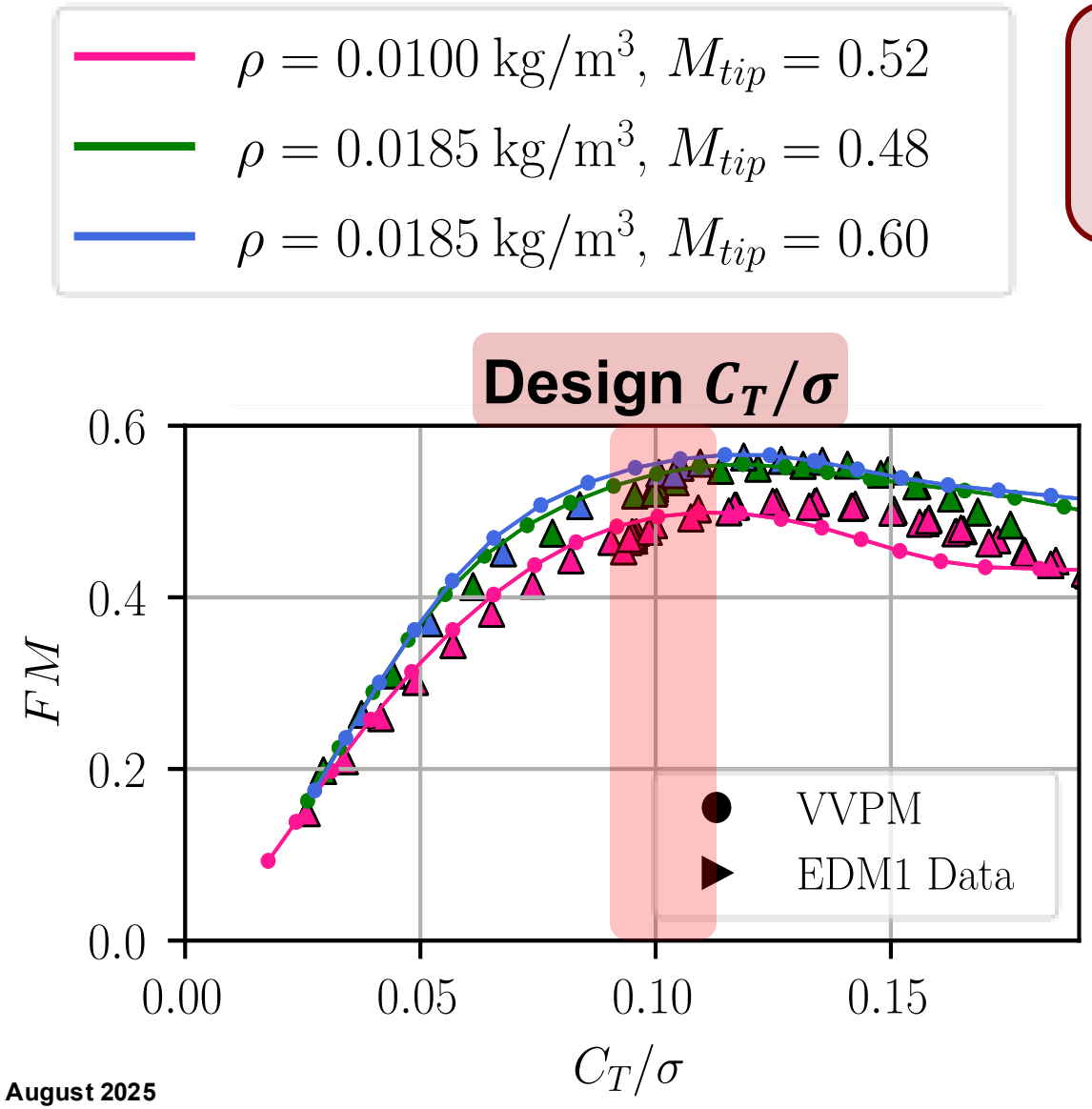


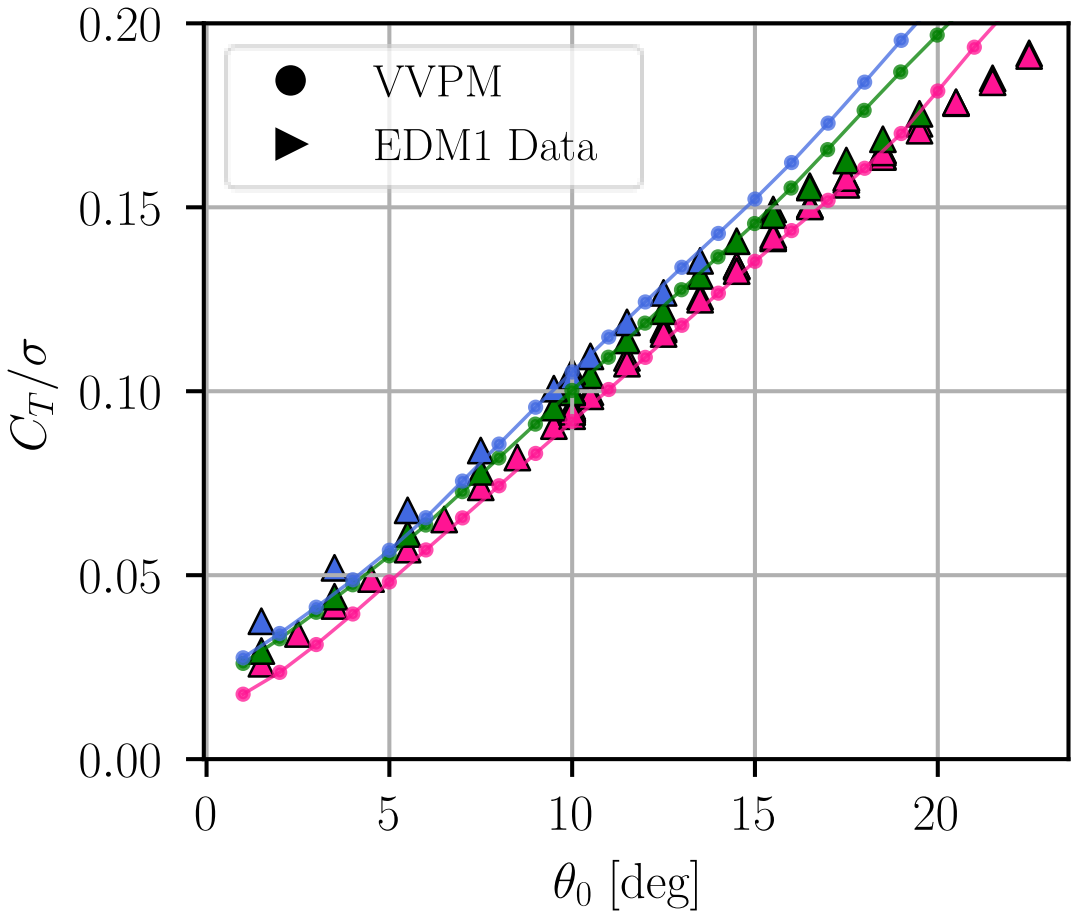
# Testing of Ingenuity in the JPL 25ft Space Simulator



