Rotor-on-Rotor Aeroacoustic Interactions of Multirotor in Hover

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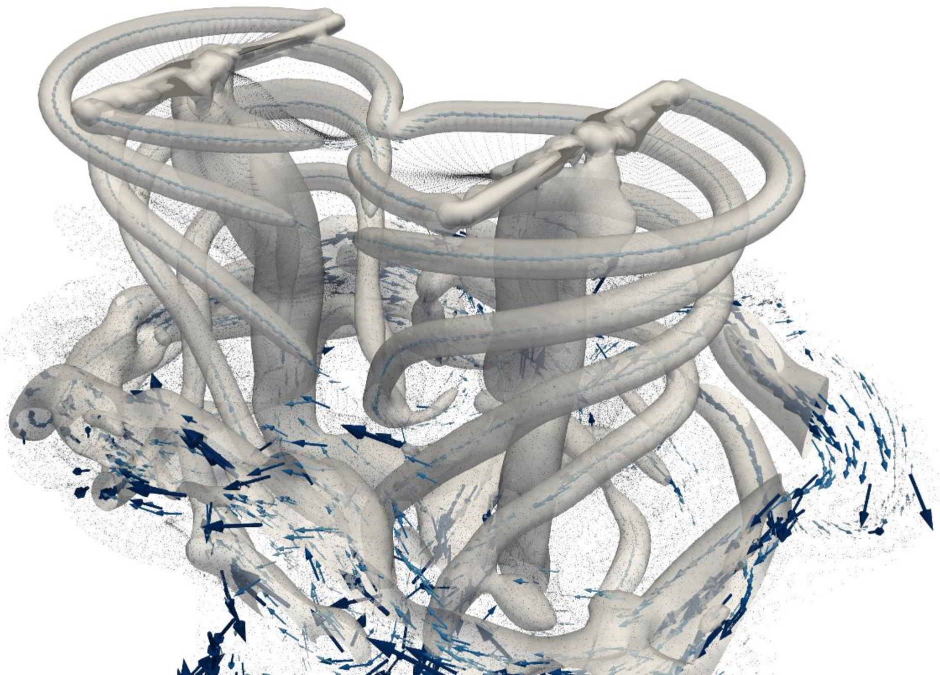
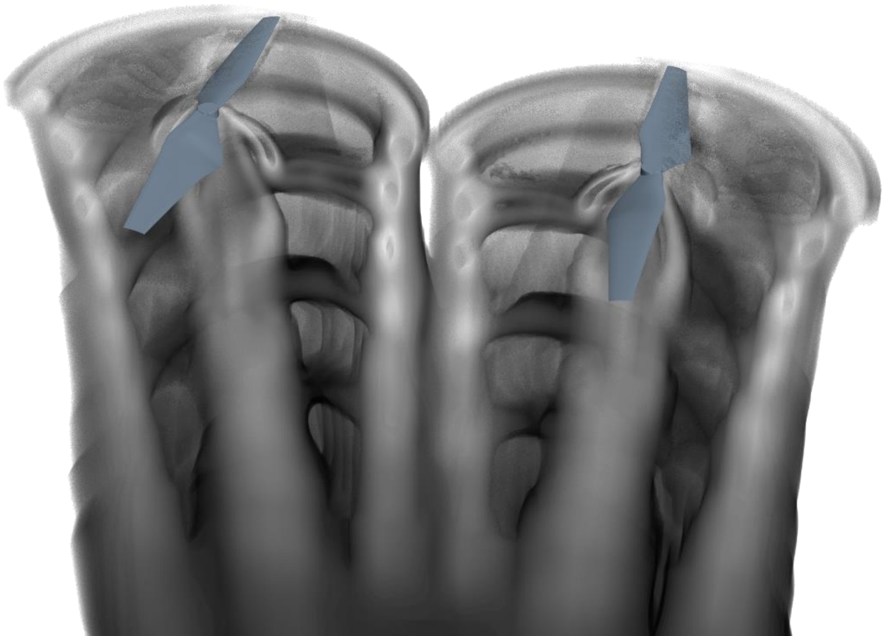
Brigham Young University, UT, USA





Motivation

NASA, X-57 Maxwell


© Joby Aviation

© Kitty Hawk, Heaviside

© Wing

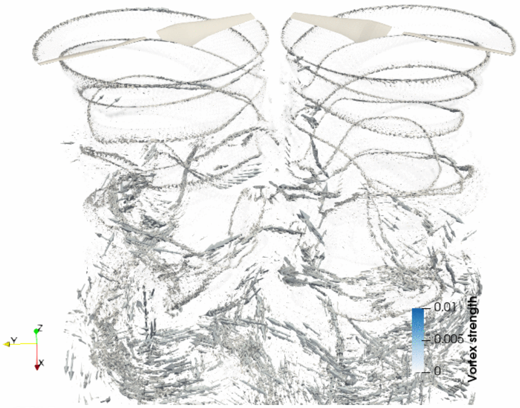
ARL, CRC

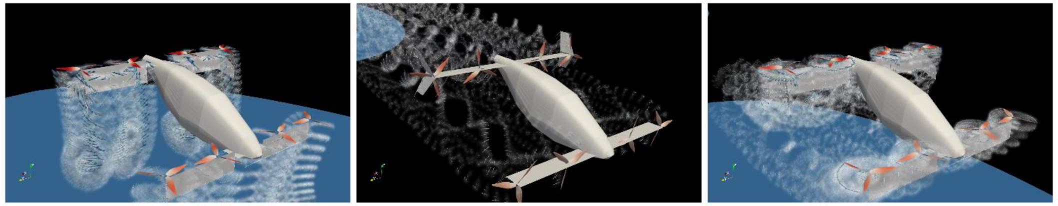

© Volocopter, VC200

Motivation

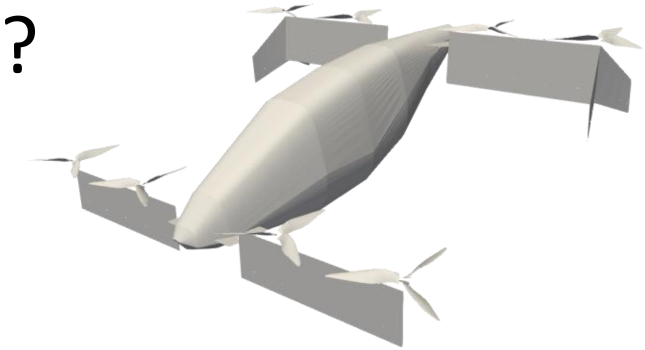
Difficulties of Multirotor Noise

- Low Reynolds number and high BPF
- Rotor-rotor unsteady interactions
- VTOL transition maneuver
- Fast enough for conceptual design?



