Modeling Multirotor Aerodynamic Interactions Through the Vortex Particle Method

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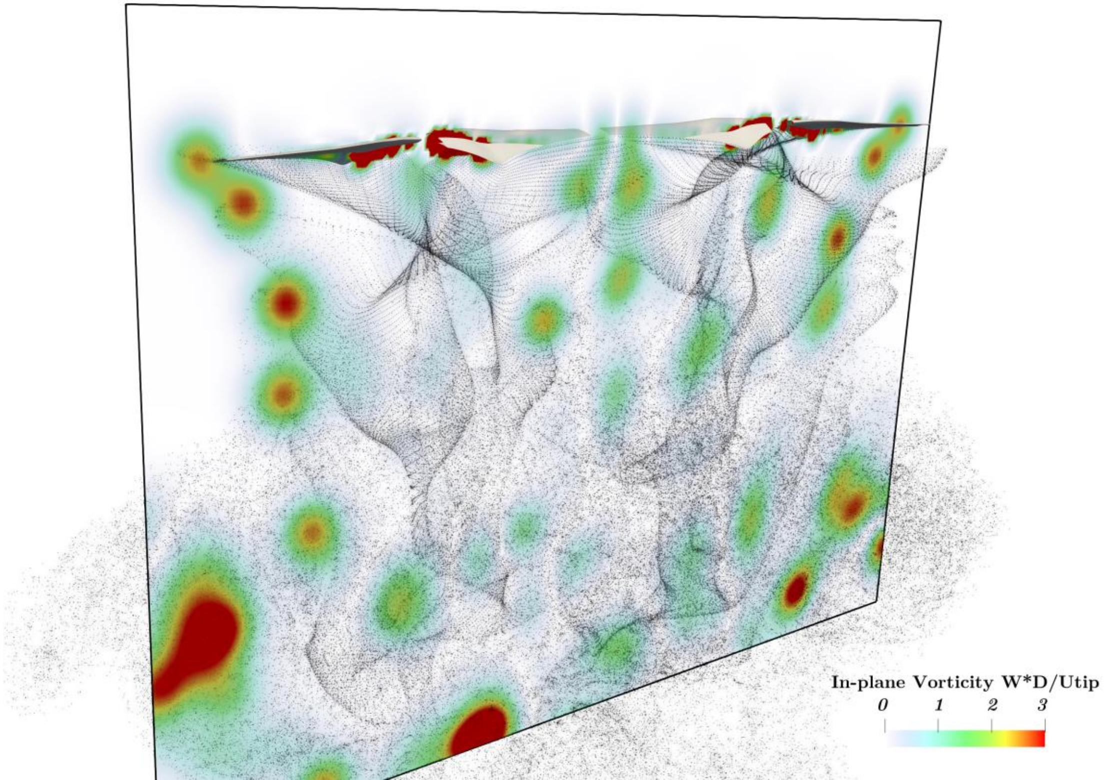
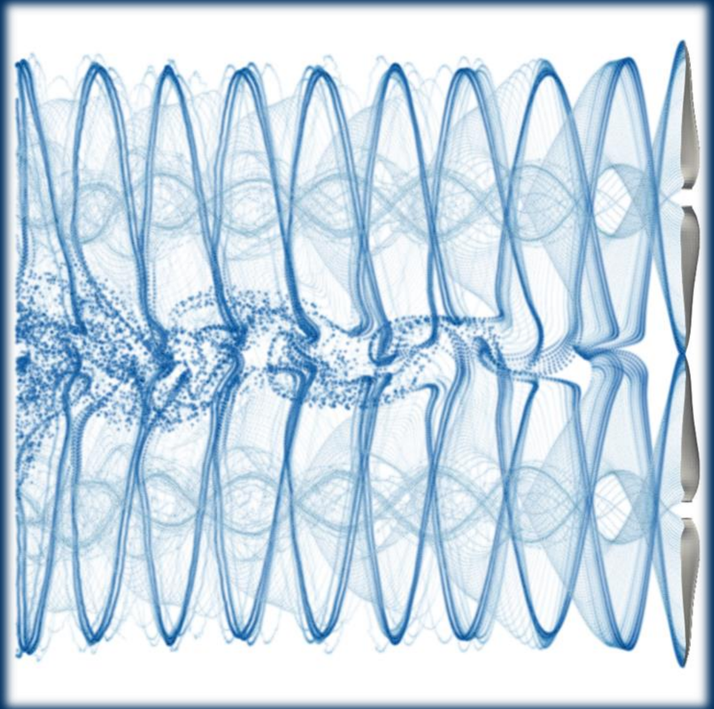


OUTLINE

- **Motivation**
- **Viscous Vortex Particle Method**
- **Propeller Model**
- **Results**
  - Individual rotor validation
  - Multirotor validation
  - Parametric study



Motivation

- eVTOL UAM is projected to grow into a $1.5 trillion industry.
- However, conventional analysis tools are unfit for conceptual design.

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© Joby Aviation

© Kitty Hawk, Flyer

© Wing

ANALYSIS TOOLS

Low fidelity ⟵⟶ High fidelity

Low computation ⟵⟶ High computation

	Momentum Theory	Free-wake Vortex Panel/Filament	RANS / LES
Viscous?	✗	✗	✓
Unsteady?	✗	✓	✓
Wake Mixing?	✗	✗	✓
Fast Enough for Design?	✓	~	✗

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ANALYSIS TOOLS

Vortex Particle Method

- Vorticity form of Navier-Stokes in Lagrangian scheme.

ANALYSIS TOOLS

Vortex Particle Method

- Vorticity form of Navier-Stokes in Lagrangian scheme.

$$\nabla \times \left(\frac{D\mathbf{u}}{Dt} \right) = \nabla \times \left(-\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u} \right)$$

$$\Rightarrow \frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} + \nu \nabla^2 \boldsymbol{\omega}$$

Particle discretization

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

Governing Equations

- $\frac{\mathrm{d}\mathbf{x}_p}{\mathrm{d}t} = \mathbf{u}(\mathbf{x}_p)$
- $\frac{\mathrm{d}\boldsymbol{\Gamma}_p}{\mathrm{d}t} = (\boldsymbol{\Gamma}_p \cdot \nabla)\mathbf{u}(\mathbf{x}_p) + \left.\frac{\mathrm{d}\boldsymbol{\Gamma}_p}{\mathrm{d}t}\right|_{\mathrm{visc}}$

ANALYSIS TOOLS

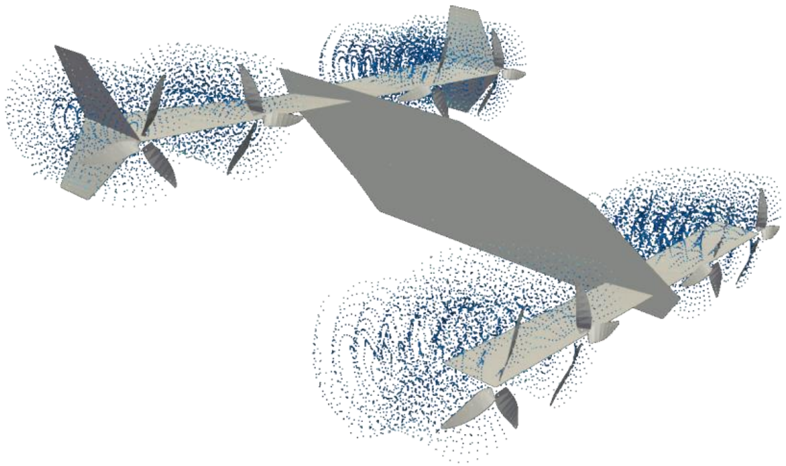
Vortex Particle Method

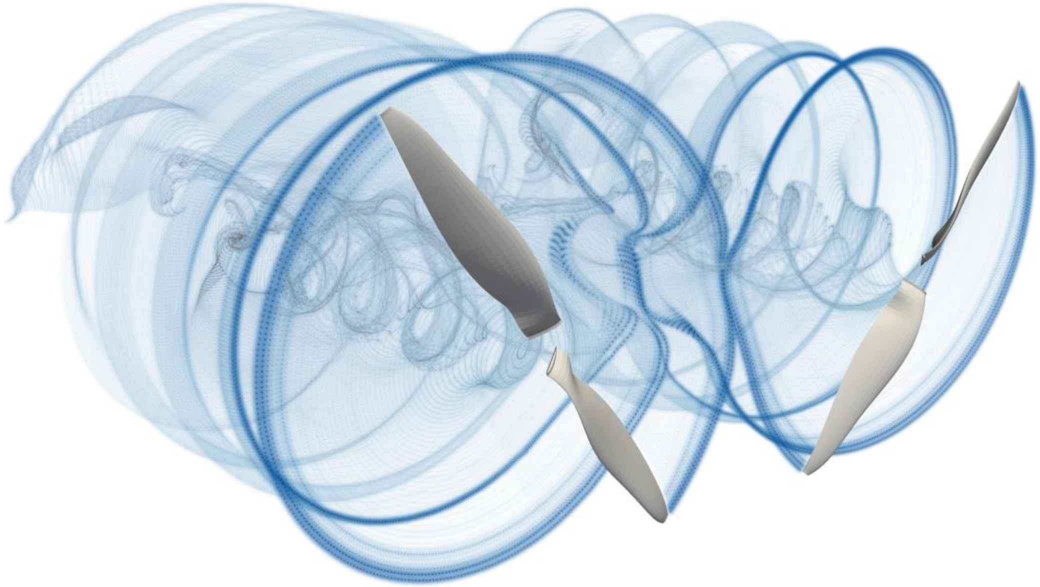
- Vorticity form of Navier-Stokes in Lagrangian scheme.
- Captures viscous diffusion, vortex mixing, and decay.
- Computationally inexpensive.
- CPU and GPU parallelizable.
- Meshless.

Variable-fidelity models through VPM

Low fidelity ⟵ ⟶ **High fidelity**

Low computation ⟵ ⟶ **High computation**



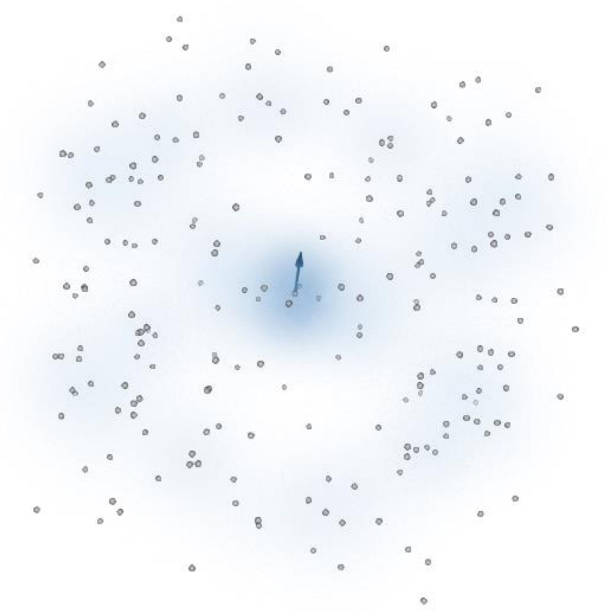


https://youtu.be/CP4jI7lLags

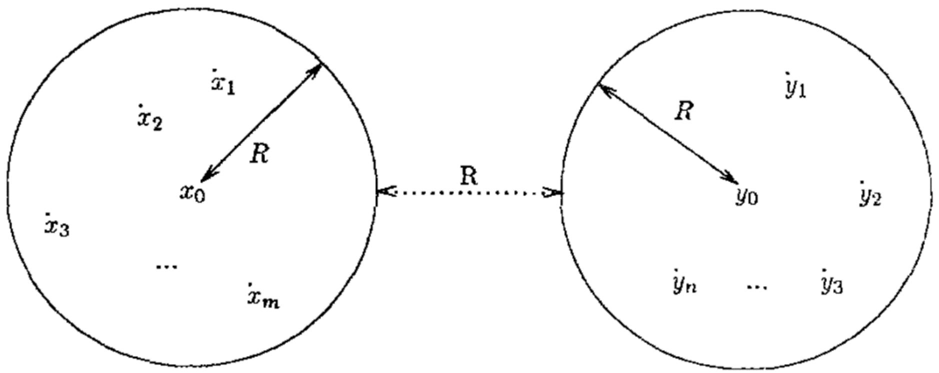
[1] Alvarez, E. and Ning, A., 2018, "Development of a Vortex Particle Code for the Modeling of Wake Interaction in Distributed Propulsion."