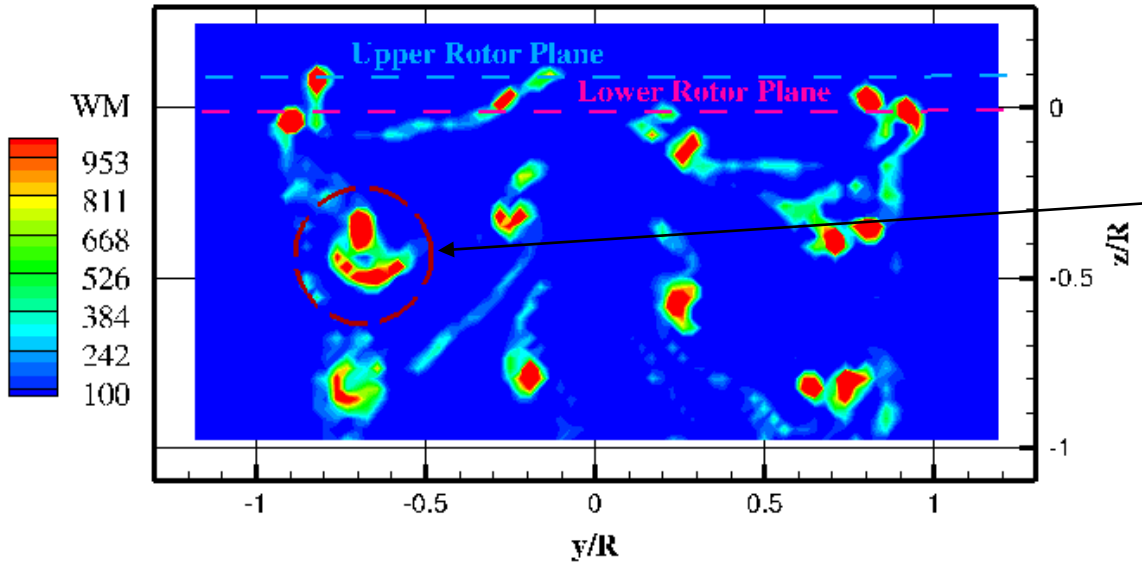
# Experimental Validation in Hover – Results

**Excellent matching of coaxial rotor performance around nominal operating blade loading of Ingenuity**

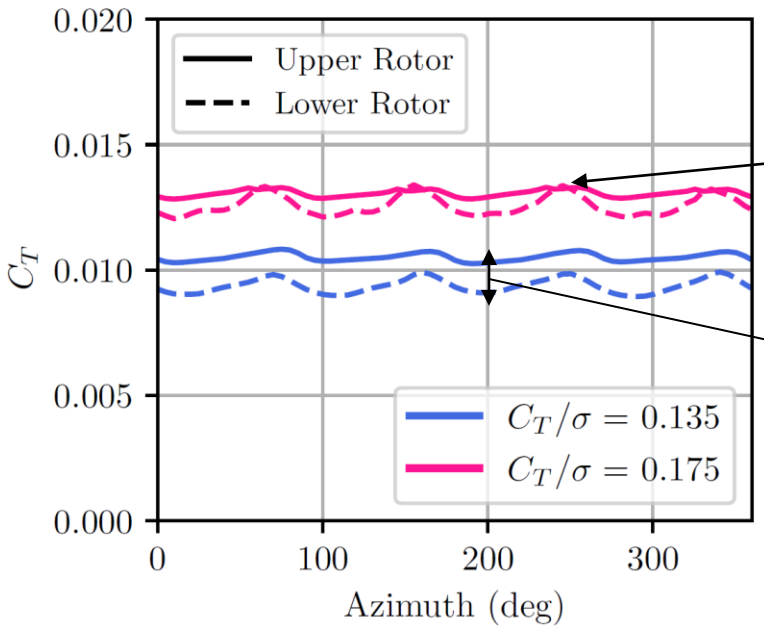


# Simulated Rotor Wake, Hover




Vortex pairing, (red) indicates inter-rotor vortex interaction




4/rev component due to bound circulation interaction at blade passings

Unequal thrust share in trim due to interference

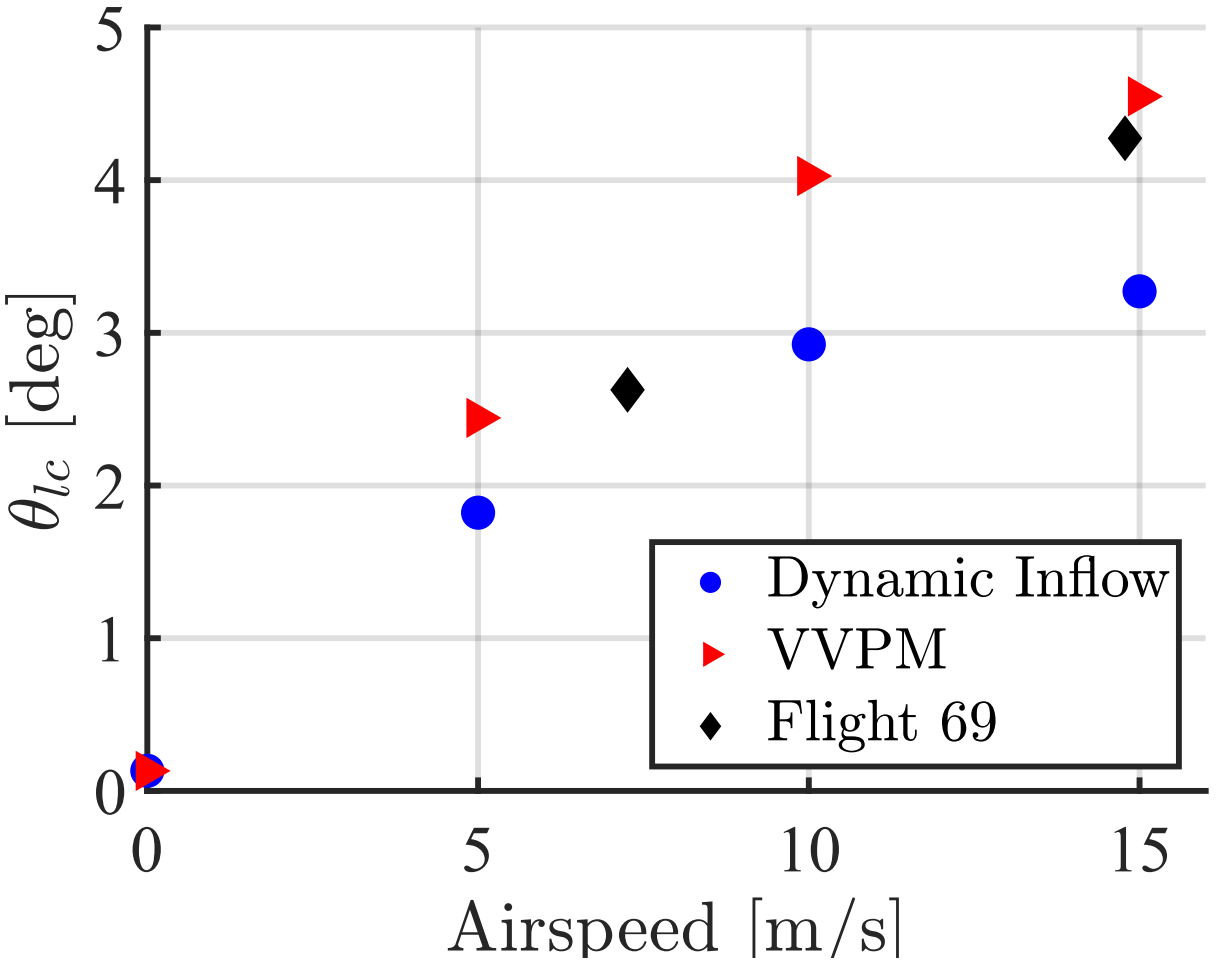
# Forward flight test led by Ames, December 2023