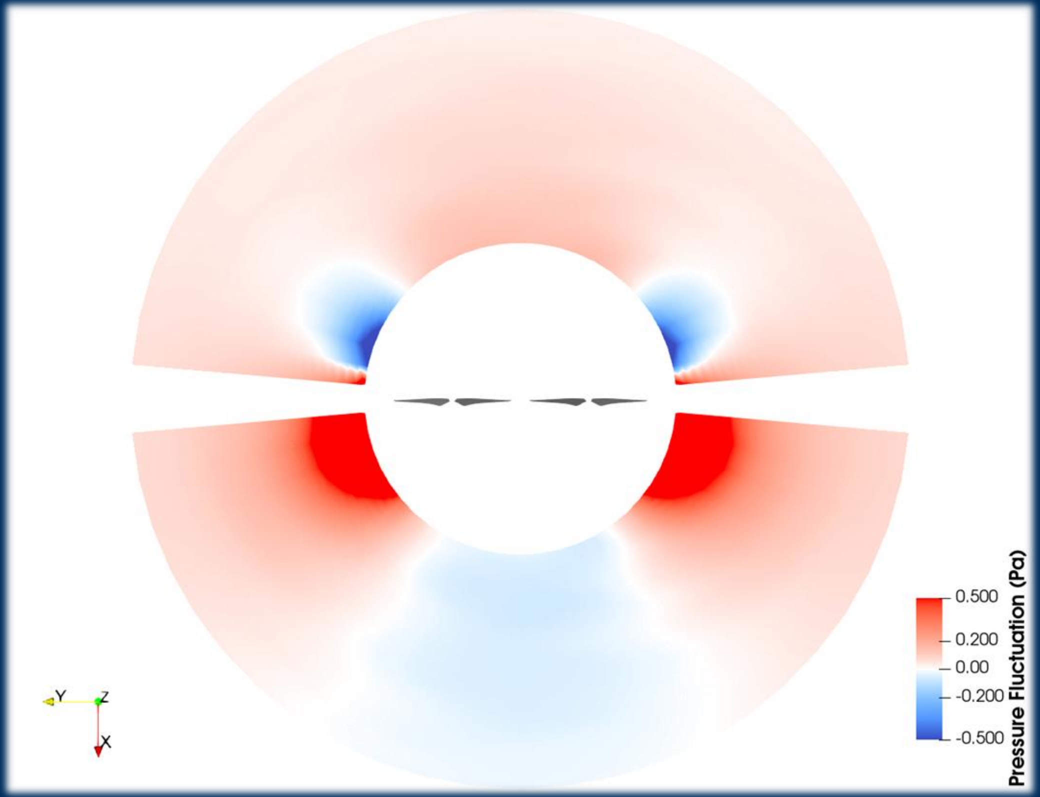


(a) Takeoff (b) Cruise (c) Cruise-Hover transition



OUTLINE

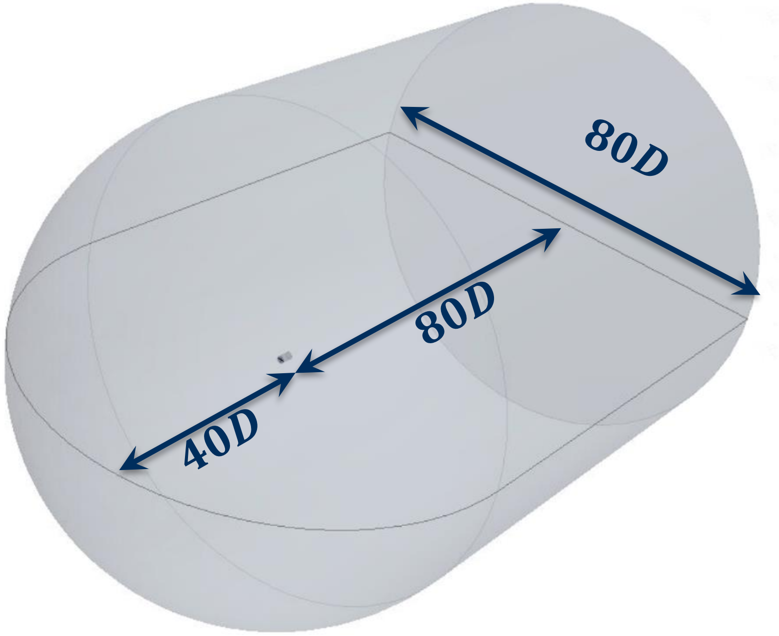
- Numerical methods
- Single-rotor validation
- Multirotor results
  - URANS vs VPM
  - Effects of tip-to-tip distance
  - Effects of downstream spacing