VPM Scaling

N-body problem $\mathcal{O}(N^2)$

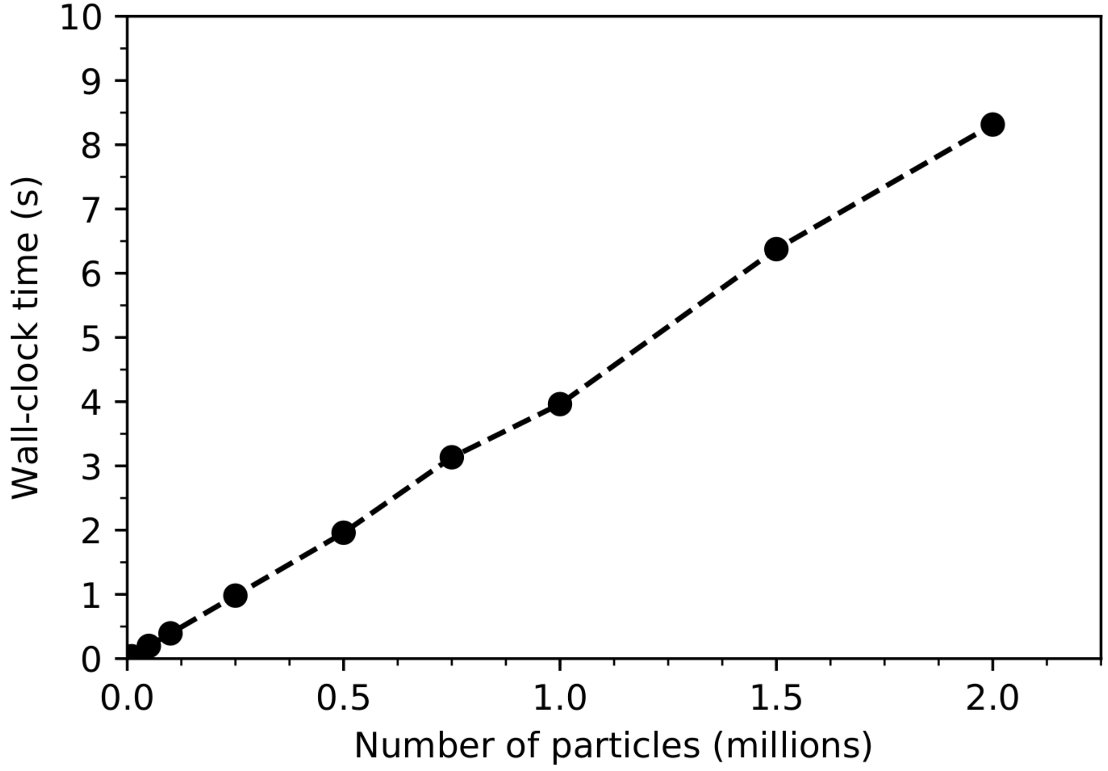


Fast multipole approximation[1,2]



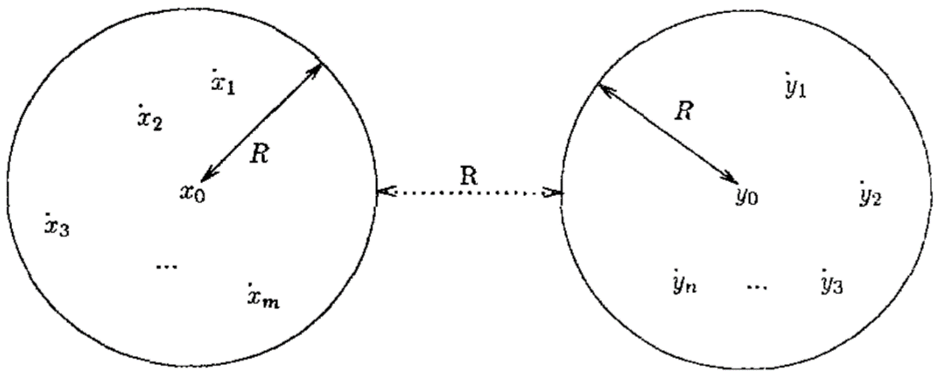
[1] www.bu.edu/exafmm
[2] Yokota, R. and Barba, L. A., 2011, “Treecode and fast multipole method for N-body simulation with CUDA.”

VPM Scaling



Fast multipole approximation[1,2]

- $\mathcal{O}(N)$ scaling
- CPU and GPU scalable



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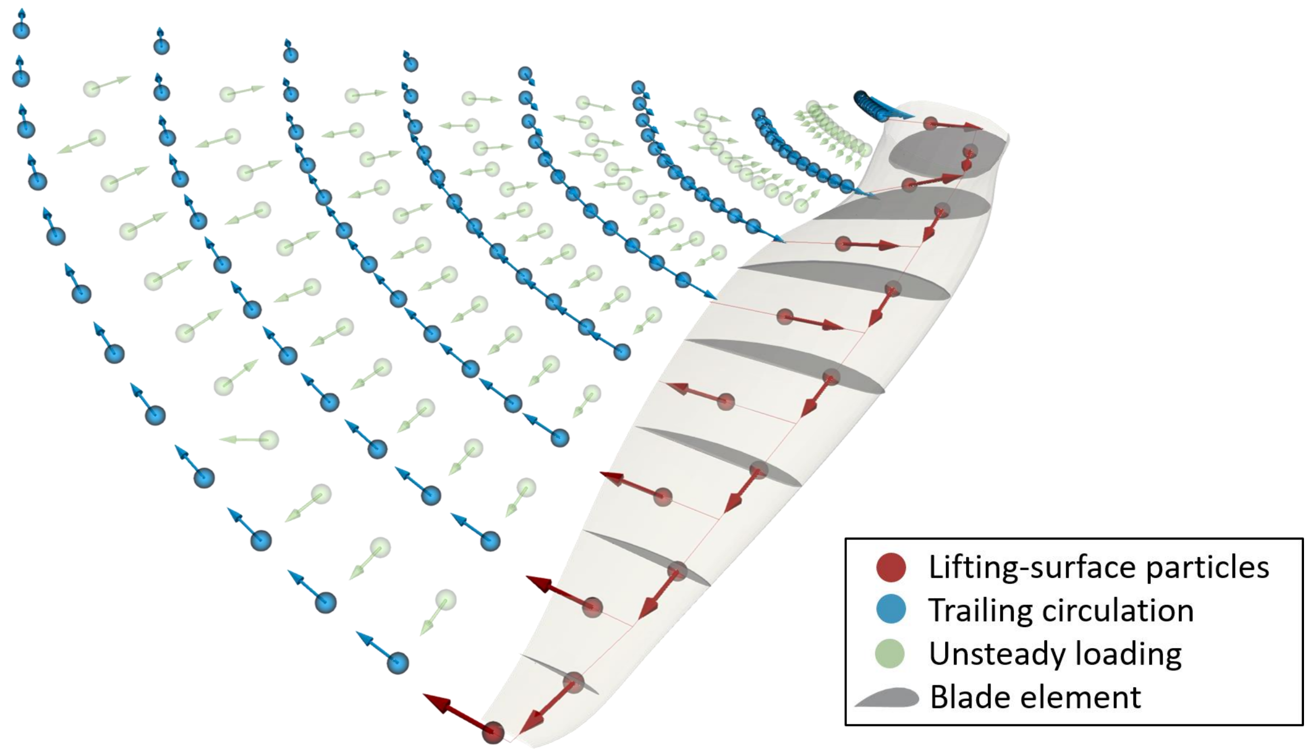
Propeller Model



TEMPORAL RESOLUTION

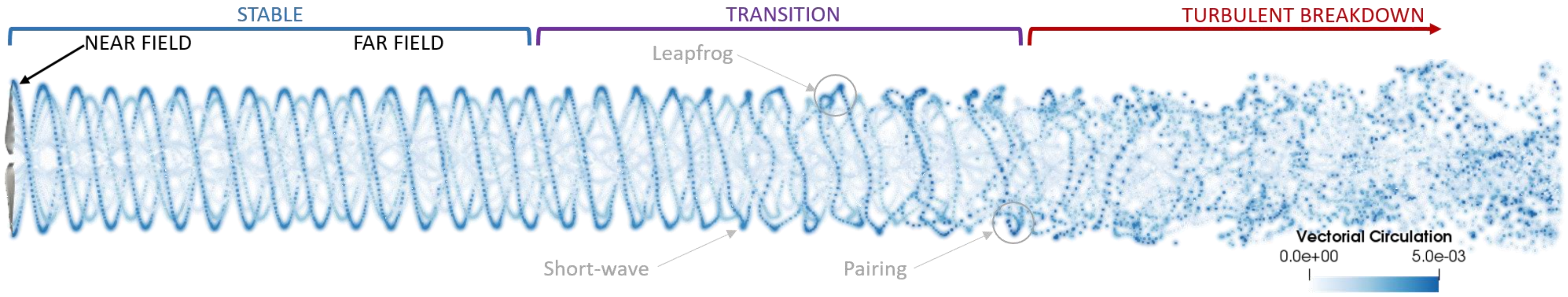
- 3rd order Runge-Kutta
- $\Delta t \longrightarrow 5°$ rotation

SPATIAL RESOLUTION

- 50 elements per blade
- 2 particles shed per step
- Core overlap σ twice the distance between particles

- Particles are created from every source of vorticity (as colored).
- Modeling lifting surfaces through embedded particles allows linear scaling of simulations, $\mathcal{O}(N)$.

Propeller Model

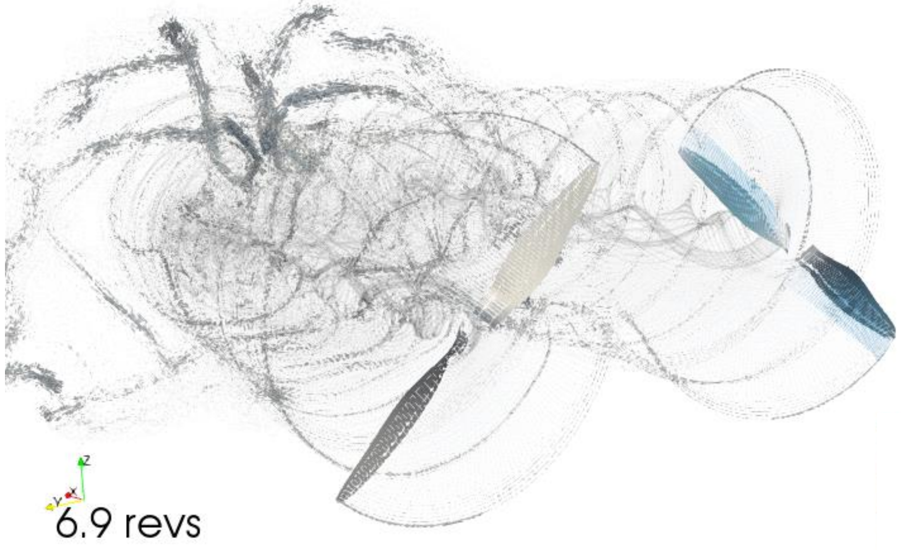


VPM captures all vortex dynamics
from near field down to turbulent breakdown

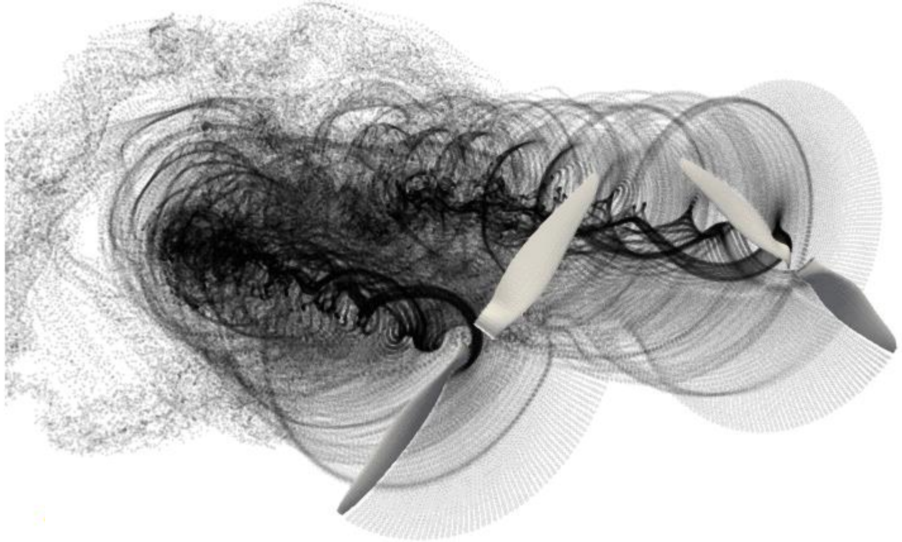
Alvarez, E. and Ning, A., AVIATION 2018,
"Development of a Vortex Particle Code for the Modeling of Wake Interaction in Distributed Propulsion"
https://scholarsarchive.byu.edu/facpub/2116/