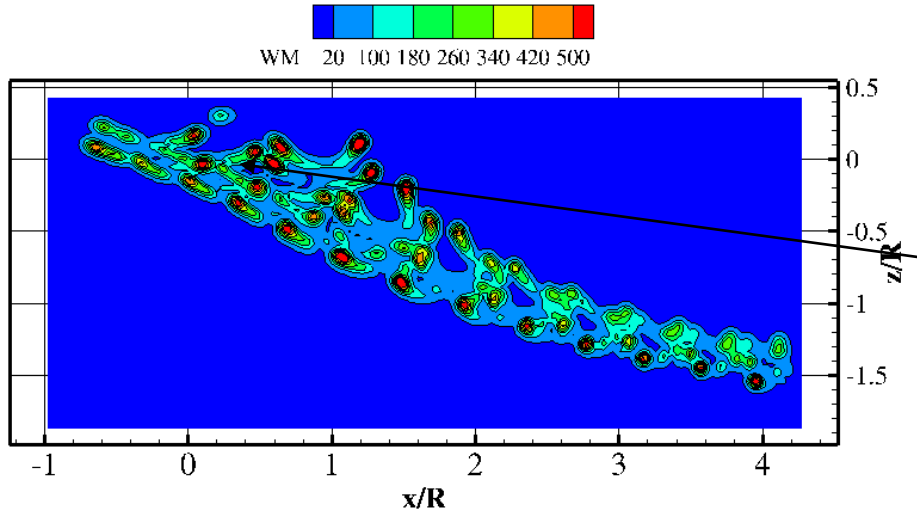
# Correlation with Ingenuity Forward Flight Data from Mars

- **Flight data from the Ingenuity forward flight System Identification tests (Flights 68 & 69) performed on Mars, December 2023**
- **Out-and-back trajectories with an acceleration to 10 m/s groundspeed**

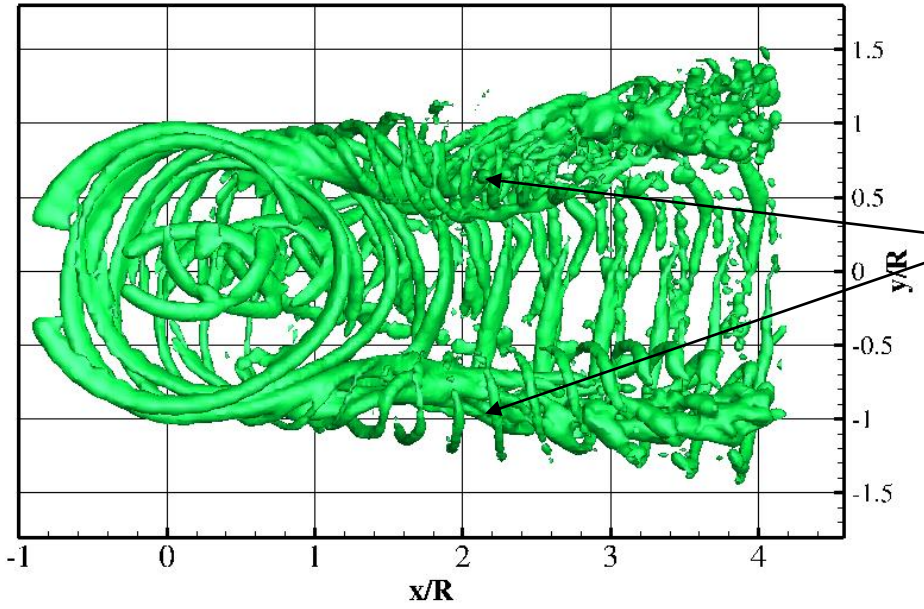
**Cyclic control efforts from steady state segments correlate well with VVPM trim solutions**



# Simulated Rotor Wake, Forward Flight




Trailed tip vortices from the upper rotor pass through the lower rotor plane



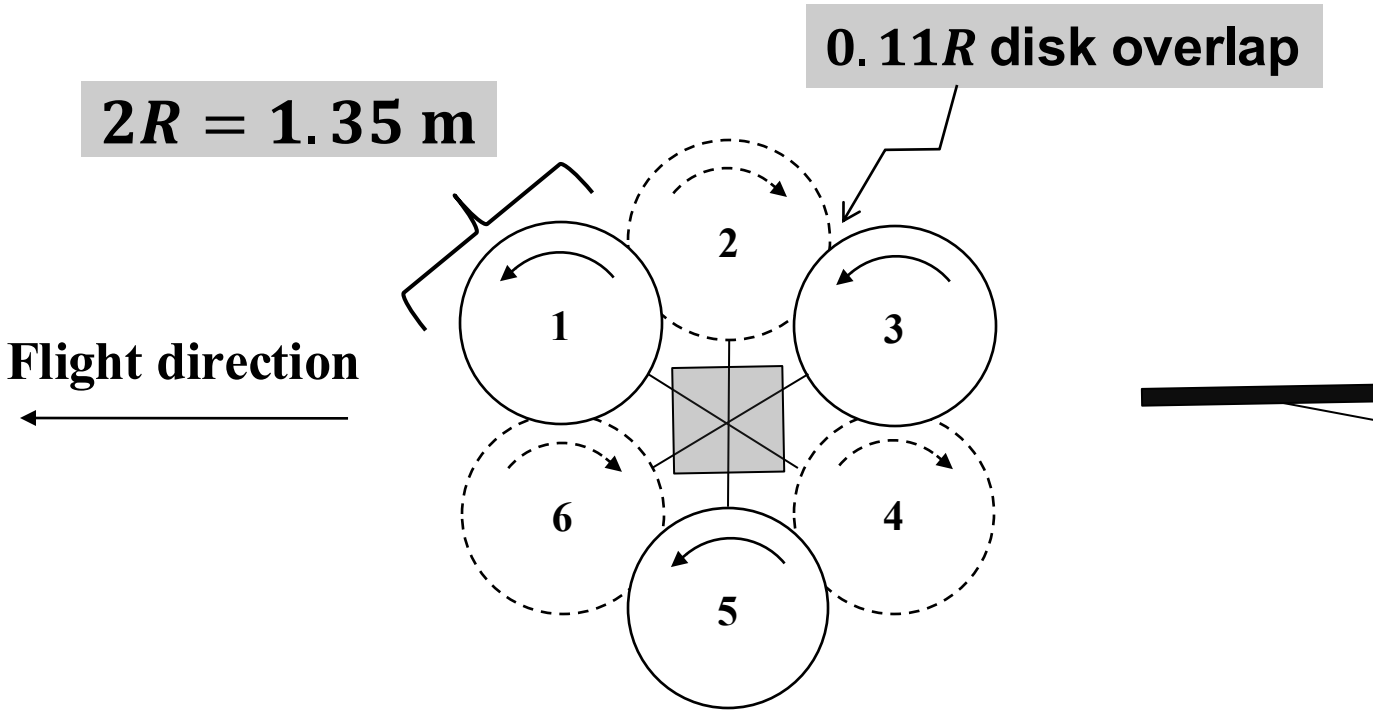

Vortex roll-up with interlocking of both the upper and lower rotor trailed tip vortices to form “supervortices”