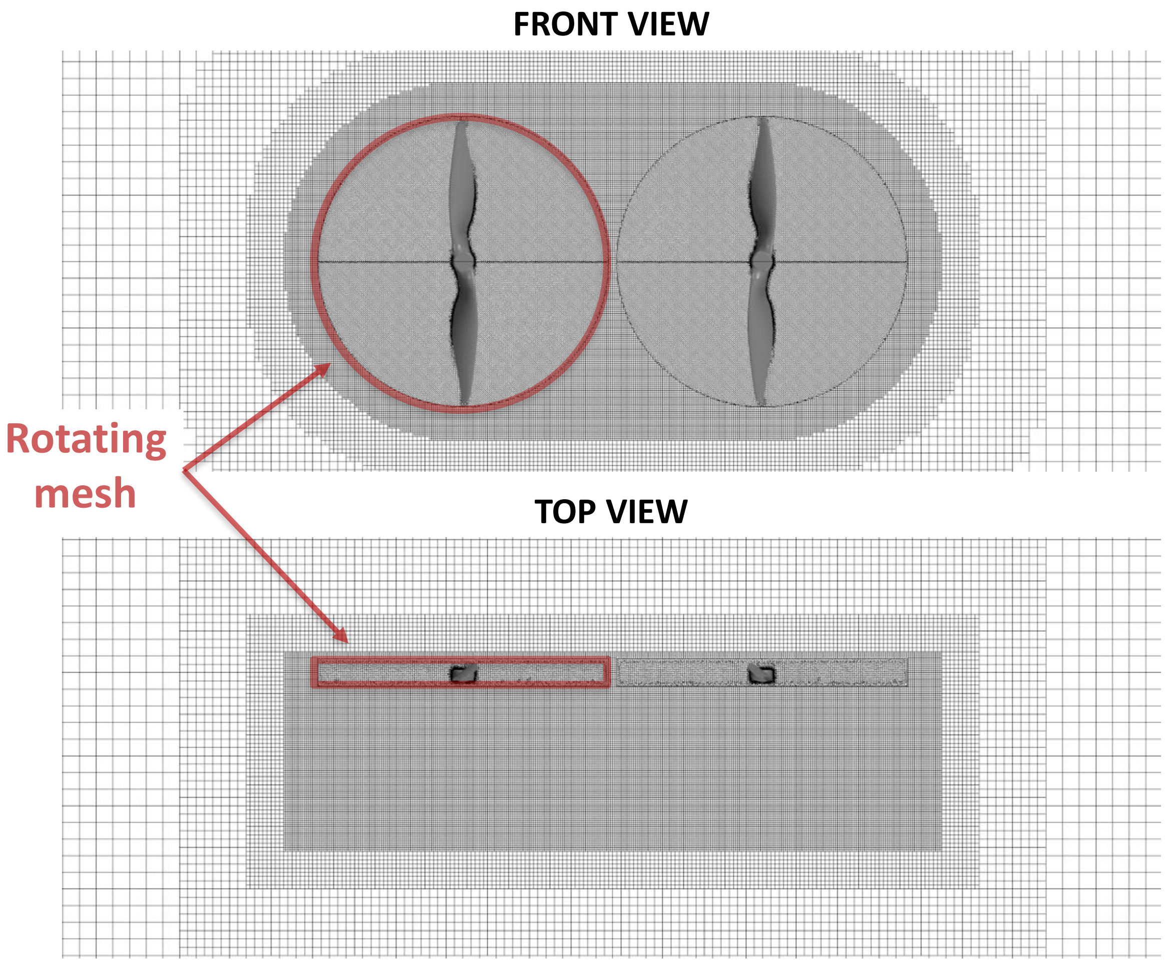


NUMERICAL METHODS

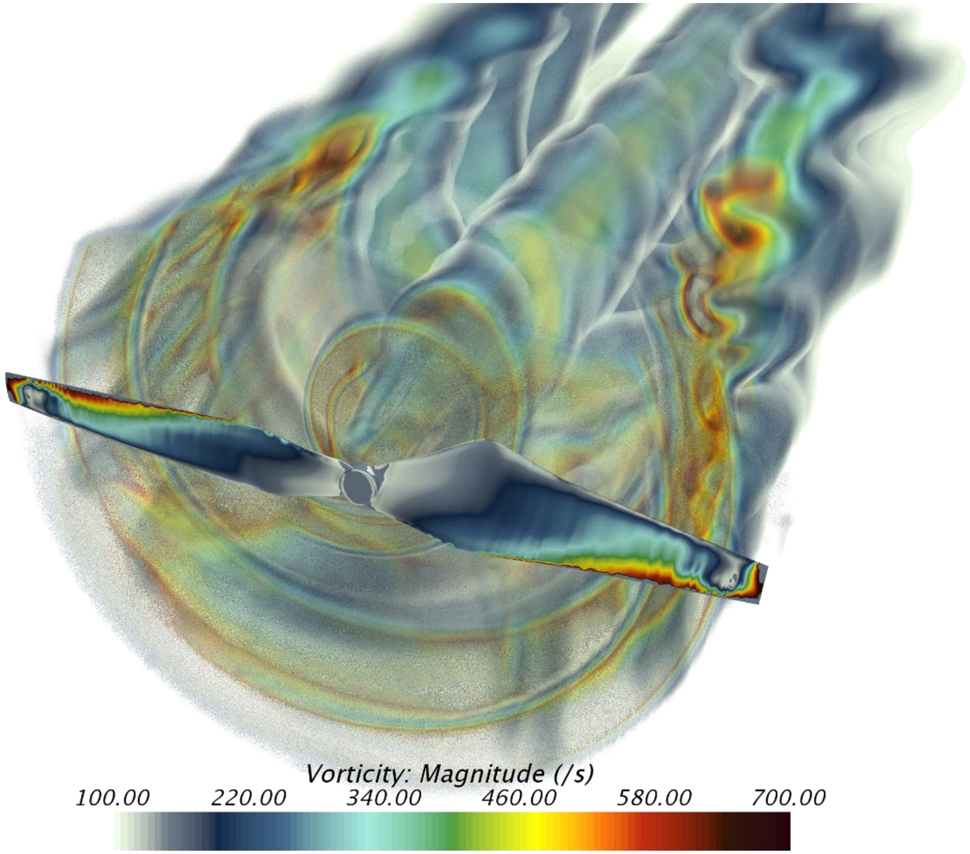
SIEMENS STAR-CCM+

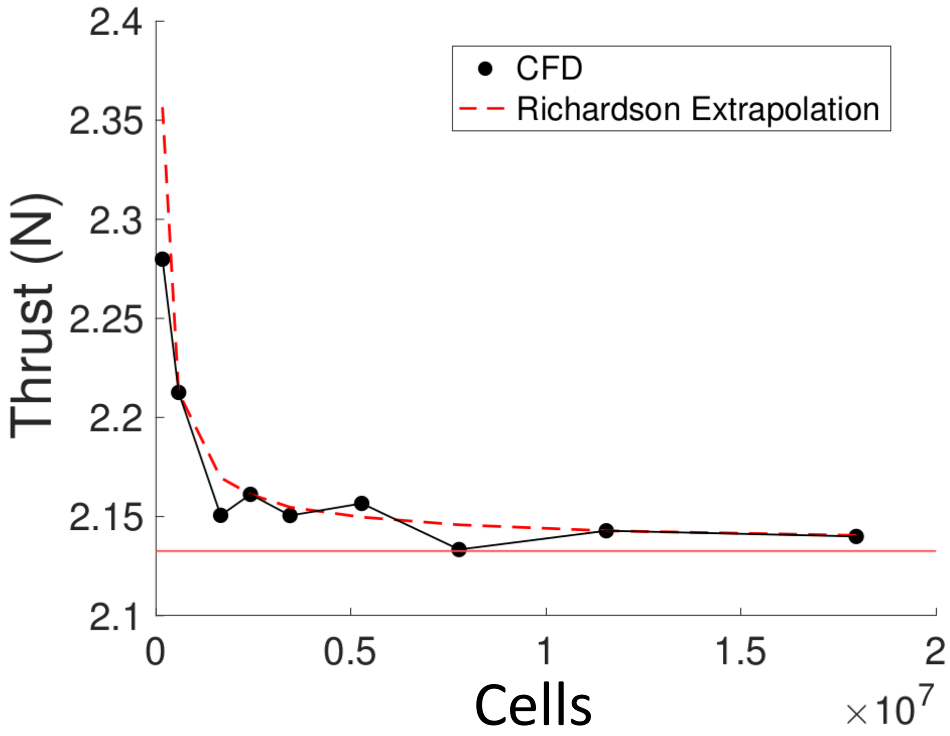
URANS



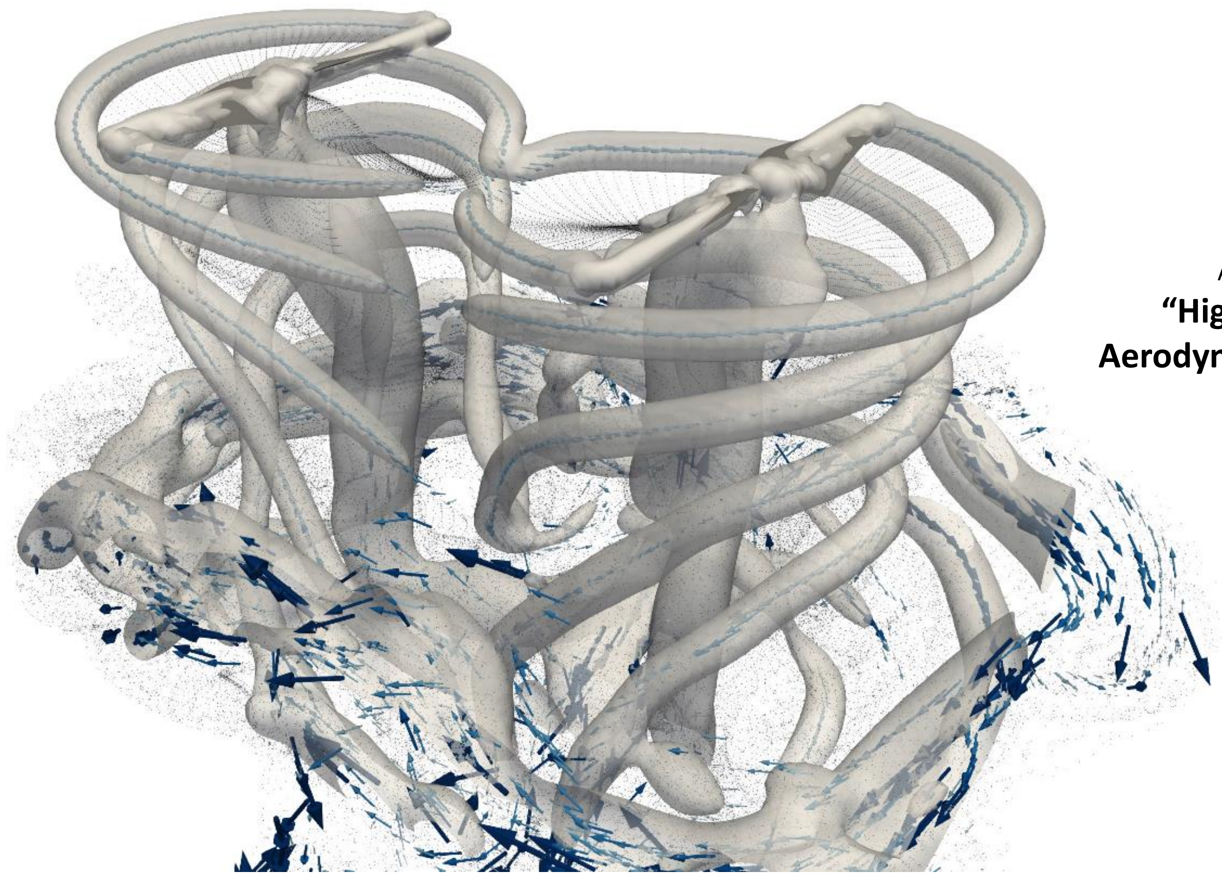


URANS


Vorticity: Magnitude (/s)
100.00
220.00
340.00
460.00
580.00
700.00


Thrust (N)
2.4
2.35
2.3
2.25
2.2
2.15
2.1
0
0.5
1
1.5
2
Cells
×10^7
CFD
Richardson Extrapolation

Viscous Vortex Particle Method (VPM)



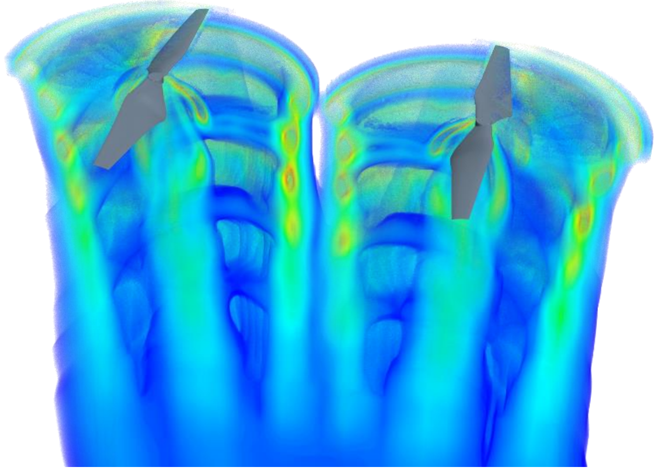
Alvarez, E. and Ning, A., AIAA Journal 2020,
“High-Fidelity Modeling of Multirotor Aerodynamic Interactions for Aircraft Design”
[LINK]