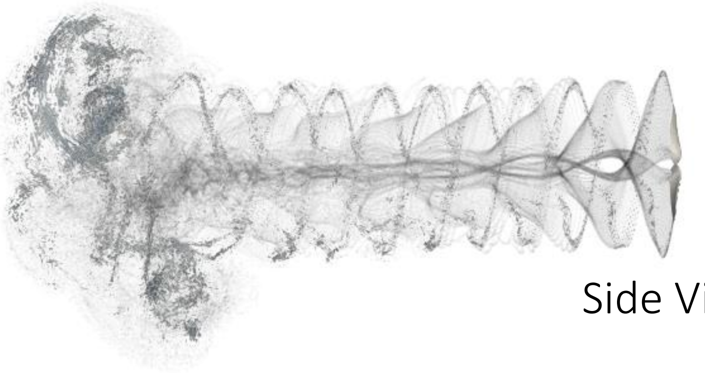
Example Simulation

Vectorial Circulation



Particles



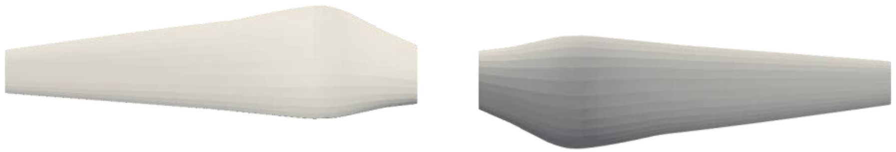


Side View

https://youtu.be/SLpnVIBpkps

Test Cases

Hover, low Reynolds
DJI Phantom II



Forward flight, high Reynolds
APC 10x7

PARAMETER	DJI Phantom II	APC 10x7
Diameter	9.4 in (240 mm)	10 in (254 mm)
Speed	4800 RPM	9200 RPM
Tip speed	0.18 Mach	0.36 Mach
Freestream	0 m/s	0 – 27 m/s
Advance ratio	0	0 – 0.75
Chord-based Reynolds	6.2×10^4	1.2×10^5
Diameter-based Reynolds	6.5×10^5	1.5×10^6

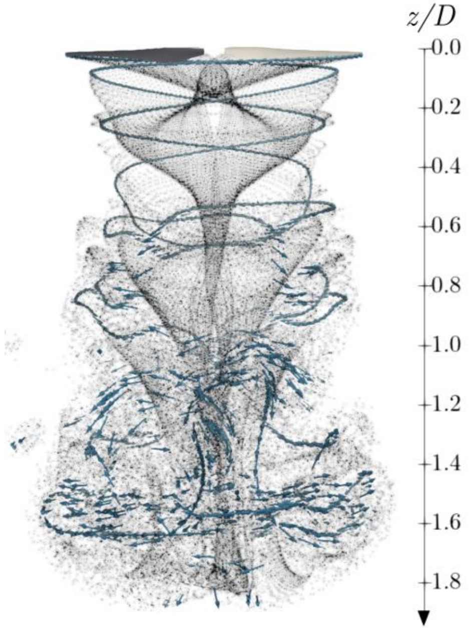
$$\mathrm{Re}_c = \frac{V_{0.7}\bar{c}}{\upsilon}$$

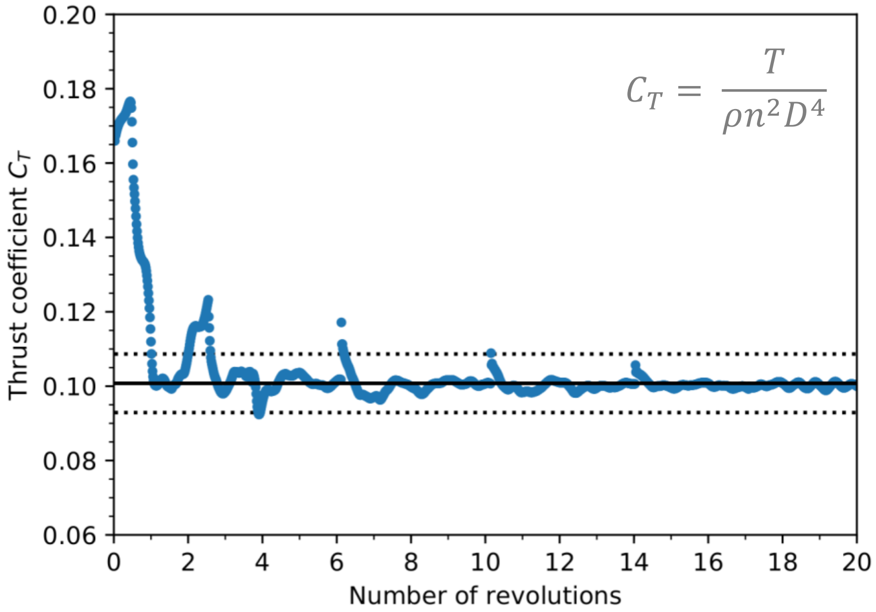
$$\mathrm{Re}_D = \frac{V_{0.7}D}{\upsilon}$$

RESULTS

INDIVIDUAL ROTOR

Hover – Individual Rotor





	Experiment[1]	Simulation	Error
Mean C_T	0.1007	0.1013	0.5 %
C_T fluctuation	0.008	0.001	

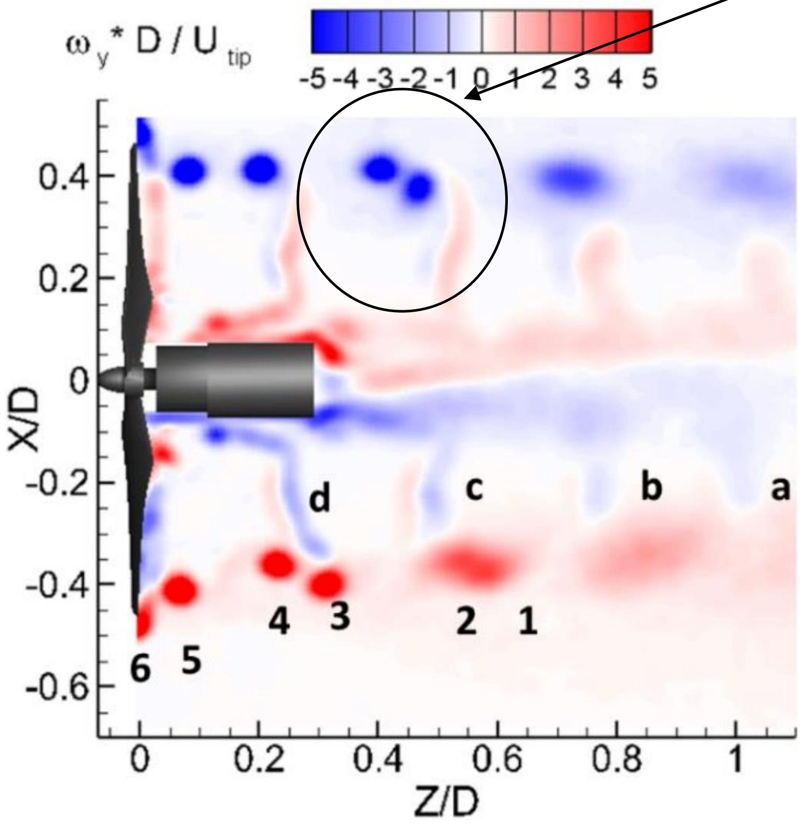
Mean C_T agreement between 0.5% →

Underpredicted C_T fluctuations due to not capturing hub and mounting-pole interactions →

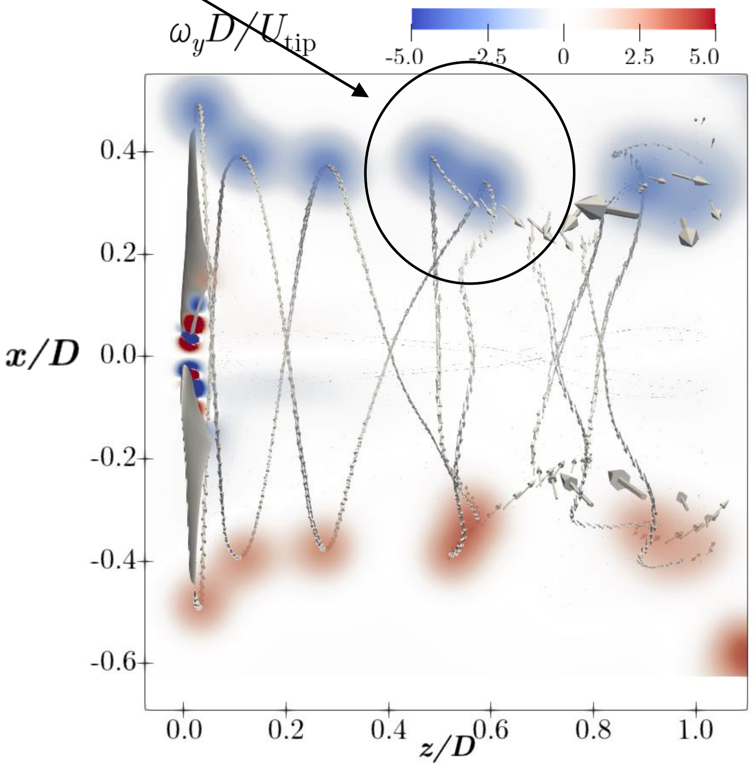
[1] Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, "An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers."