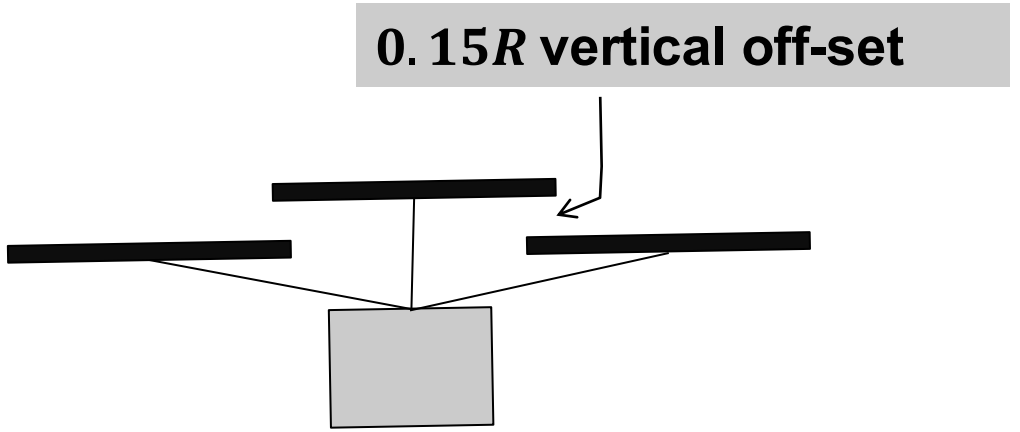
NASA’s Mars Chopper Concept (Animation)

# Introducing the Next-generation Mars Rotorcraft

- **The Chopper concept: A large-scale Mars hexacopter**
  - Mass >10×Ingenuity, increased rotor solidity
  - Expanded flight envelope, $\mu \leq 0.275$





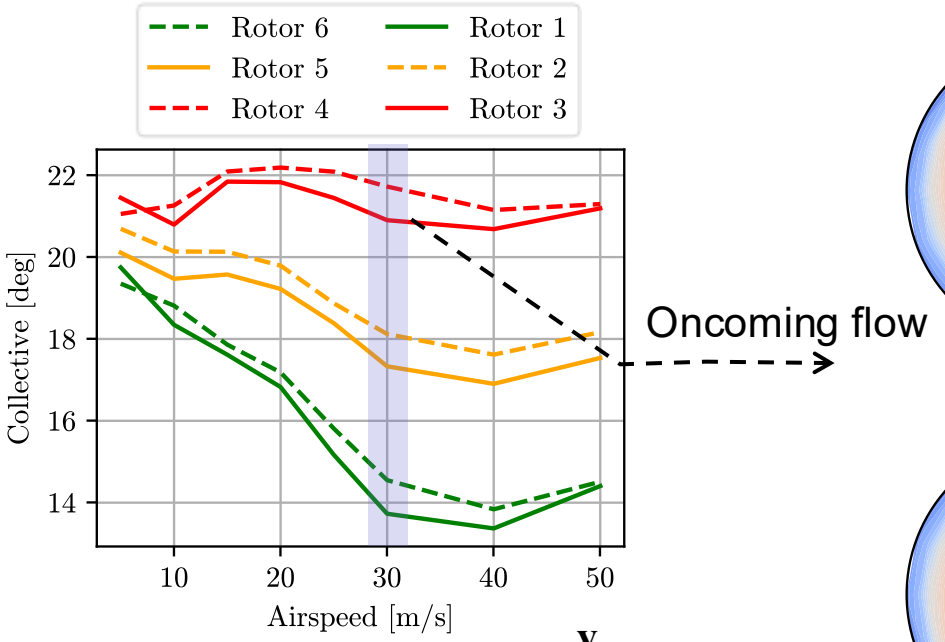





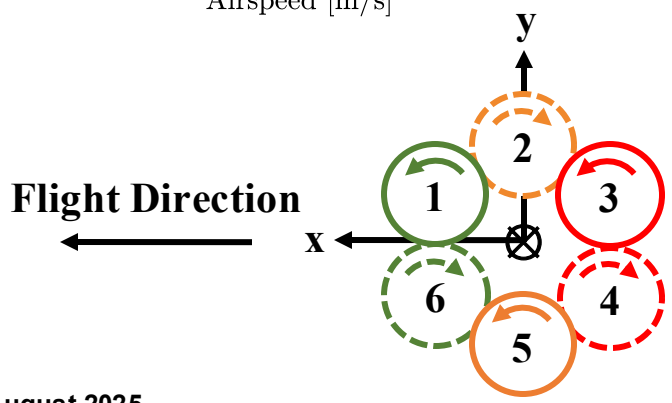
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# Multi-Rotor Wake Analysis - Overview