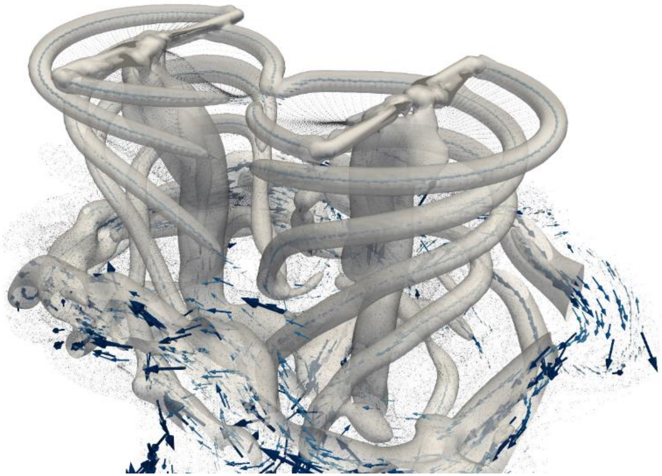
Video: https://youtu.be/SLpnVIBpkps

FLOWUnsteady
github.com/byuflowlab/FLOWUnsteady

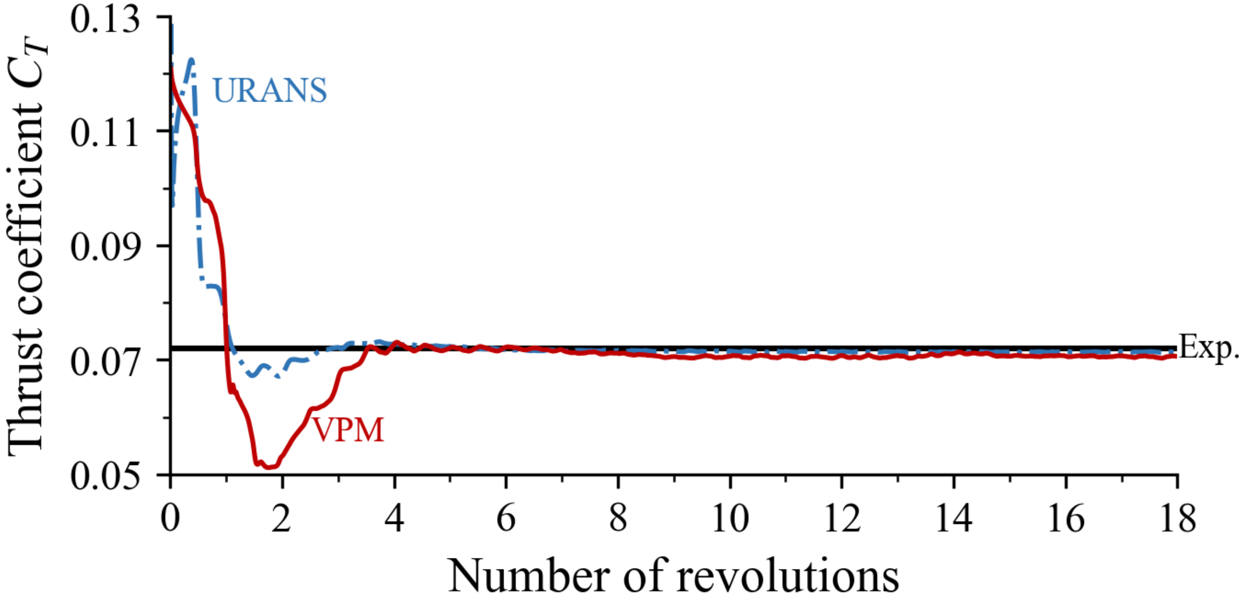
	URANS	VPM
Governing equation	Linear momentum eq. $\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u}$	Angular momentum eq. $\frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega}\cdot\nabla)\mathbf{u} + \nu\nabla^2\boldsymbol{\omega}$
Numerical scheme	Eulerian (mesh)	Lagrangian (meshless)
Boundary layer	Wall function	Momentum integral
Turbulence model	SST $k-\omega$	None (unresolved DNS)
Simulation	50 revolutions	50 revolutions
Computational resources	192 CPU cores for 48 hours	32 CPU cores for 2 hours
Computational cost	**9200 processor-hours**	**64 processor-hours**

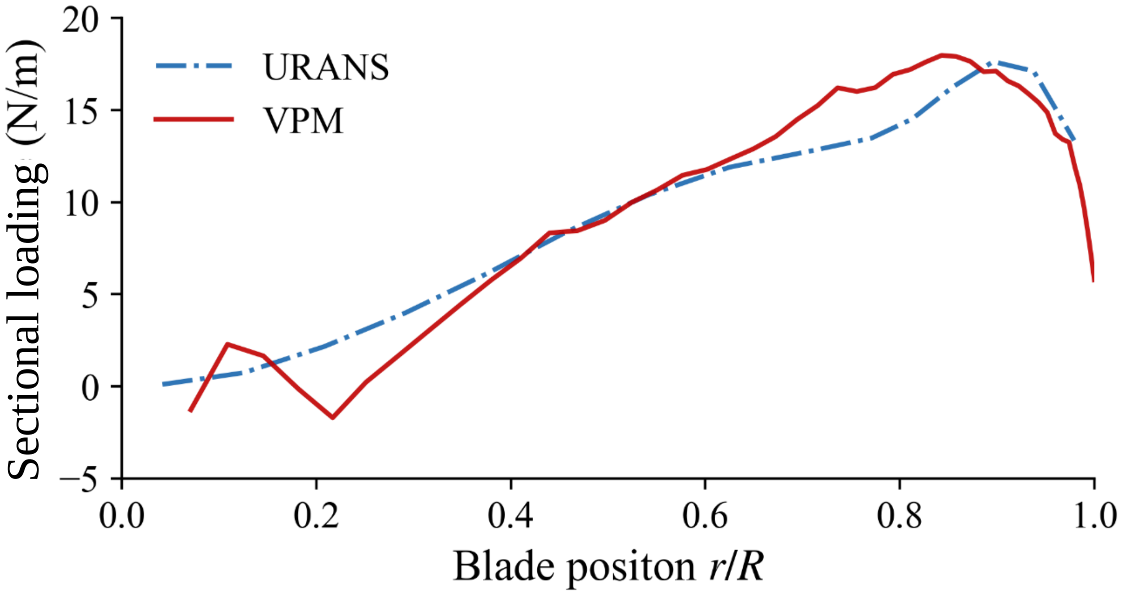
100x faster!





SINGLE-ROTOR VALIDATION





DJI 9443

EXPERIMENTAL DATA: Zawodny, N., Boyd, D., and Burley, C., 2017, “Acoustic Characterization and Prediction of Representative, Small-Scale Rotary-Wing UAS Components.”

Aeroacoustics Solver

Tonal Noise

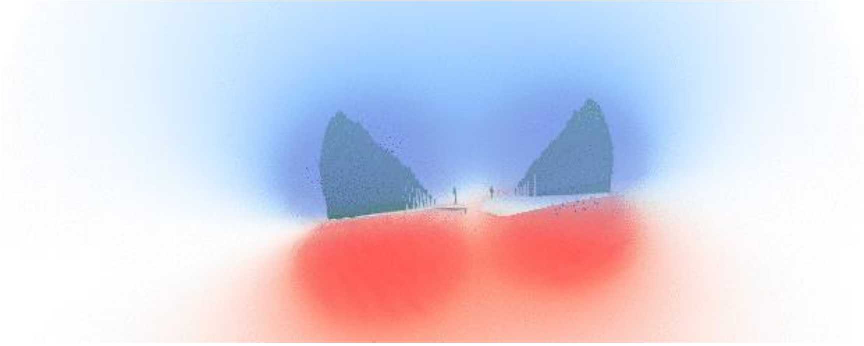
- Ffowcs Williams-Hawkings (FW-H) equation

$$\bar{\Box}^2 p'(\mathbf{x},t) = \underbrace{\frac{\partial}{\partial t}\left(\rho_0 \mathbf{u}_n \delta(f)\right)}_{\text{thickness}} - \underbrace{\frac{\partial}{\partial x_i}\left(\Delta P_{ij}\hat{\mathbf{n}}_j \delta(f)\right)}_{\text{loading}}$$