Hover – Individual Rotor

Leapfrogging is accurately predicted at $z/D \approx 0.5$



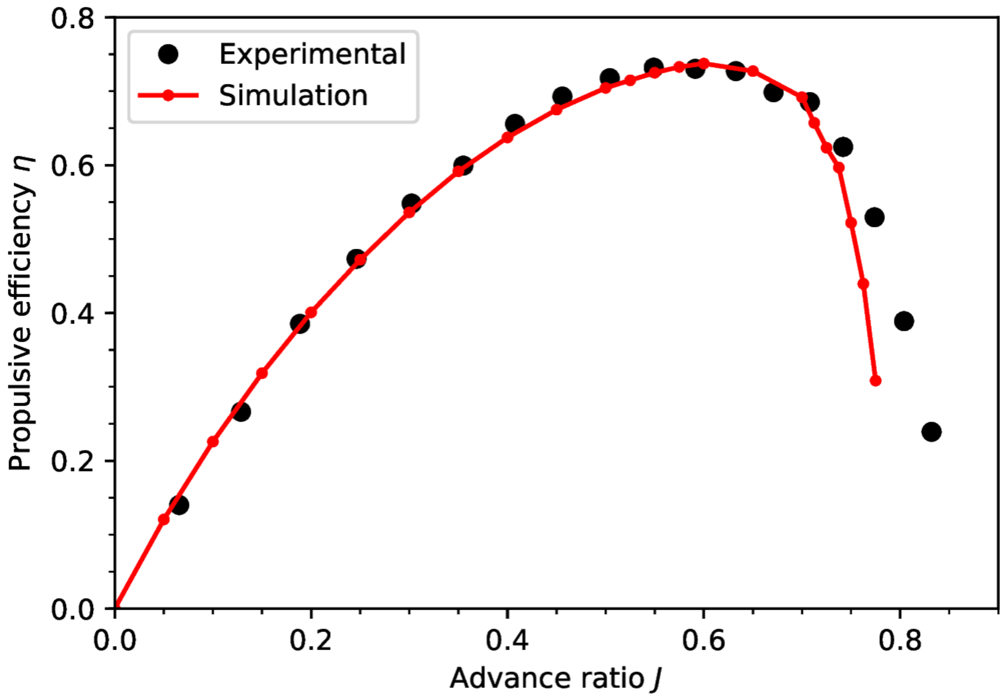
EXPERIMENT[1]

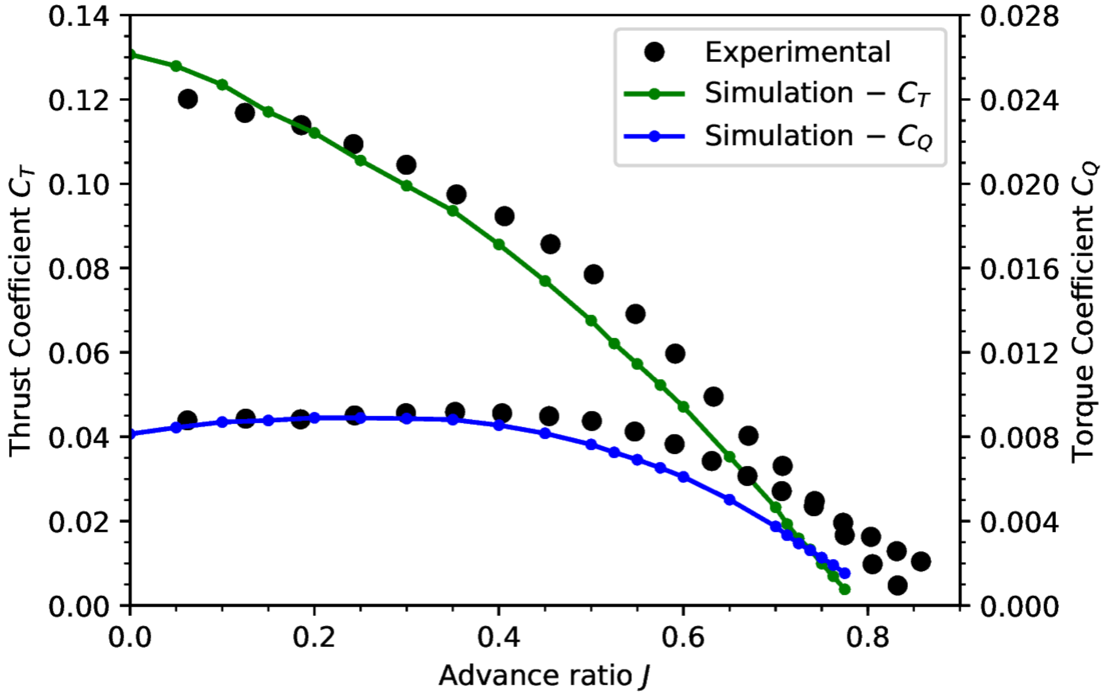


SIMULATION

[1] Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, "An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers."

Forward Flight – Individual Rotor





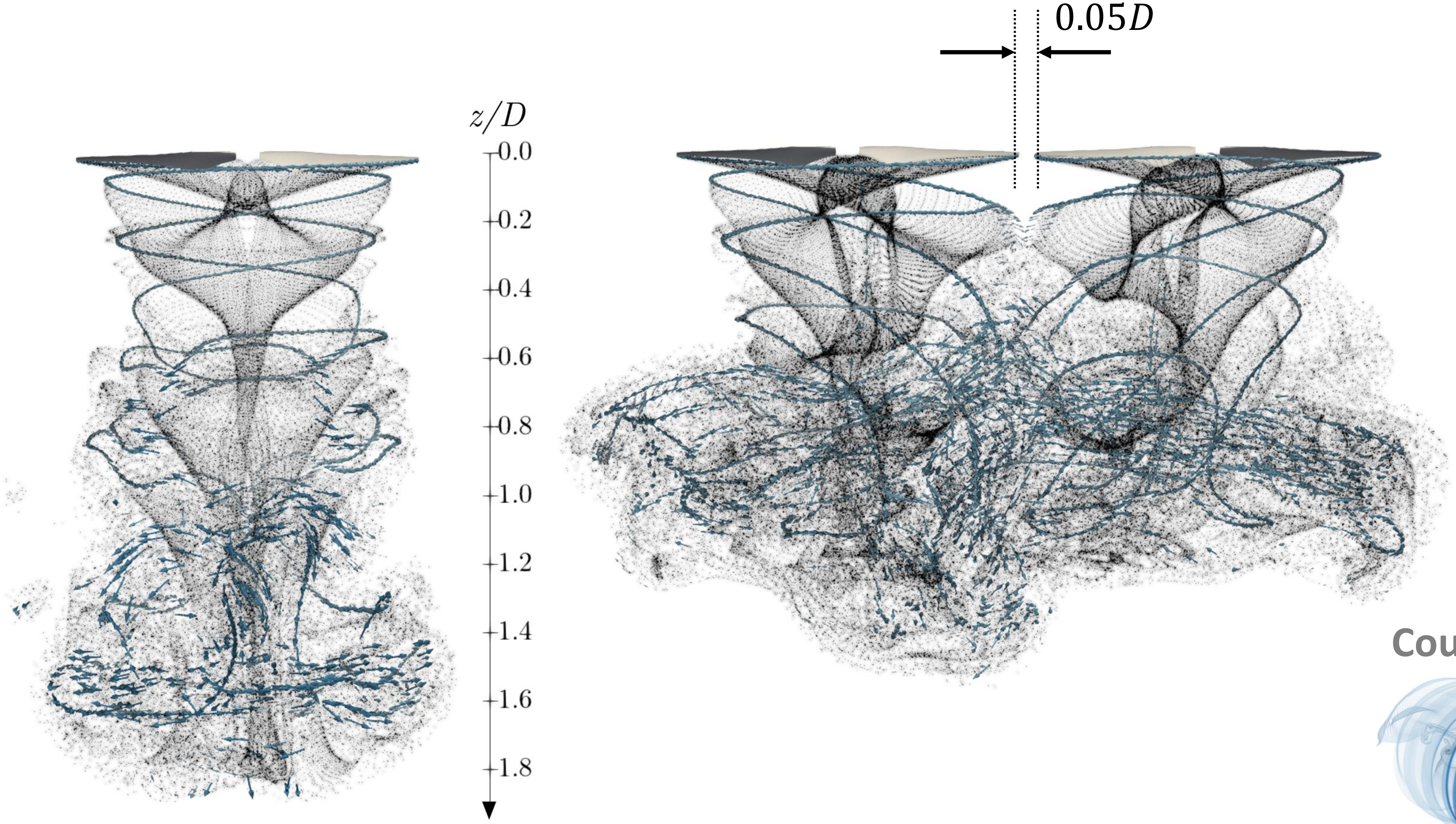
$$\eta = \frac{TU_\infty}{2\pi nQ} \qquad C_T = \frac{T}{\rho n^2 D^4} \qquad C_Q = \frac{Q}{\rho n^2 D^5}$$

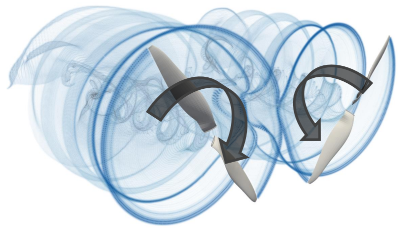
[1] McCrink, M. H. and Gregory, J. W., 2017, “Blade Element Momentum Modeling of Low-Reynolds Electric Propulsion Systems.”

RESULTS

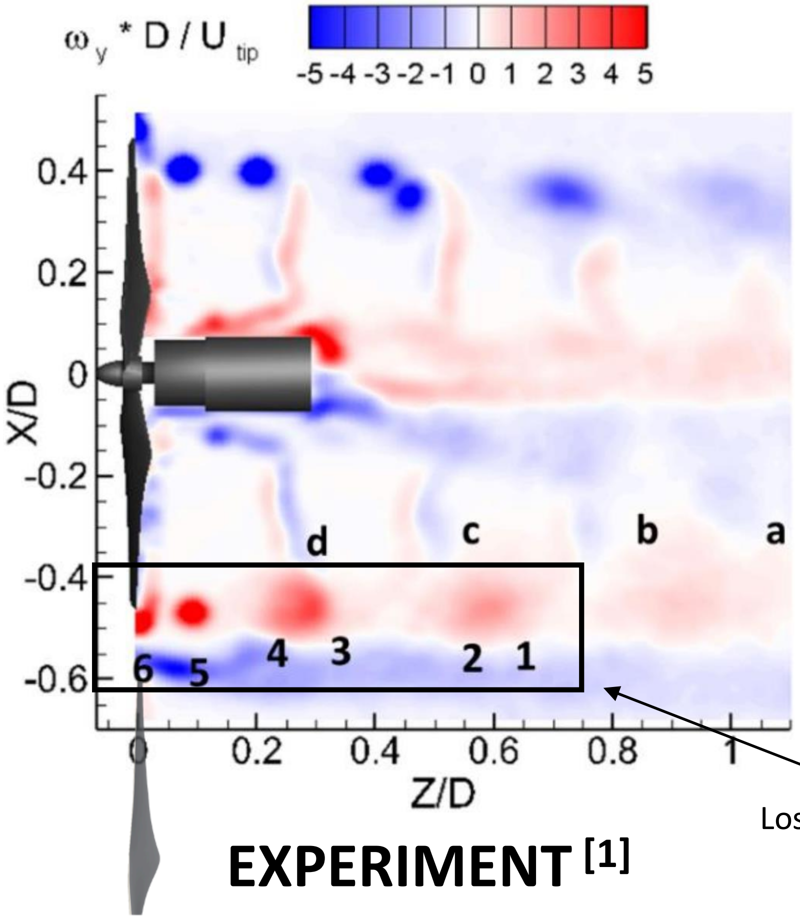
MULTIROTOR

Hover – Multirotor



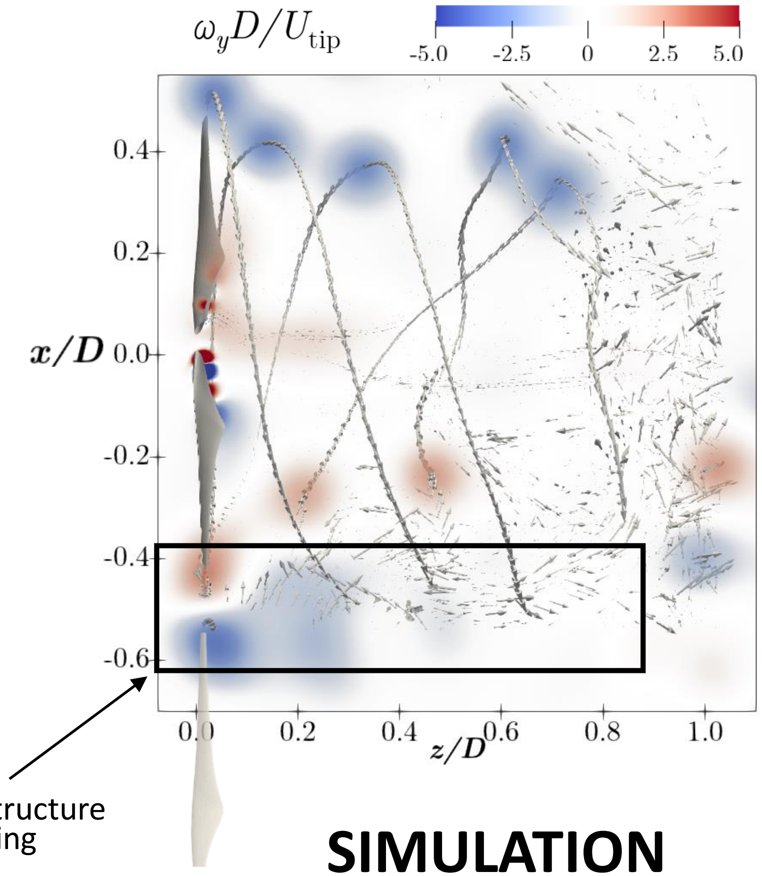


Hover – Multirotor



EXPERIMENT [1]