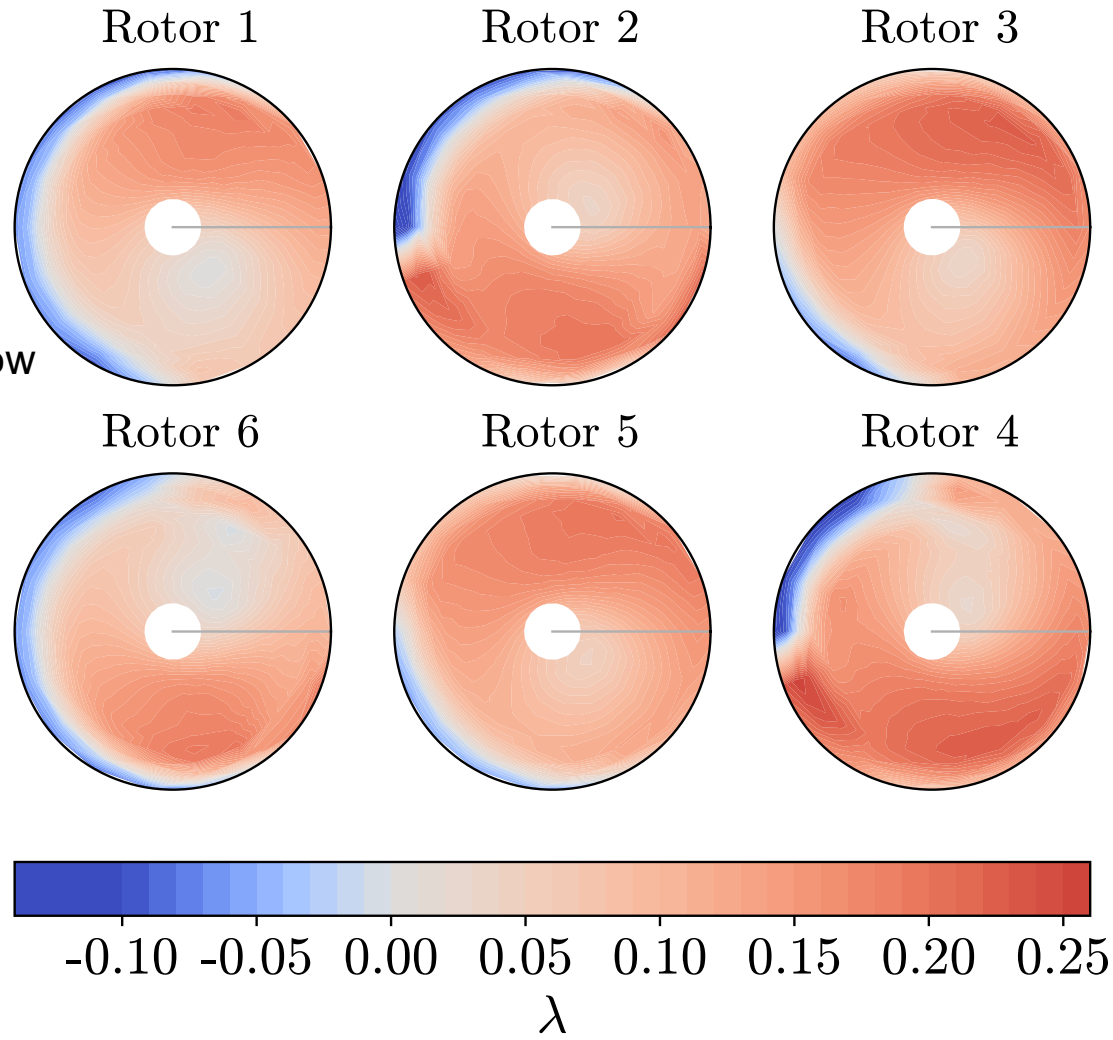
## Trim sweep in forward flight




Oncoming flow



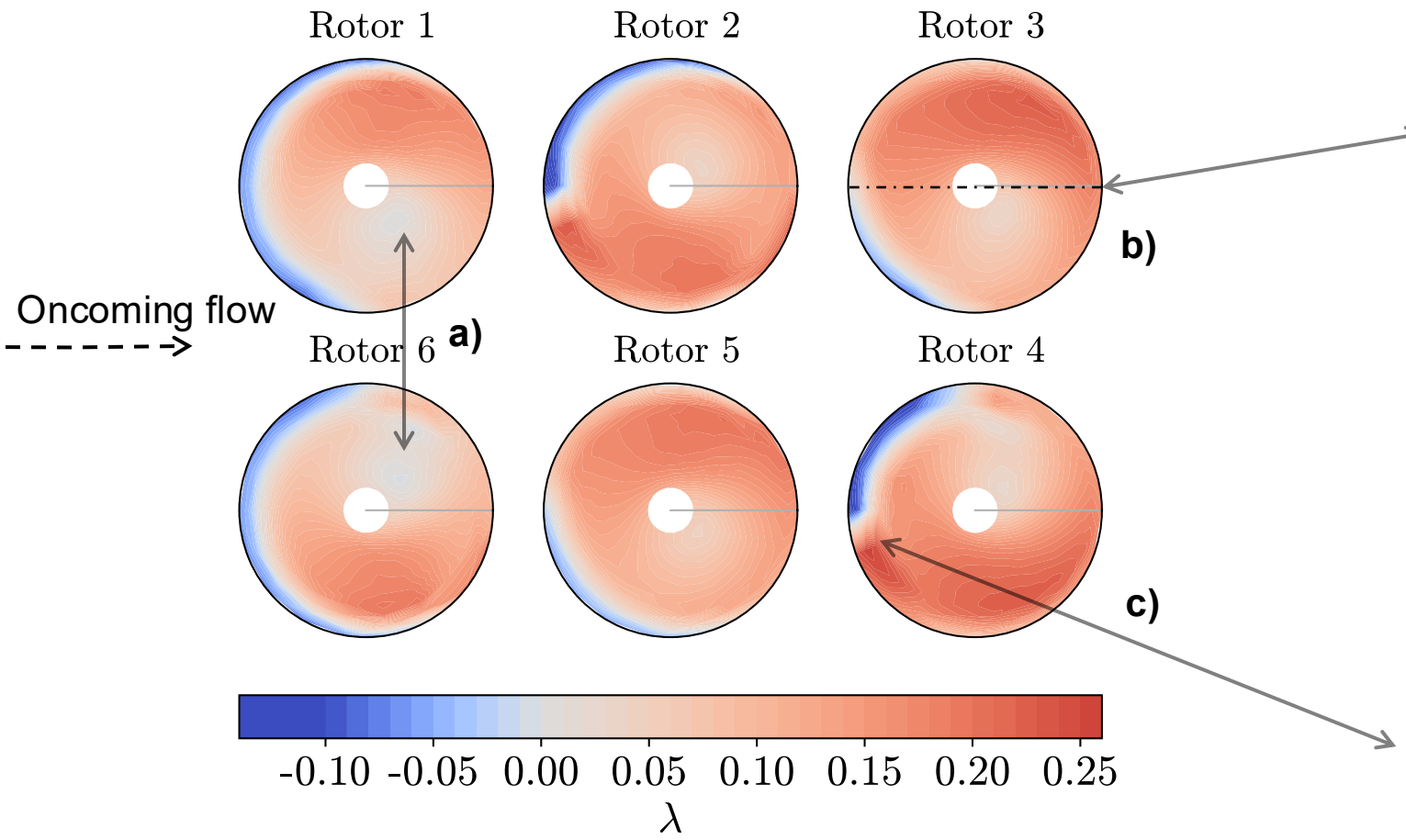

## Contours of VVPM inflow, $\lambda := w/\Omega R$






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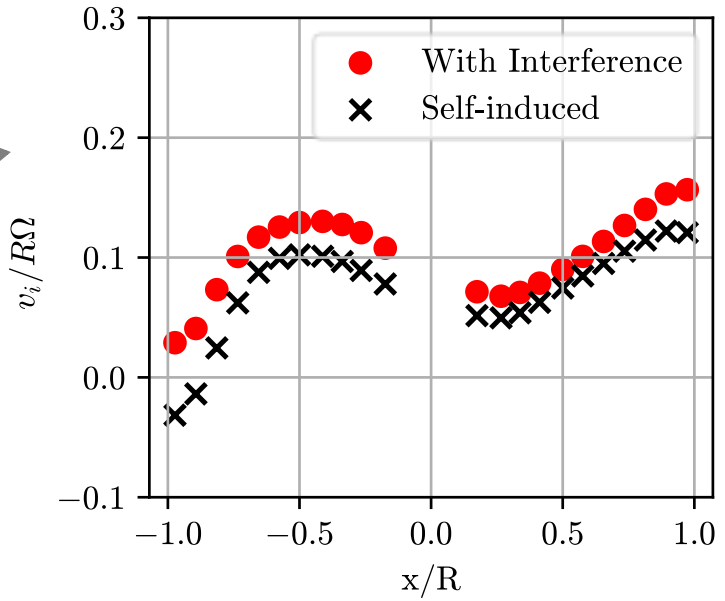
# Multi-Rotor Wake Analysis - Overview