- Loading through compact patches
- PSU-WOPWOP

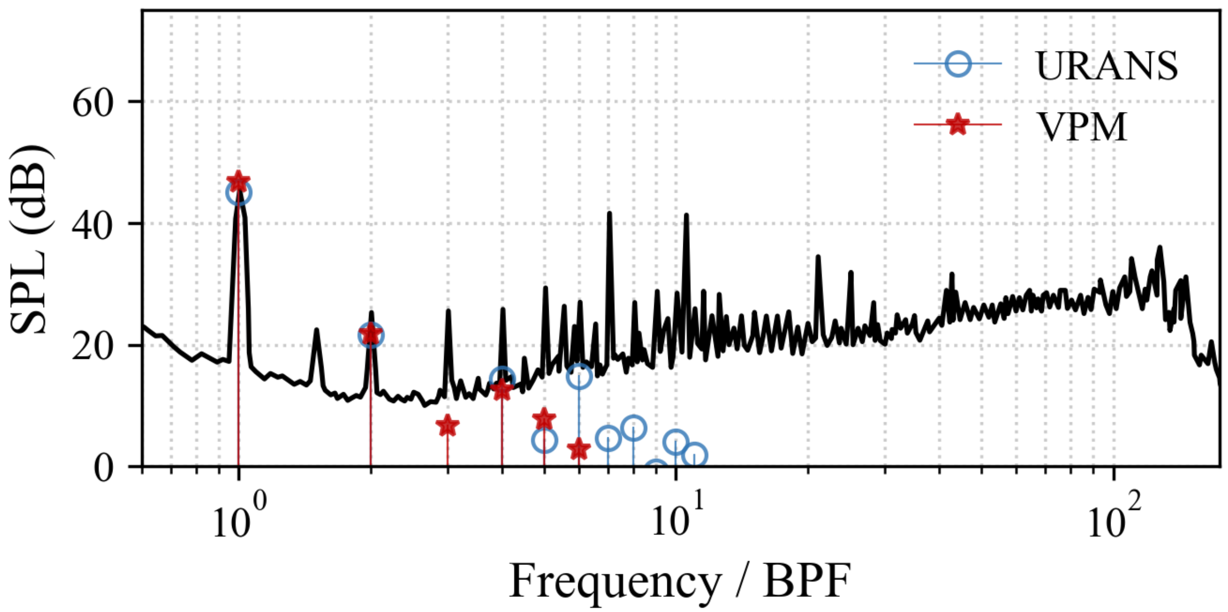
Broadband Noise

- Brooks, Pope, and Marcolini (BPM) method
- Separation stall, tip vortex formation, Turbulent BL edge, laminar BL vortex shedding, and TE bluntness.
- **FLOWUnsteady**
  github.com/byuflowlab/FLOWUnsteady

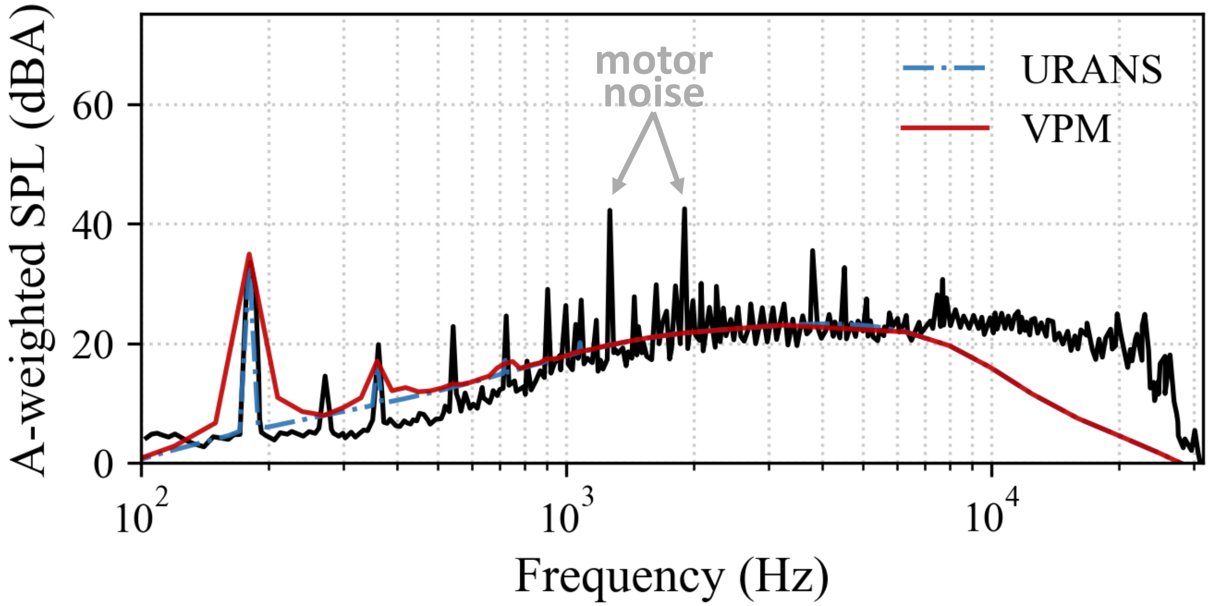


SINGLE-ROTOR VALIDATION

Tonal Noise



Broadband Noise



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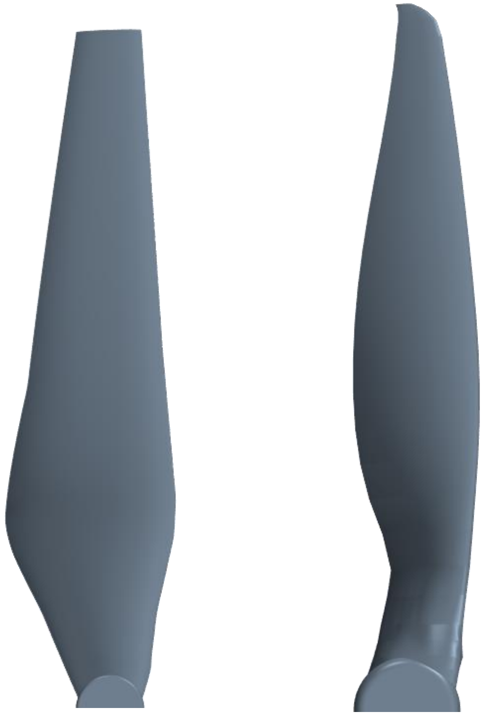
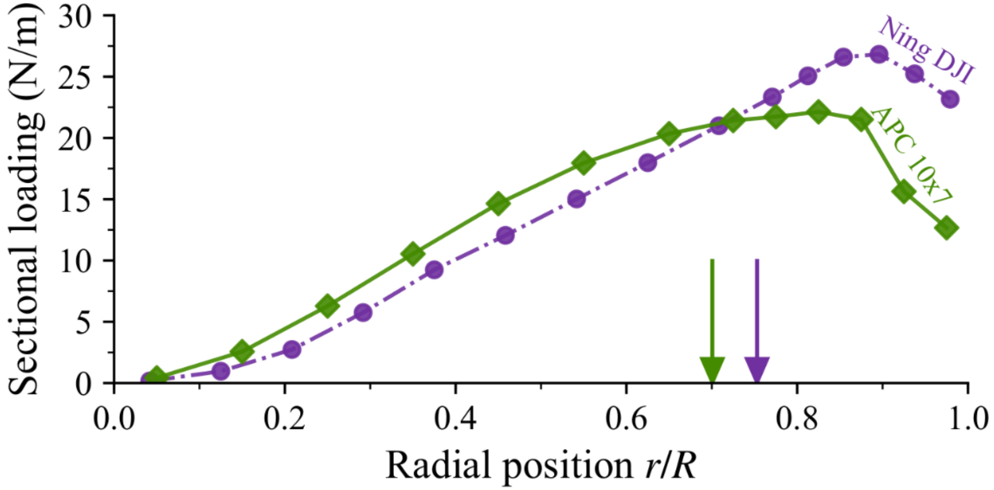
ROTORS



	Ning DJI[1]	APC 10x7
Diameter	9.4 in	10 in
Speed	4860 RPM	4600 RPM

- Number of blades: 2
- Solidity: ~0.1
- Tip speed: ~0.2 Mach
- $Re_c = 6 \times 10^4$
- $Re_D = 7 \times 10^5$