Loss of vortical structure
in wake mixing



SIMULATION

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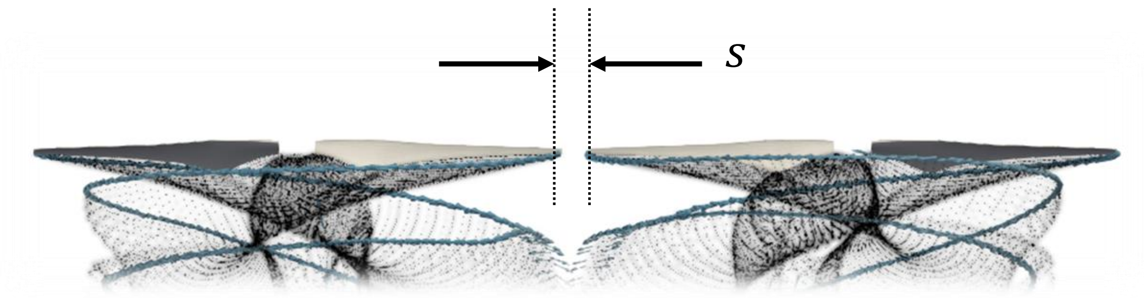
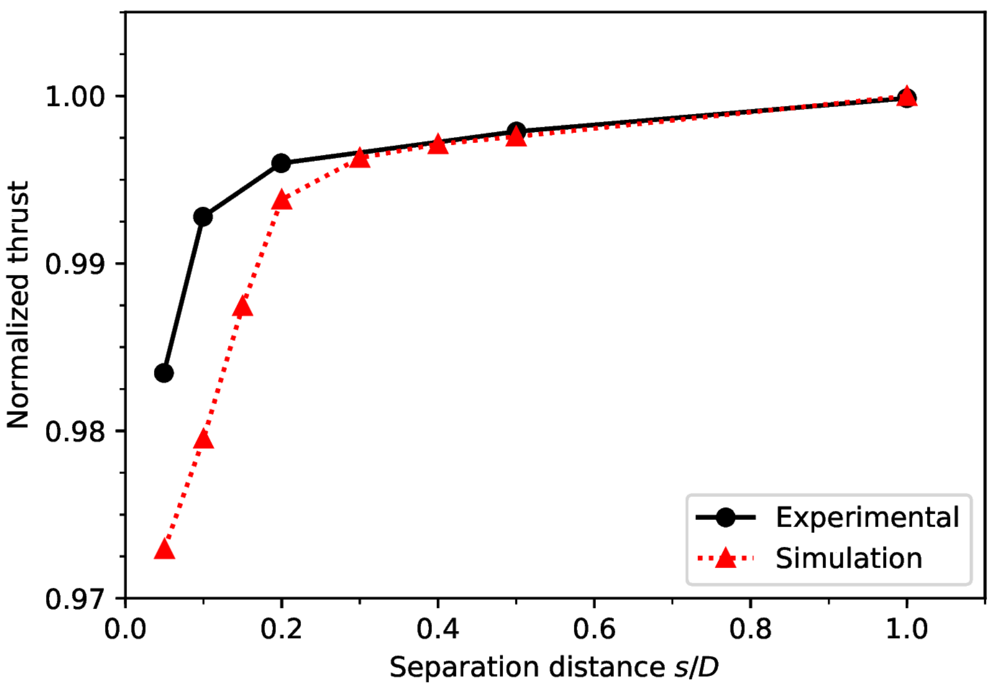
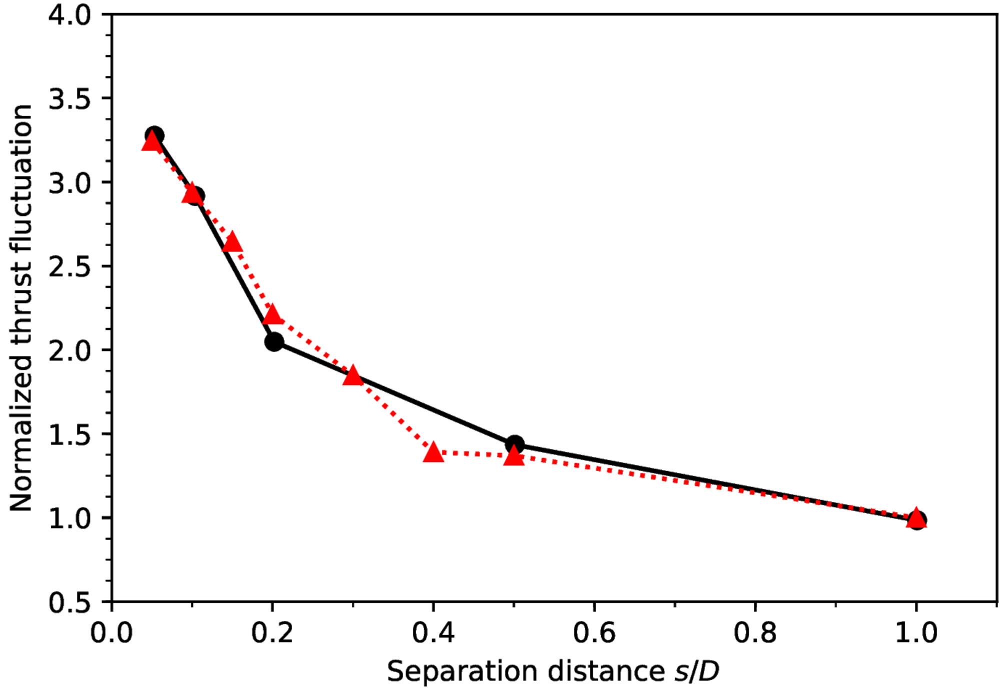
Hover – Multirotor



Rotor-on-rotor interactions (thrust drop and unsteady loading) are predicted with sufficient accuracy

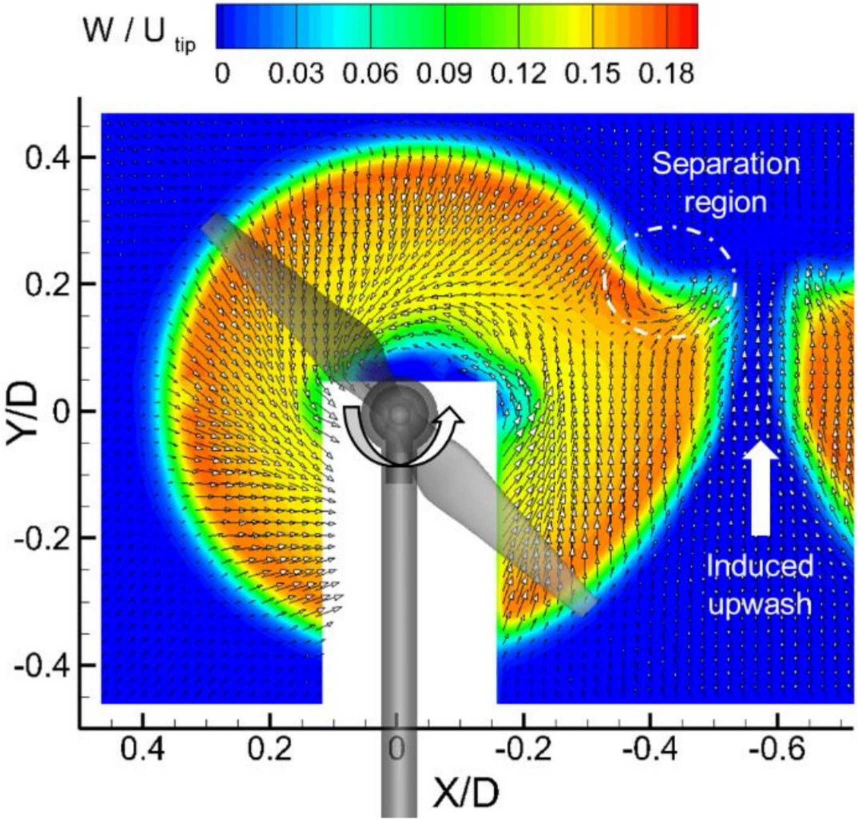




[1] Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, "An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers."

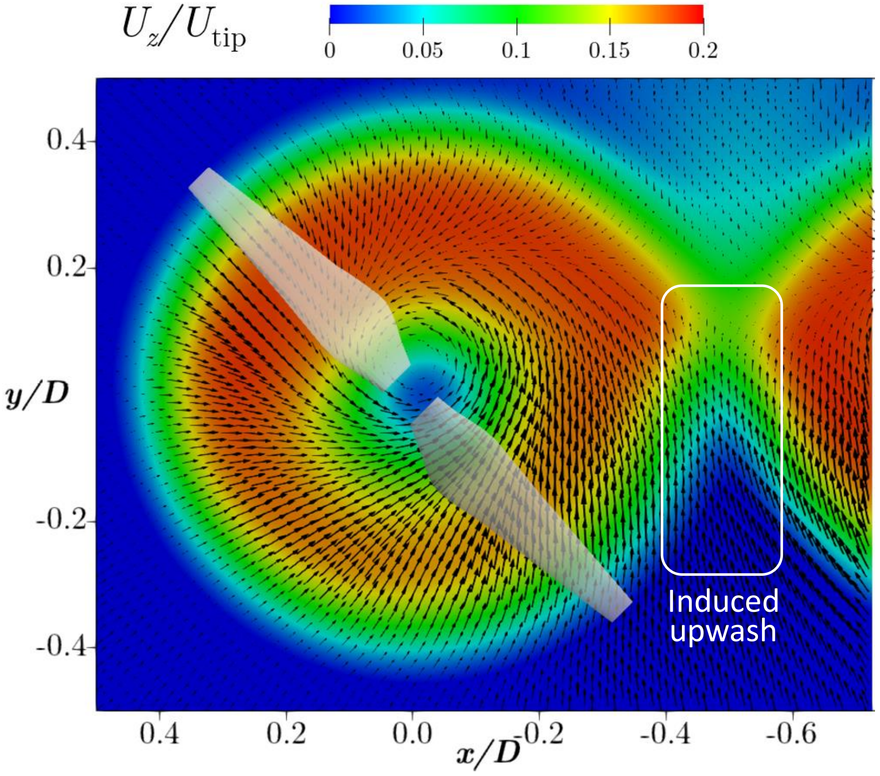
Hover – Individual Rotor

Simulation captures similar near-field than observed in PIV



EXPERIMENT [1]