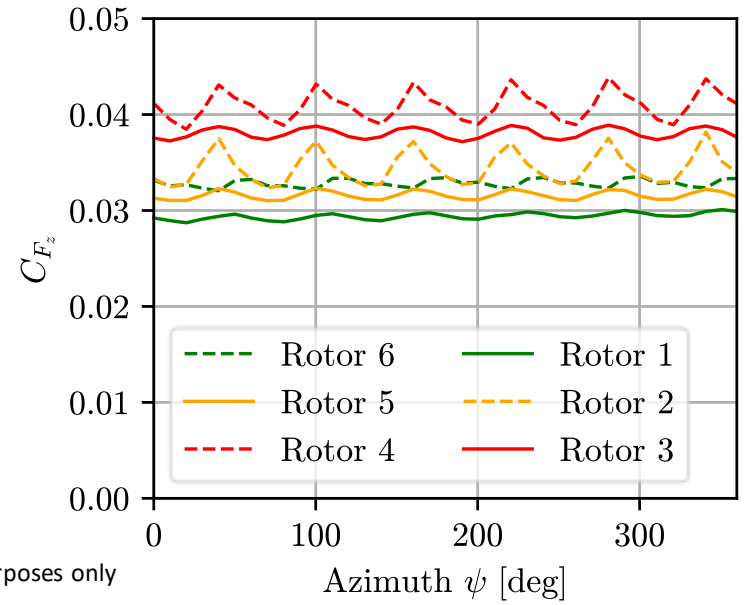



a) Mutual upwash effects in side-by-side pairs

b) Downwash from upstream to downstream

c) Blade vortex interactions at disk overlaps

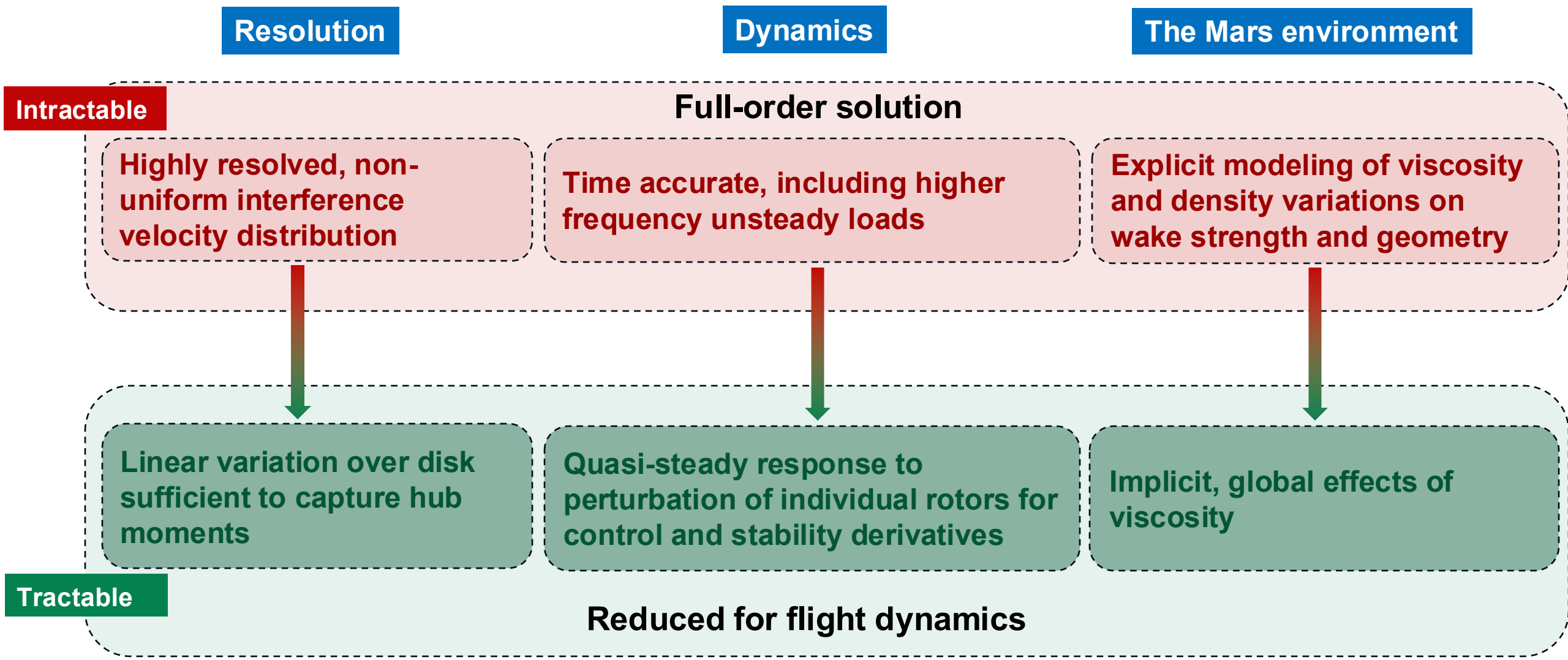


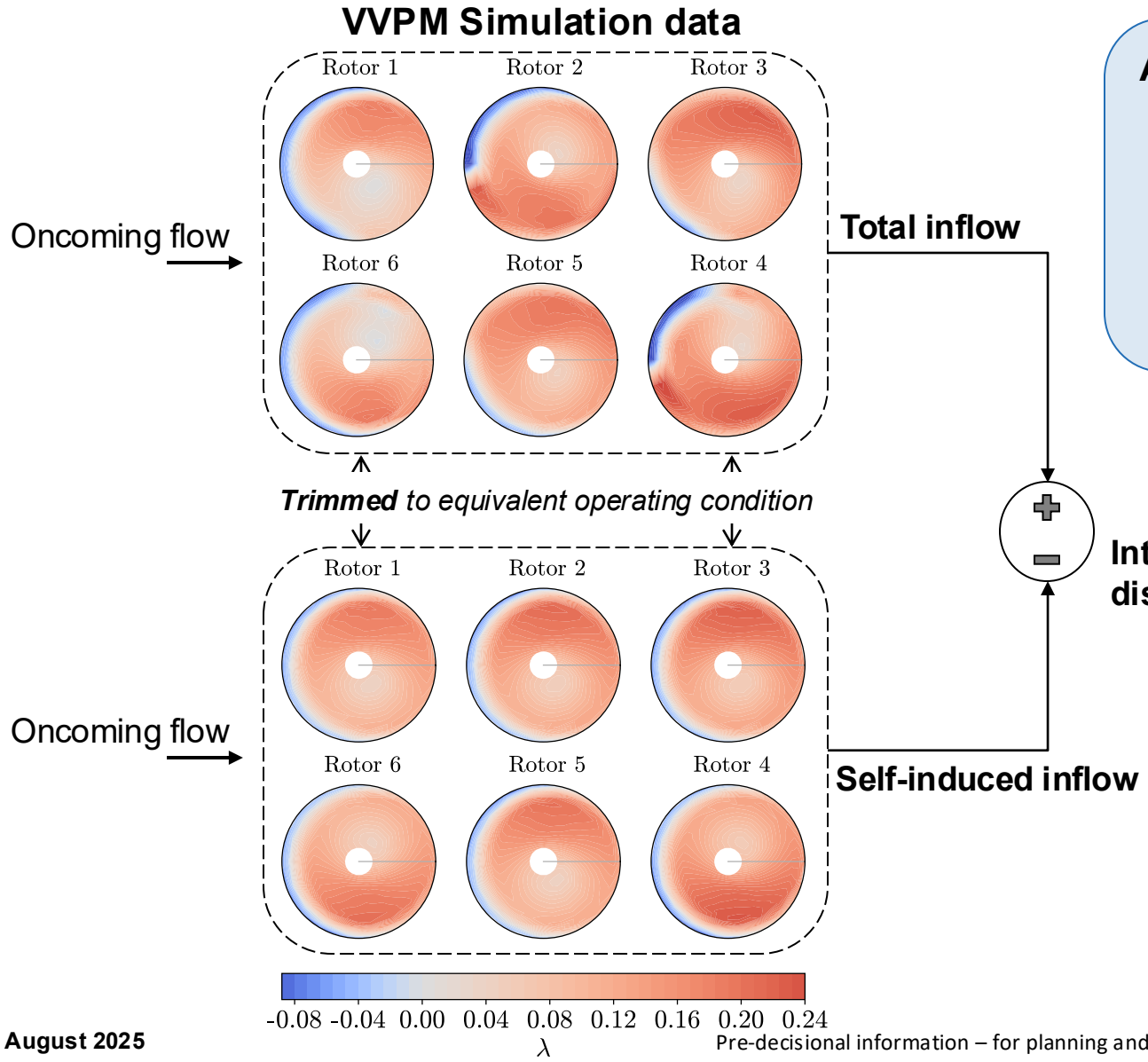



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# Toward a Reduced-Order Model for Rotor-on-Rotor Interference



# Toward a Reduced-Order Model for Rotor-on-Rotor Interference

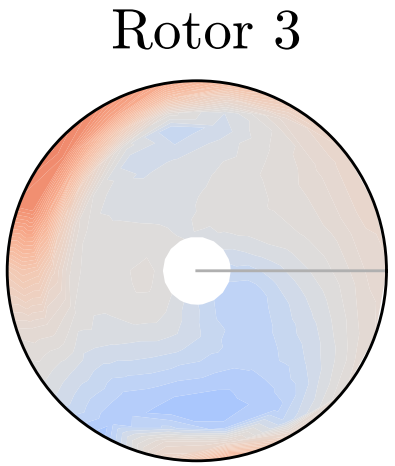



**Assume the interference distribution of a rotor:**

a) Can be superimposed with the self-induced inflow distribution

b) Can be added independently from interfering rotors

c) Is uniform over the receiving rotor disk



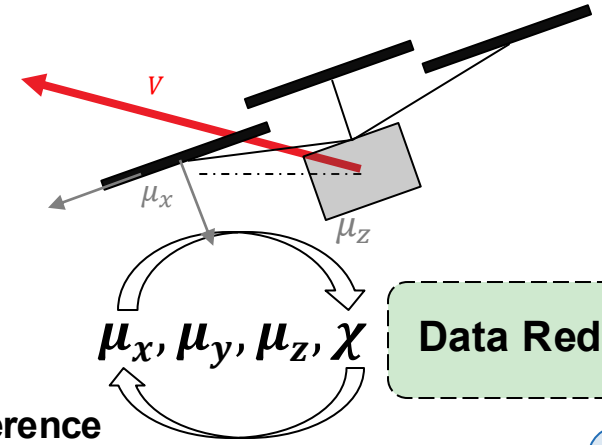

$$\lambda_{i,0}^{intf} = \sum_{j \neq i}^{N_r} \lambda_{ij,0}^{intf}$$