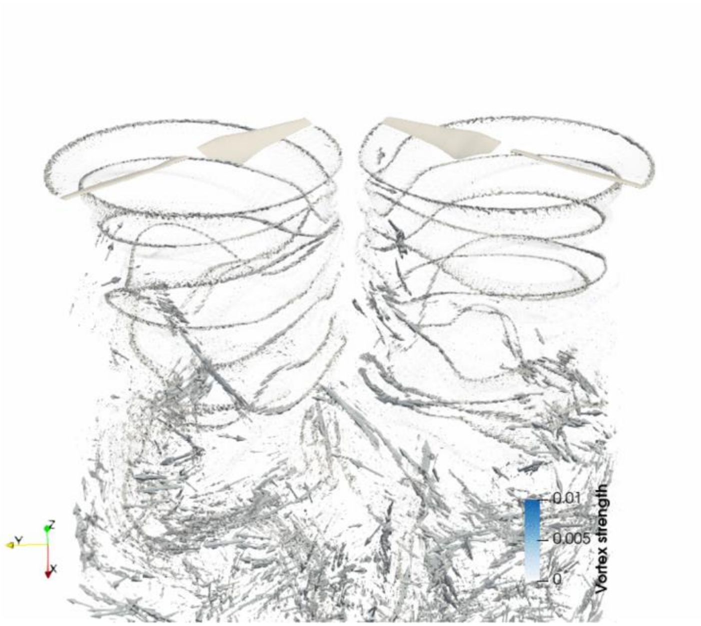


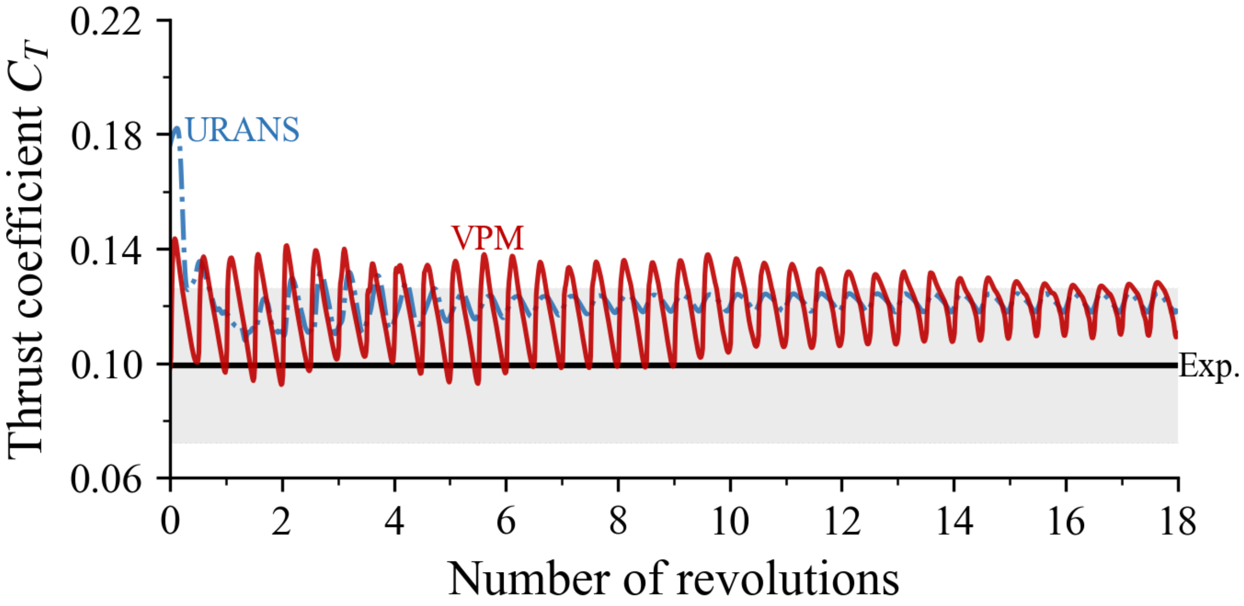
[1] Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, "An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers."

MULTIROTOR RESULTS

RESULTS

Aerodynamic Interactions





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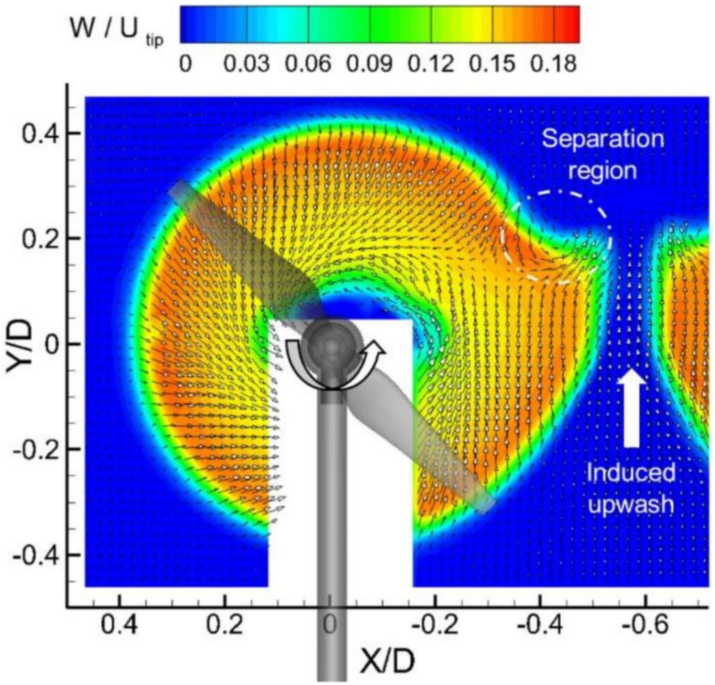
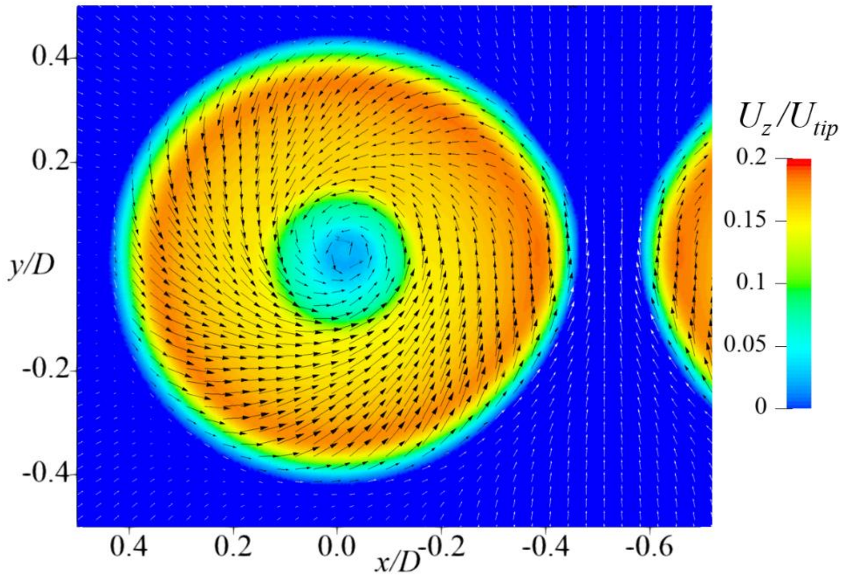
RESULTS

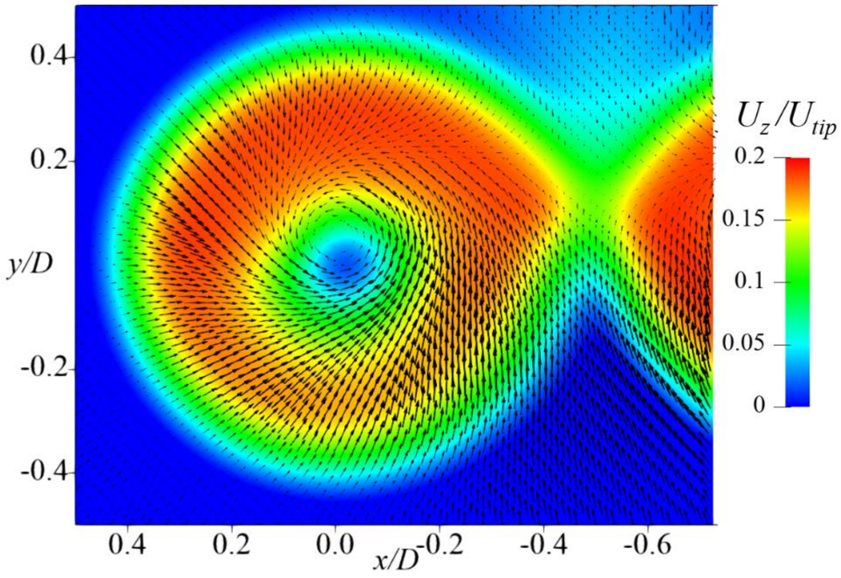
Aerodynamic Interactions



Experimental



URANS



VPM

EXPERIMENTAL DATA: Zhou, W., Ning, Z., Li, H., and Hu, H., 2017, “An Experimental Investigation on Rotor-to-Rotor Interactions of Small UAV Propellers.”