Ensemble Average



SIMULATION

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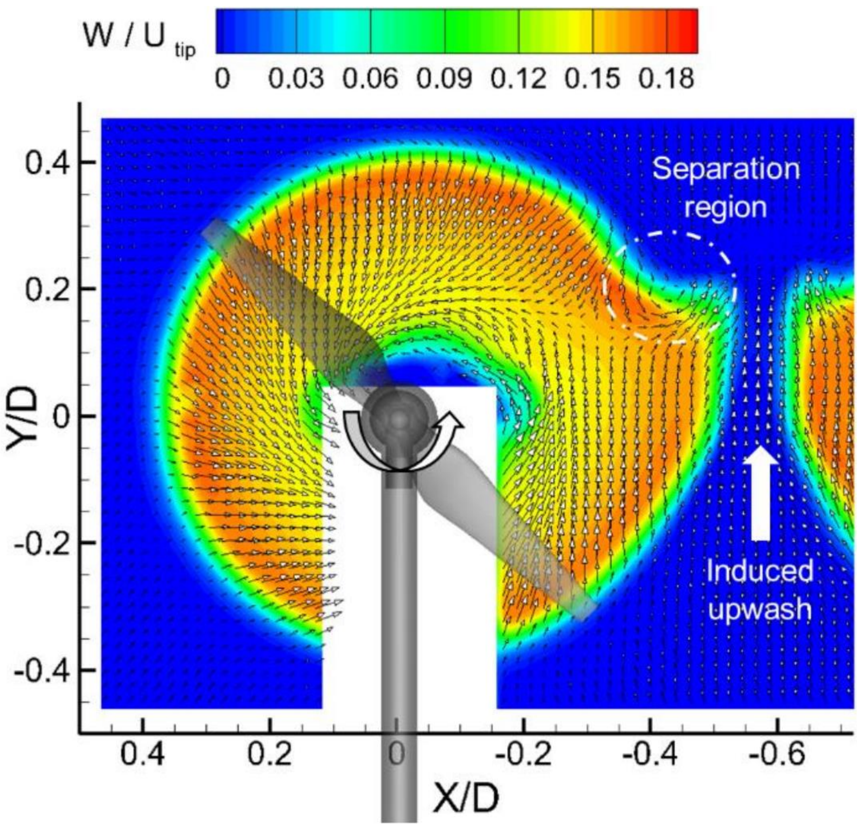
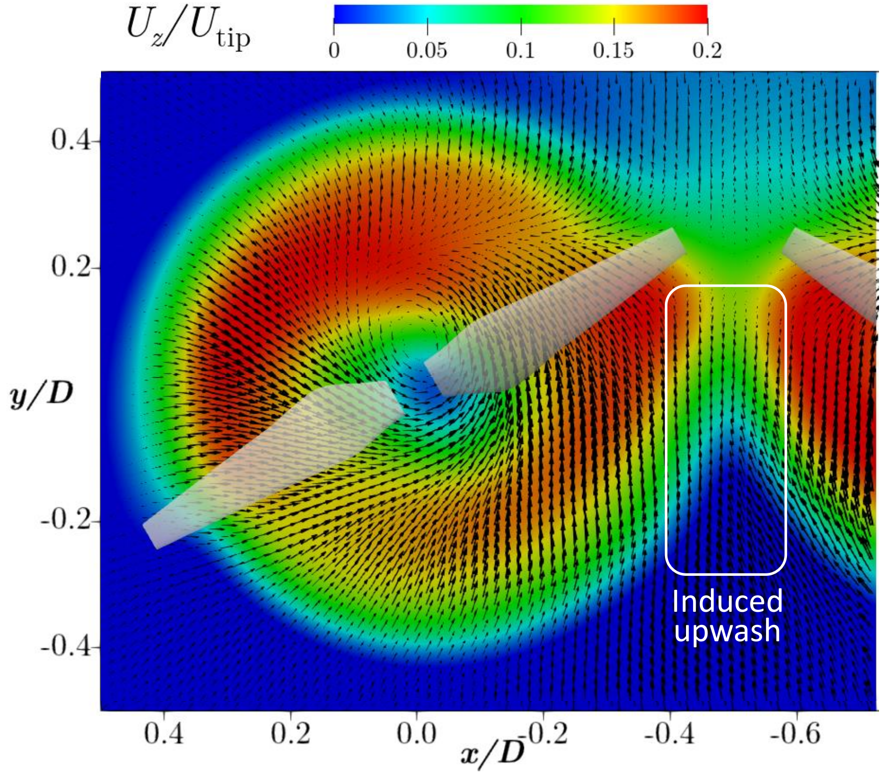


EXPERIMENT [1]

Phase-locked



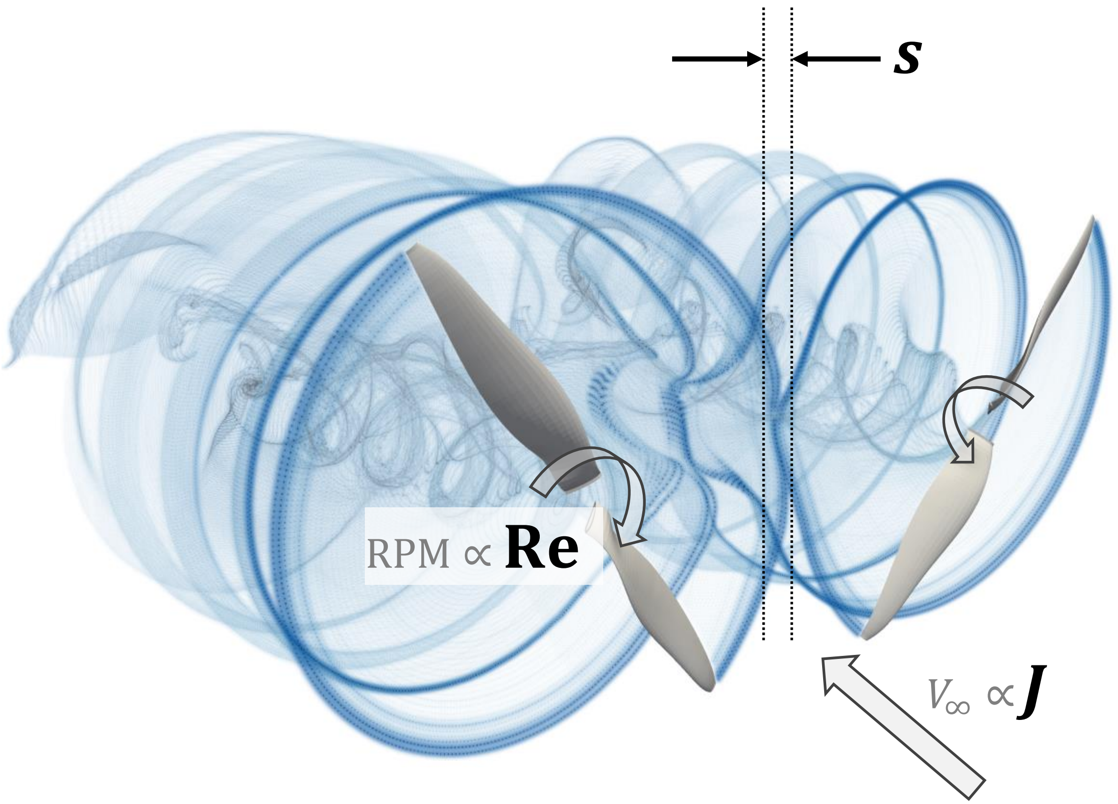
SIMULATION

[1] Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, "An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers."

RESULTS

PARAMETRIC STUDY

Multirotor Parametric Study



- OPERATIONAL PARAMETERS
  - **Re** – Reynolds number
  - J – Advance ratio
  - s – Separation
  - Counter or co-rotation

- 6 response surfaces

  C_T, C_Q, η – mean and fluctuations

- 1152 simulations

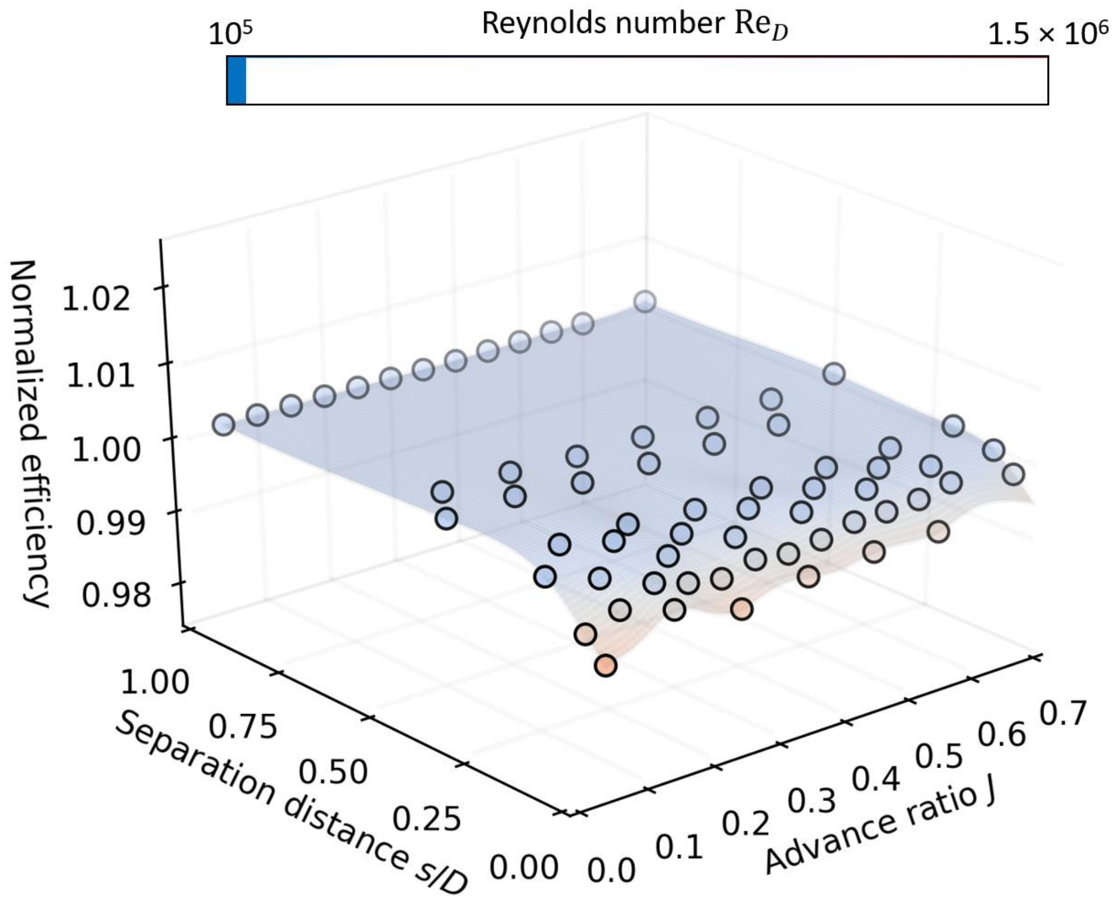
- ~3.5 days on desktop computer

  Intel(R) Xeon(R) CPU E5-2699 v3 @ 2.30GHz

~4 minutes per simulation

Multirotor Parametric Study

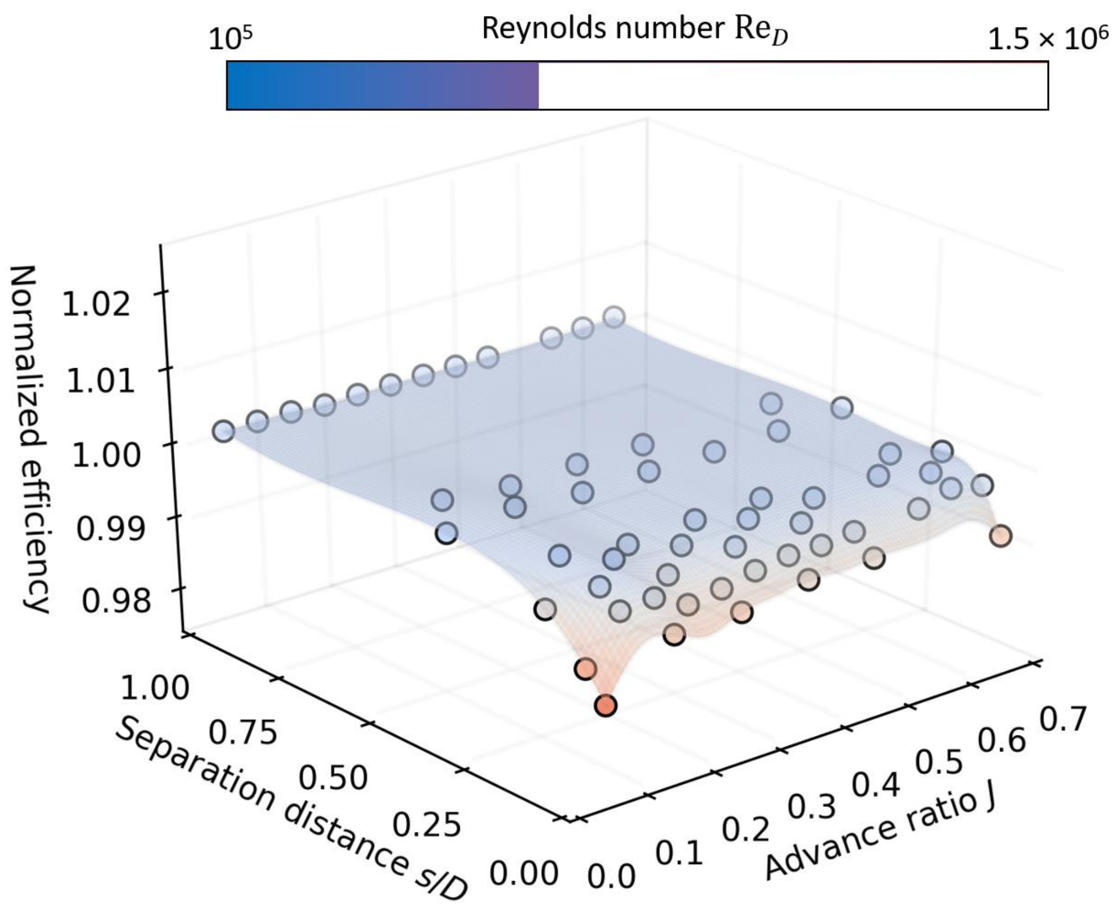
Efficiency Response Surface



- Performance drops in all configurations
- Largest interactions in hover and near hover
- $\sim 3\%$ max drop