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# Model Derivation

Uniform velocity components from interfering rotors are added to the self-induced inflow

Total inflow

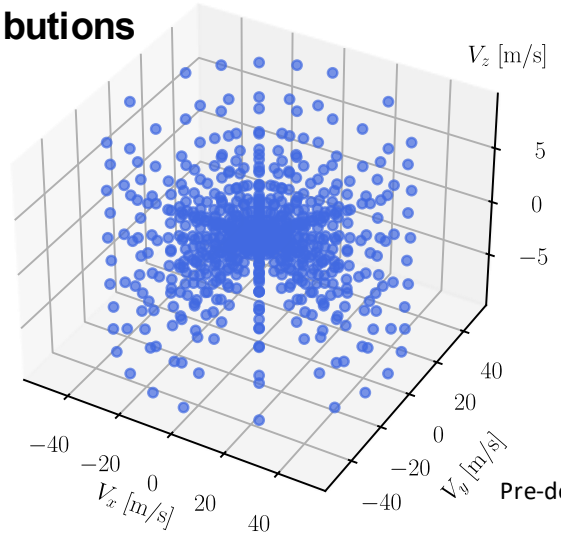



Self-induced inflow

**Data Reduction**

$\{M\}_k$

Interference distributions




Set of interference gain matrices (interpolated for continuous predictions)

**Flight Dynamics Model**

**Interference Model**

$$\frac{\boldsymbol{w^{intf}}}{\boldsymbol{\Omega R}} = \boldsymbol{\lambda^{intf}} = \begin{bmatrix} \lambda_{1,0}^{intf} \\ \lambda_{2,0}^{intf} \\ \vdots \\ \lambda_{6,0}^{intf} \end{bmatrix} = \boldsymbol{M(\mu)} \begin{bmatrix} C_{T_1} \\ C_{T_2} \\ \vdots \\ C_{T_6} \end{bmatrix}$$

$w^{intf}$

**Total inflow distributions for rotor $i$,**

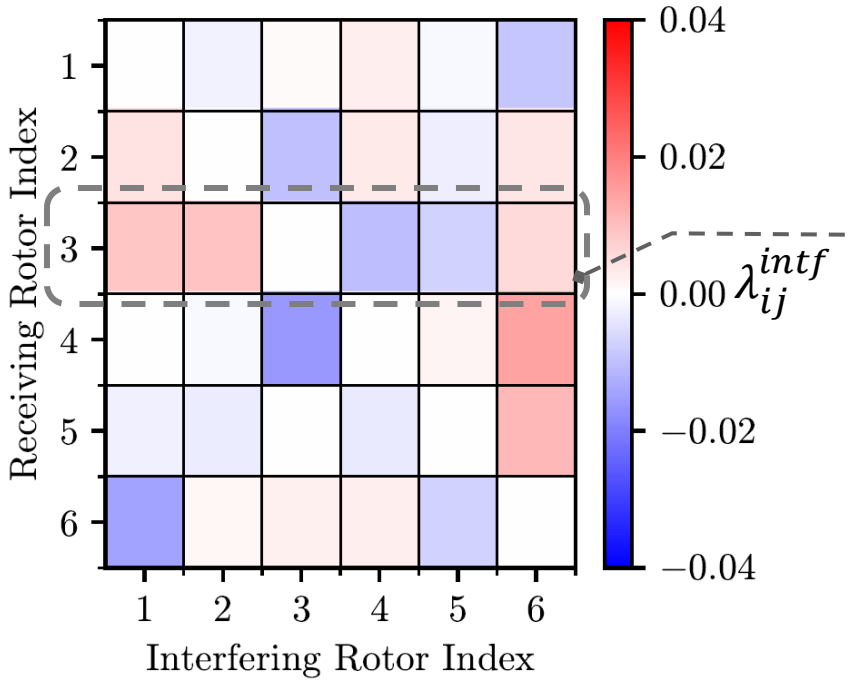
$$w_i = w_i^{self-induced} + w_i^{intf}$$