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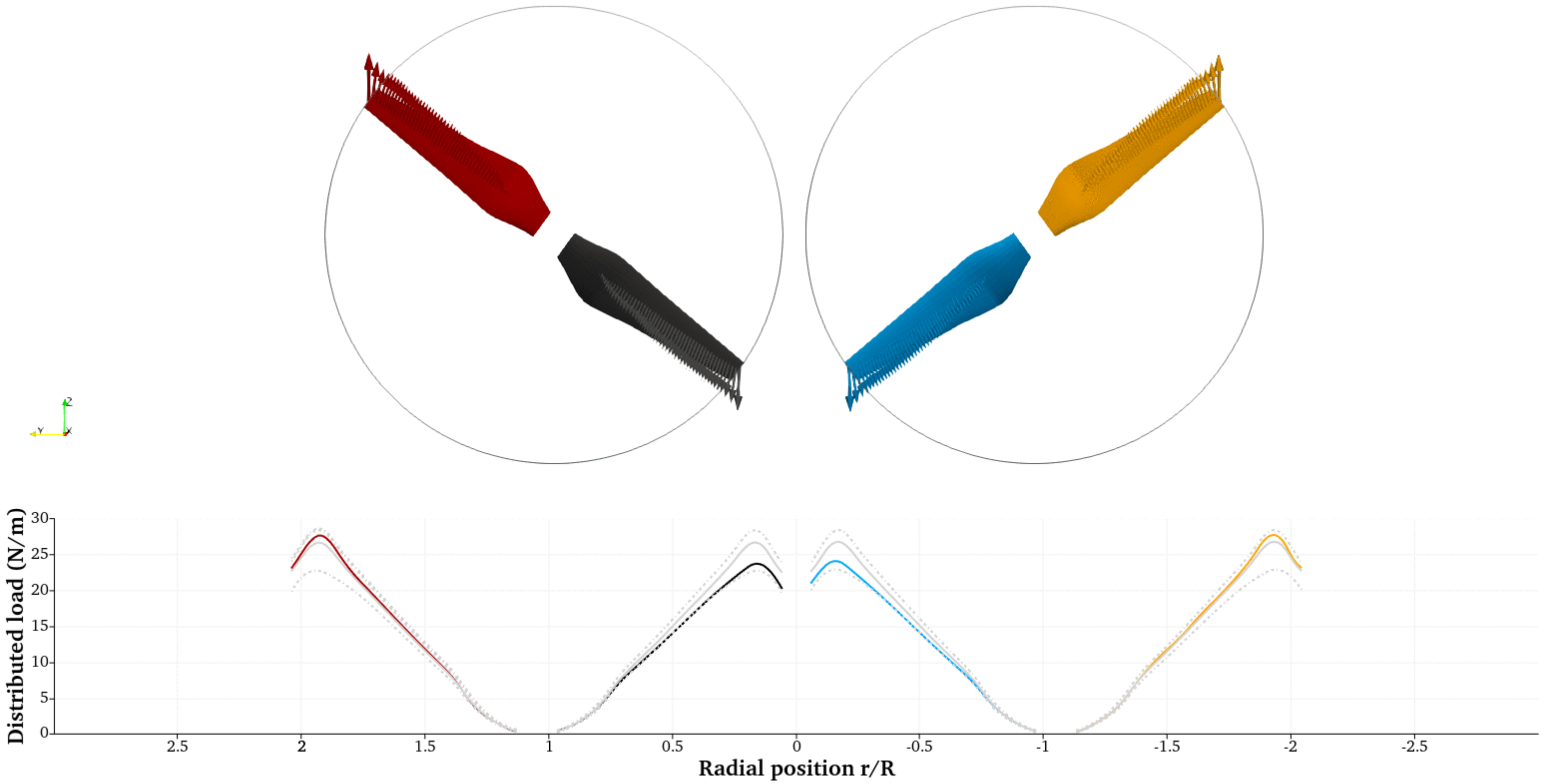
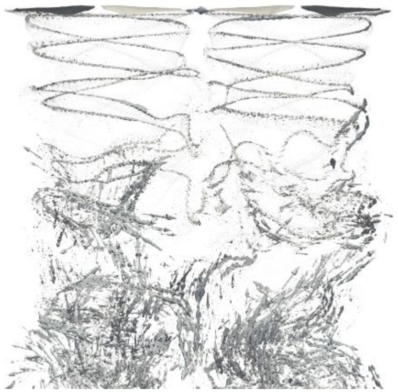
Aerodynamic Interactions