Multirotor Parametric Study

Efficiency Response Surface



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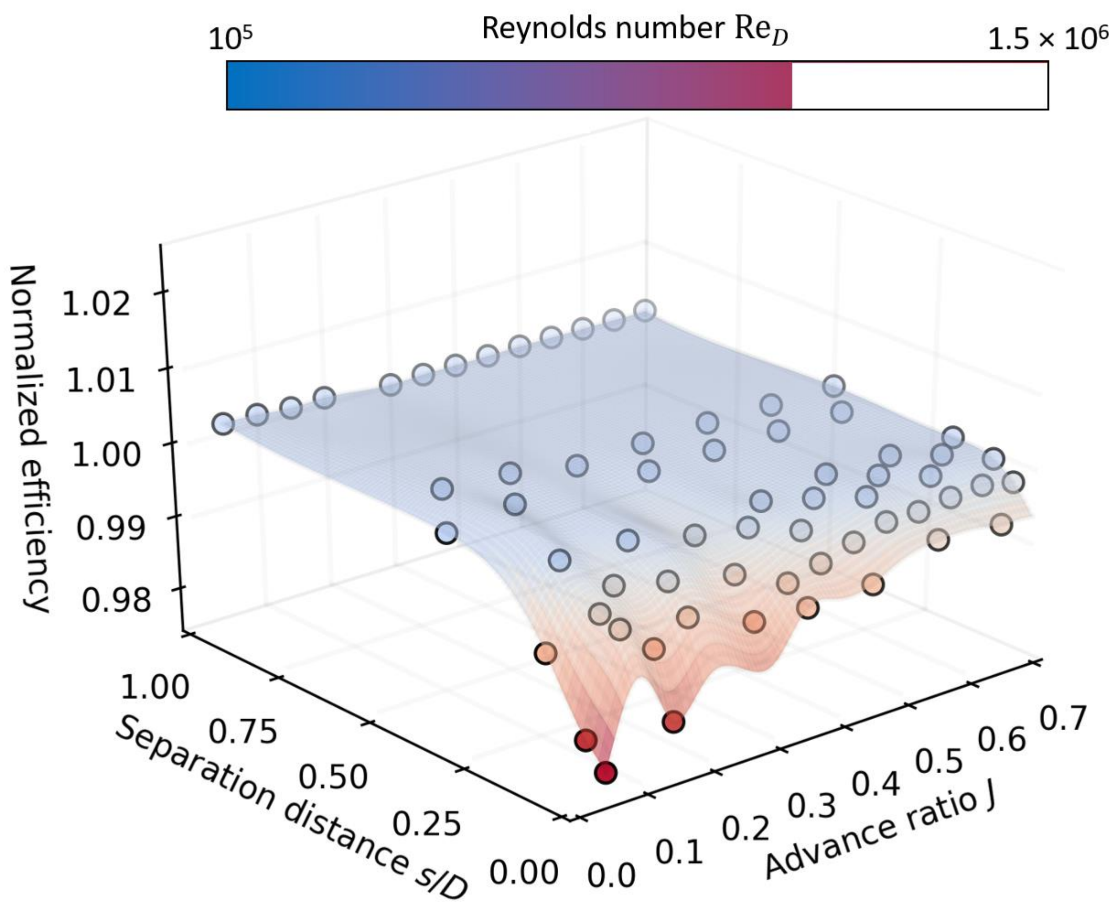

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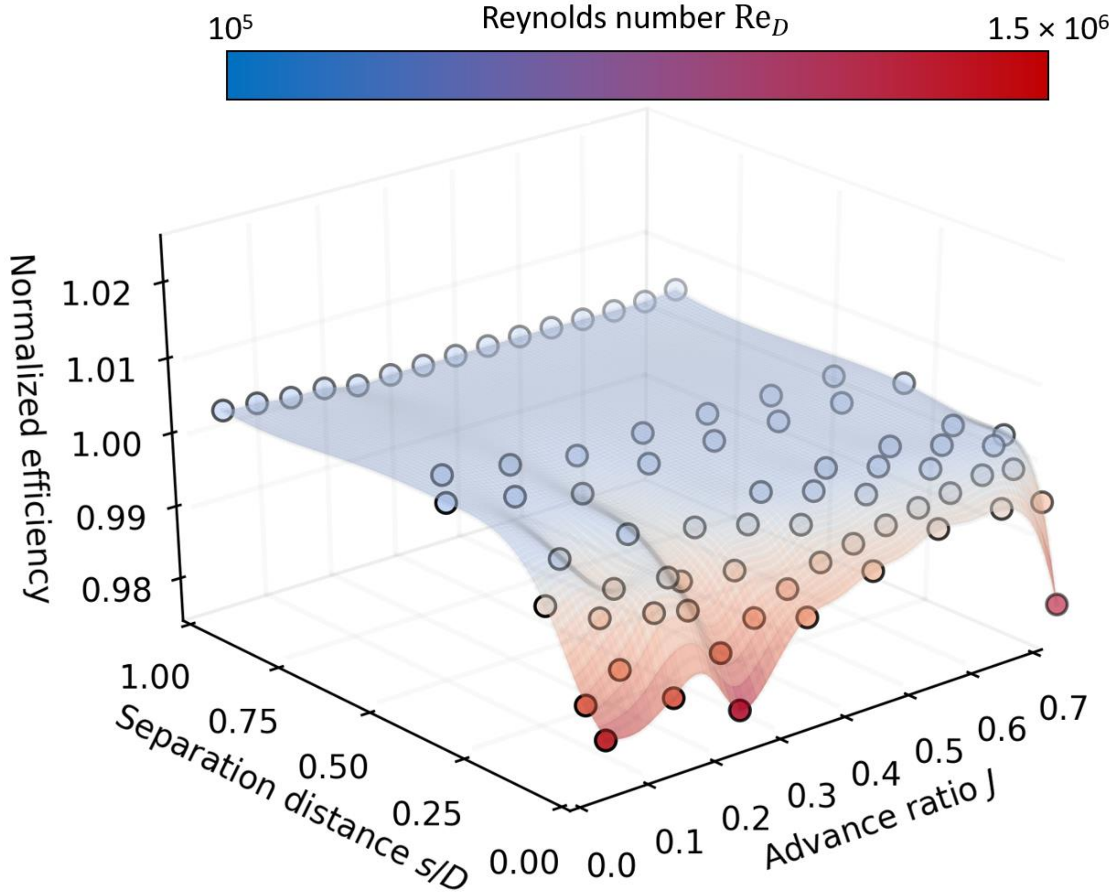

- Performance drops in all configurations
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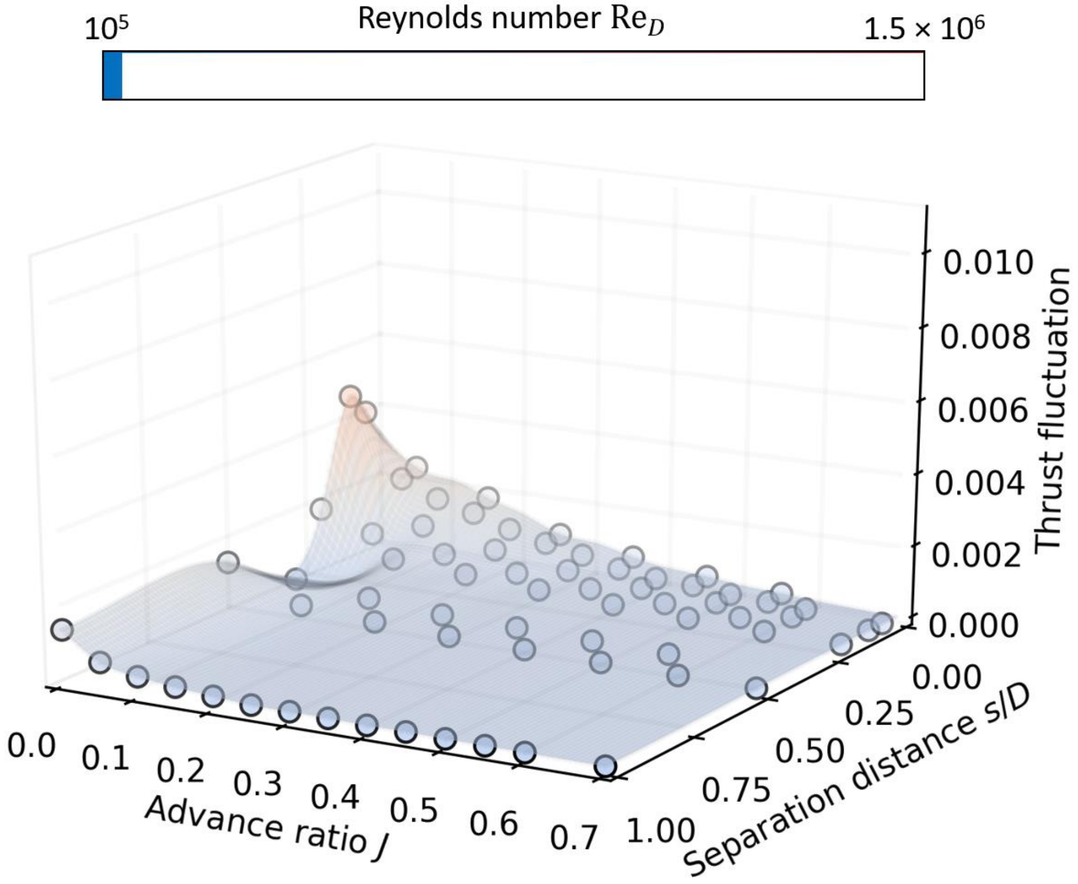
Multirotor Parametric Study

Thrust Fluctuation Response Surface

- Largest fluctuations in hover and near-hover
- Fluctuations increase with Reynolds number