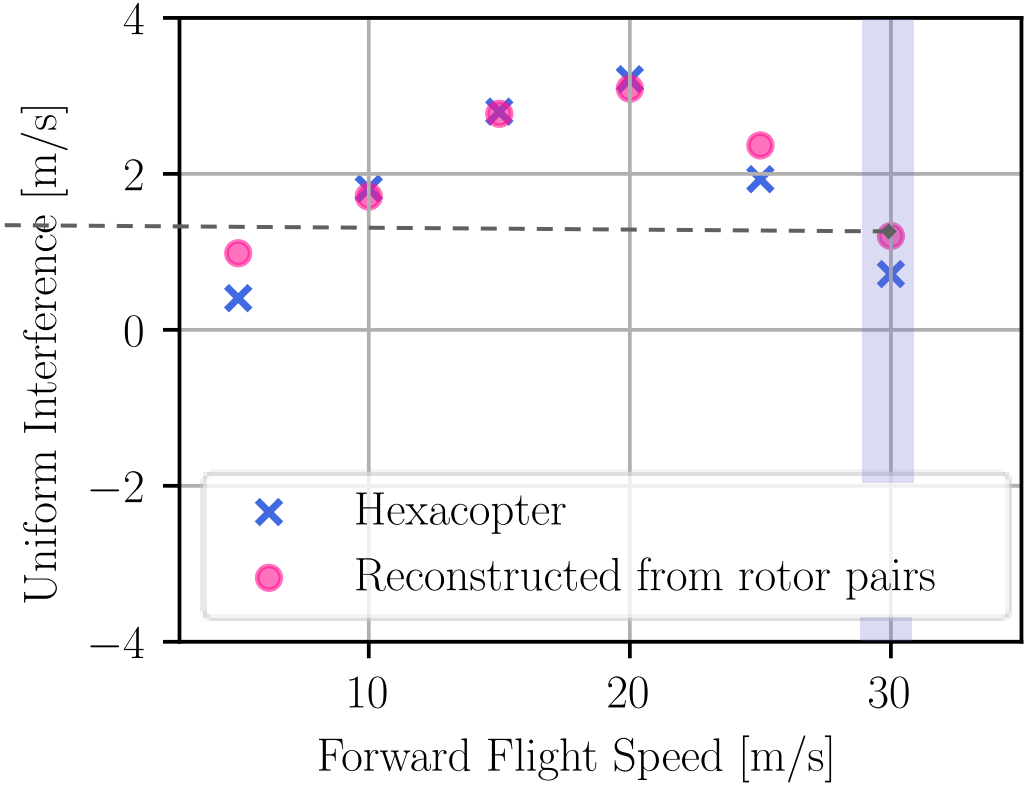
**Model maps rotor thrust(s) to total interference velocities through variable gain matrices $M$ parametrized with flight condition**

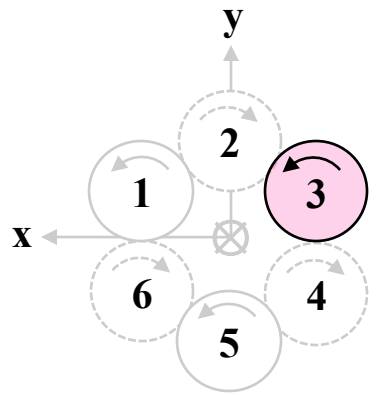

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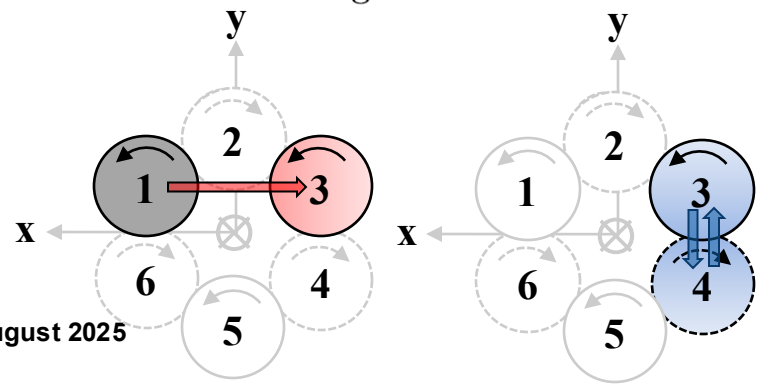
# Aggregate Uniform Interference Velocities

- **Total interference is reconstructed from pairwise distributions** $\lambda_i^{intf} = \sum_{j \neq i}^{N_r} \lambda_{ij}^{intf}$







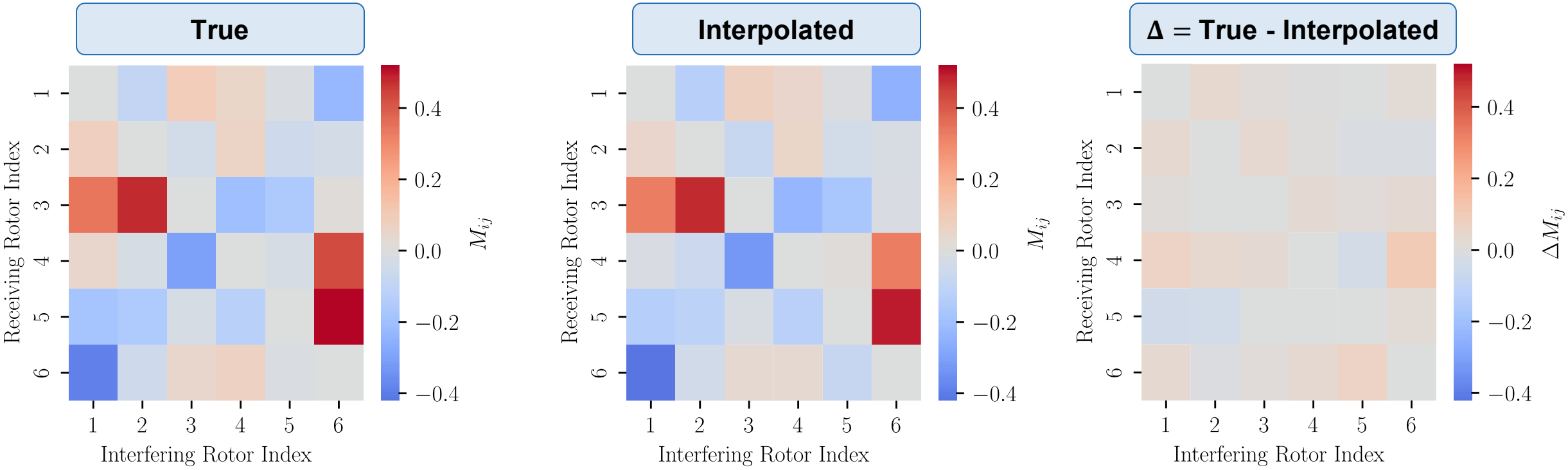
**Assumption of de-coupled interference contributions holds, at least up to target cruise speeds**



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# Quantifying Interpolation Errors: Validation Case

- **Interference gain matrices are linearly interpolated based on advance ratios**
- **Example validation case, not in database, $V = 35\ \mathrm{m/s}, \gamma_h = 10^\circ, \gamma_v = 0^\circ$**






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# Summary & Conclusions

- VVPM wake validated against experimental data for the Ingenuity Mars Helicopter
- Showcased the utility of VVPM to Mars multi-rotor wake predictions and reduced-order modeling of rotor-on-rotor interference
- Impact: Enabling increased fidelity in flight dynamics analysis and control system design of next-generation Mars rotorcraft