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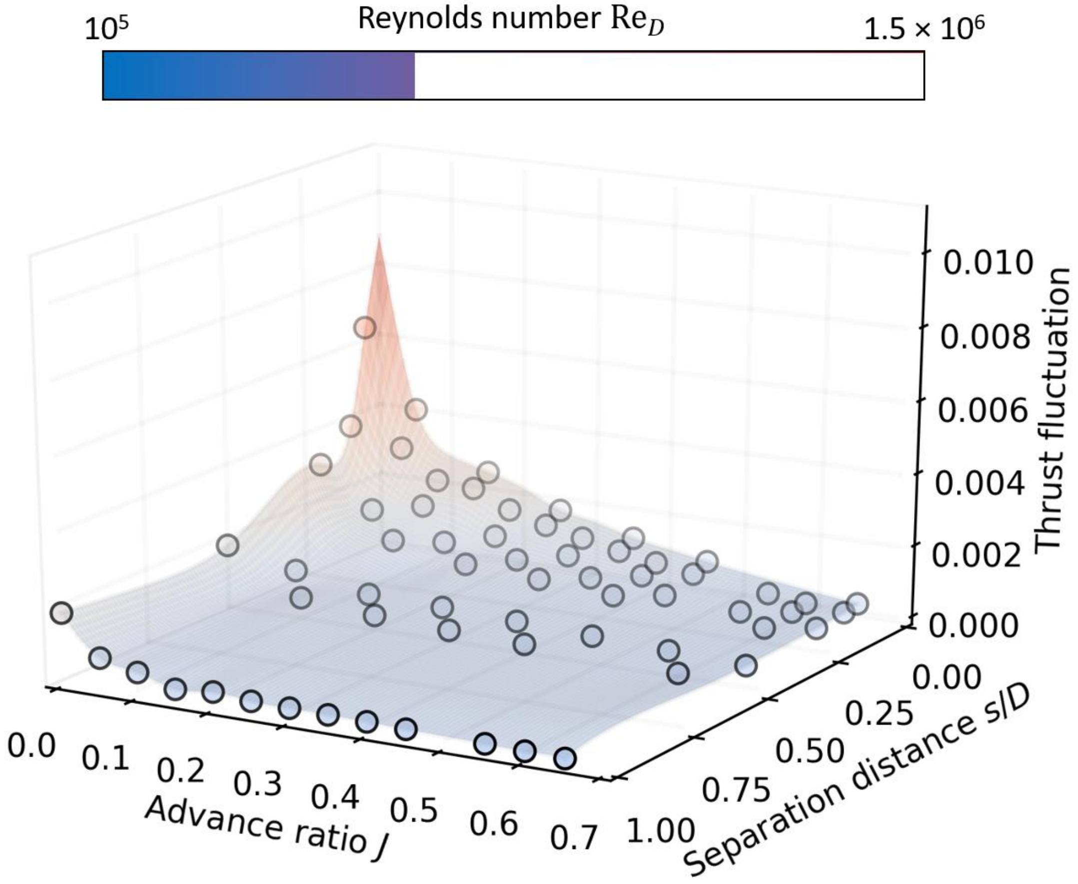

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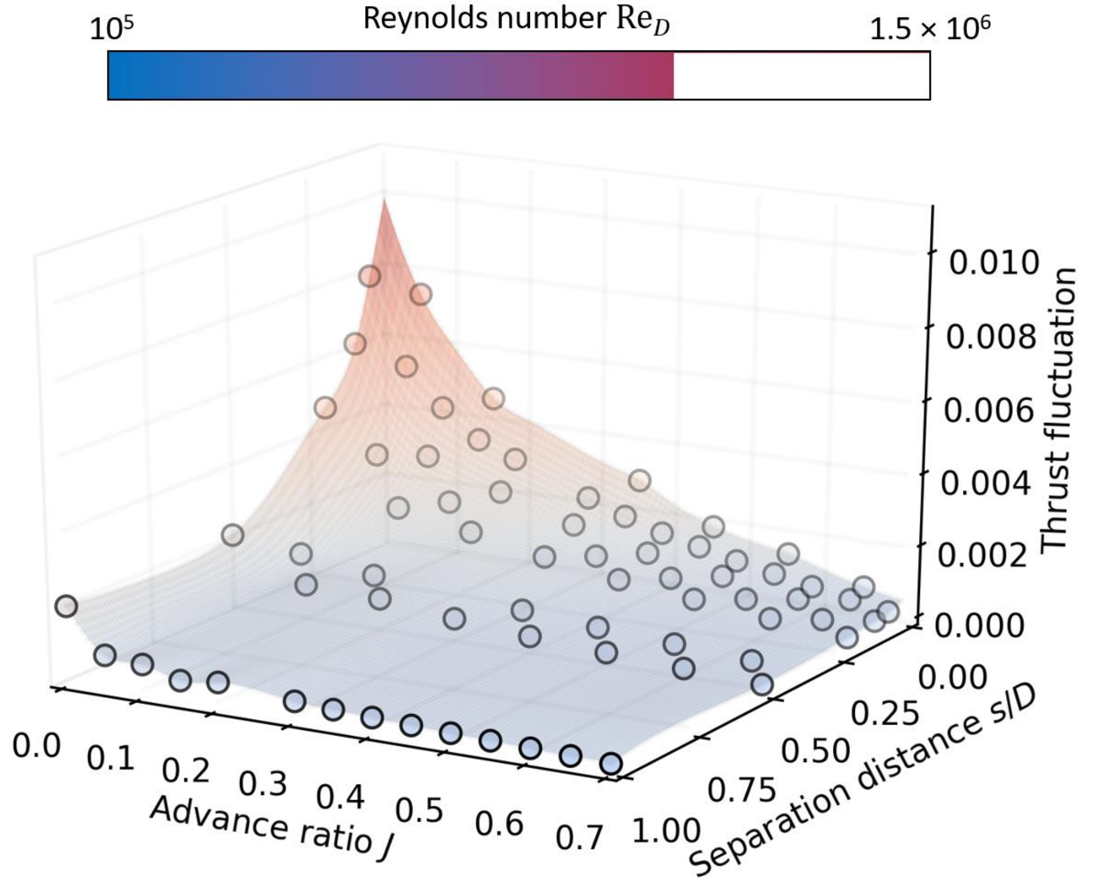

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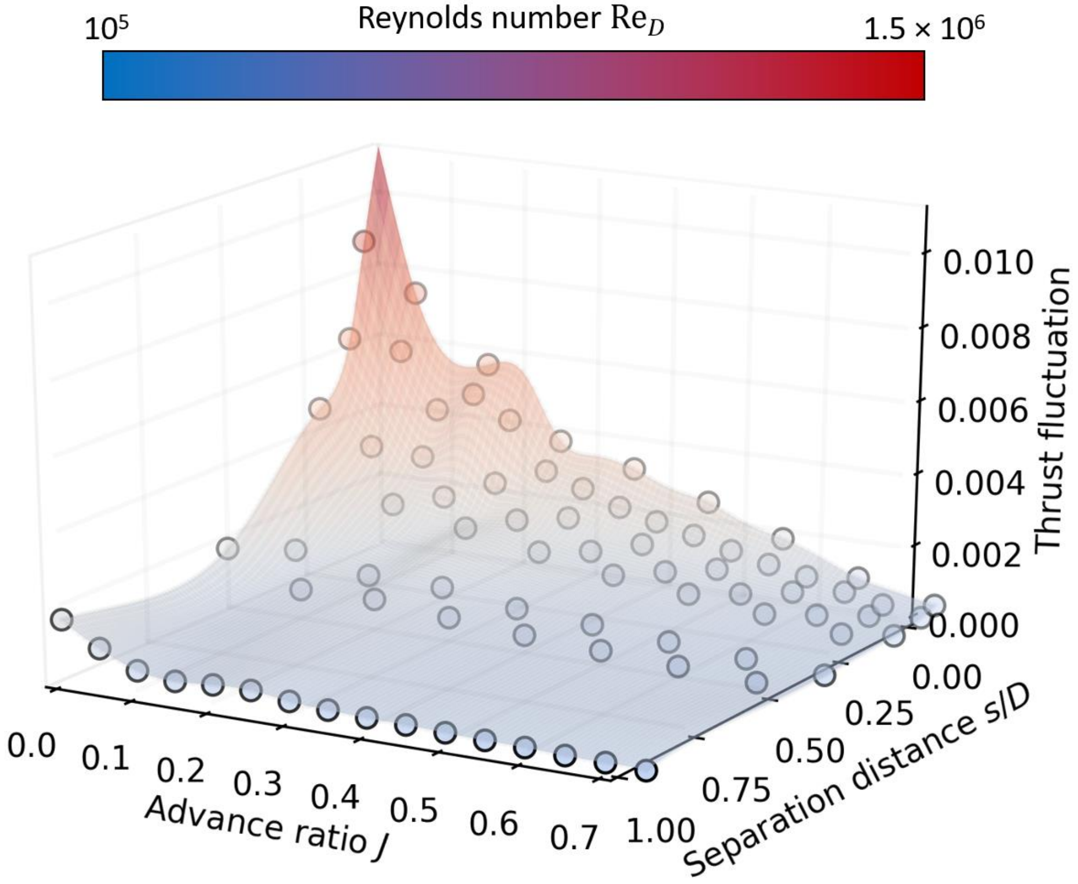
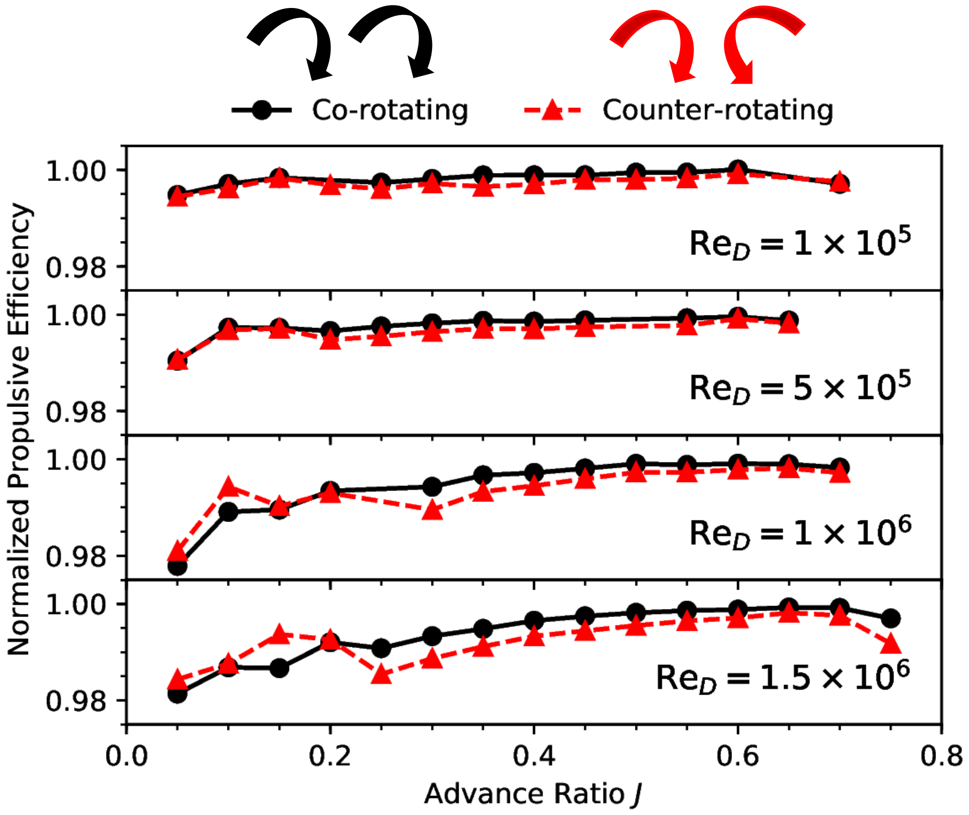


Multirotor Parametric Study

Co-rotation vs Counter-rotation



- Counter-rotation is slightly less efficient than co-rotation for $J > 0.25$

  ($\sim$0.5% less efficient)

CONCLUSIONS

VPM multirotor model

- Validated in hover and forward flight.
- Validated at low and high Reynolds.

Multirotor parametric study

- Interactions are detrimental across all advance ratios and Reynolds numbers.
- Performance drop accentuated at $J < 0.2$
- Largest thrust fluctuations at $J < 0.2$
- Counter-rotation is slightly less efficient at $J > 0.25$
- Higher Reynolds number accentuates interactions in a lightly tip-loaded rotor.

FUTURE WORK

- Coupling with FW-H noise code.
- Automatic derivatives for gradient-based design optimization.

FLOW Lab

http://flow.byu.edu/
https://github.com/byuflowlab/

Work funded by the High Impact Doctoral Research fellowship granted by BYU