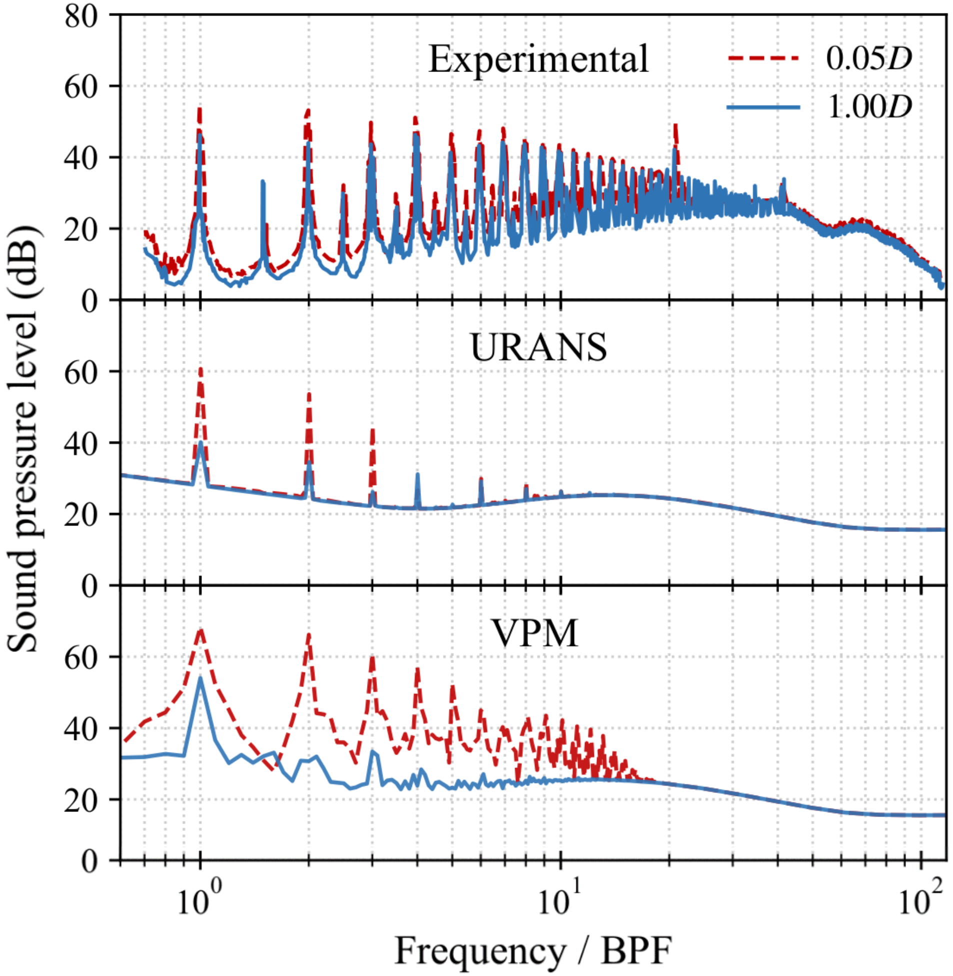


Video: https://youtu.be/ji6UZRxqjM4

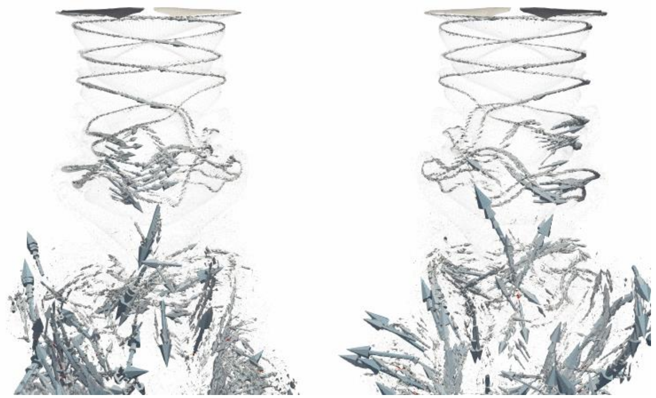
Acoustic Interactions

0.05D





1D



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

RESULTS

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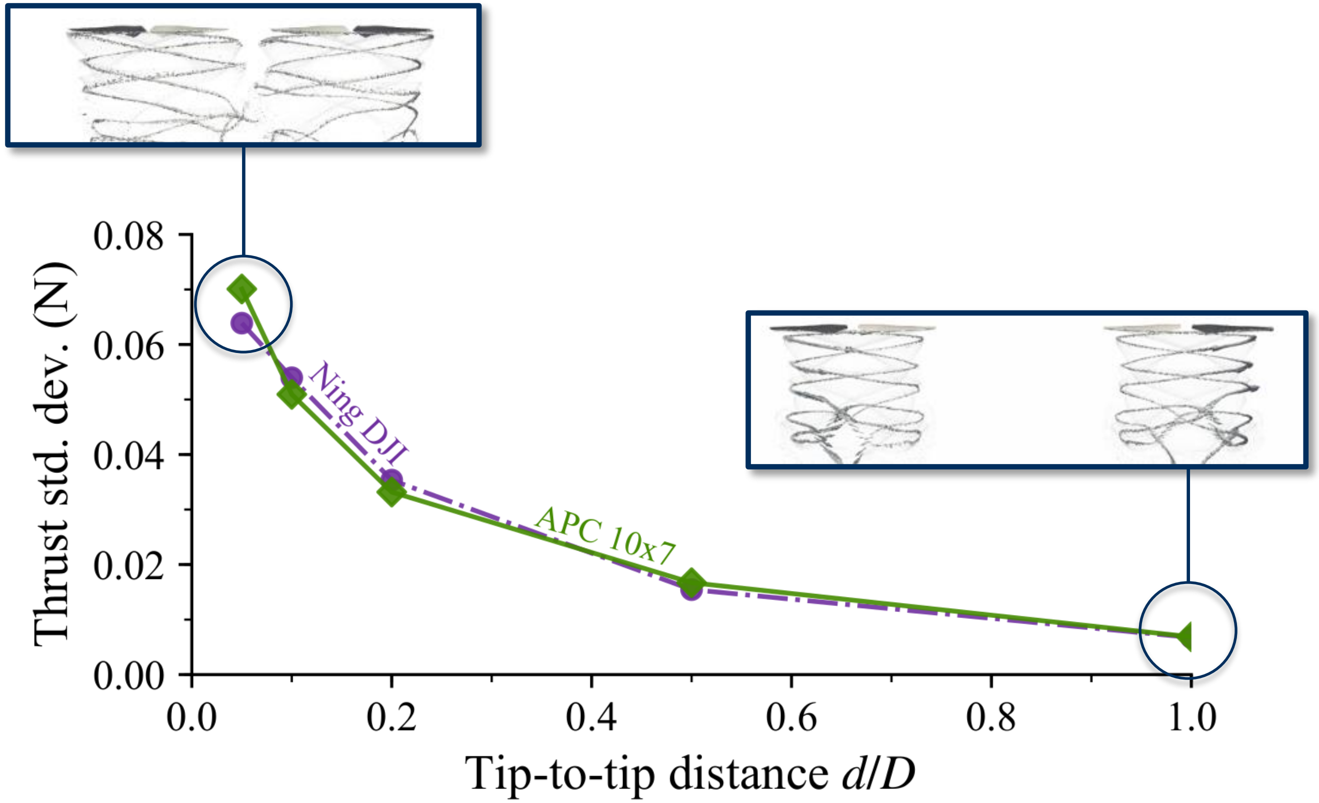
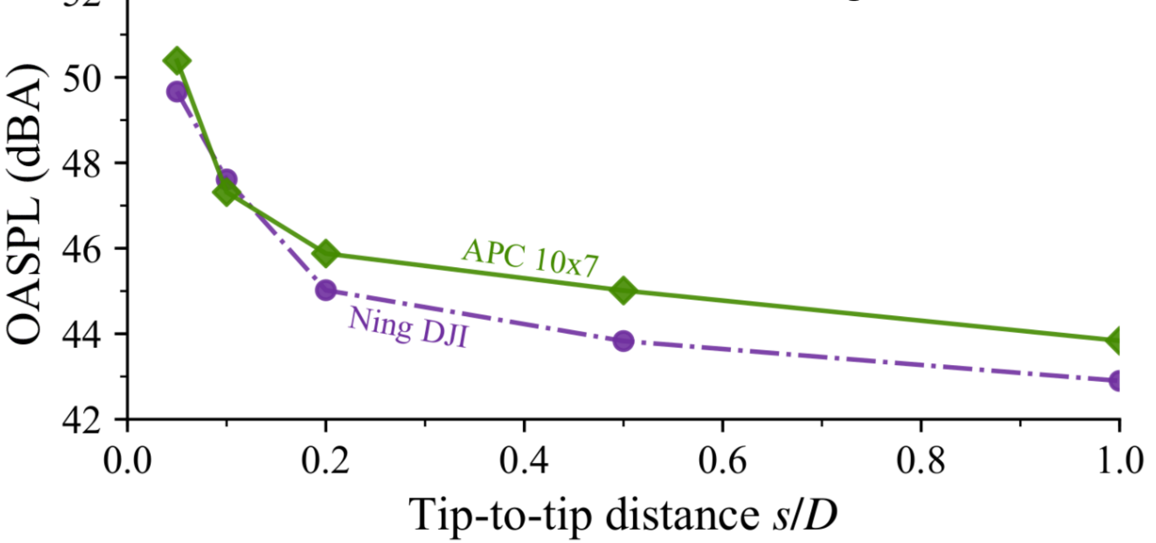
Effects of Tip-to-Tip Distance

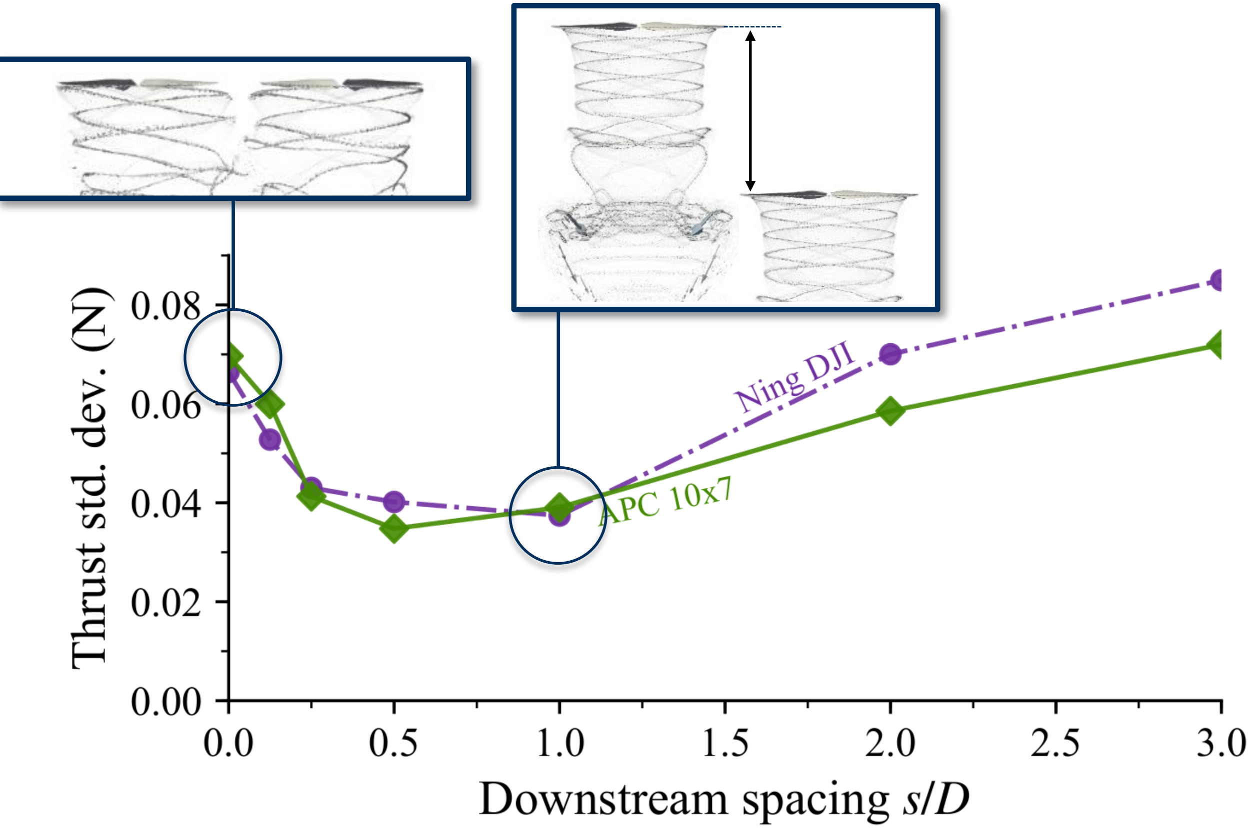


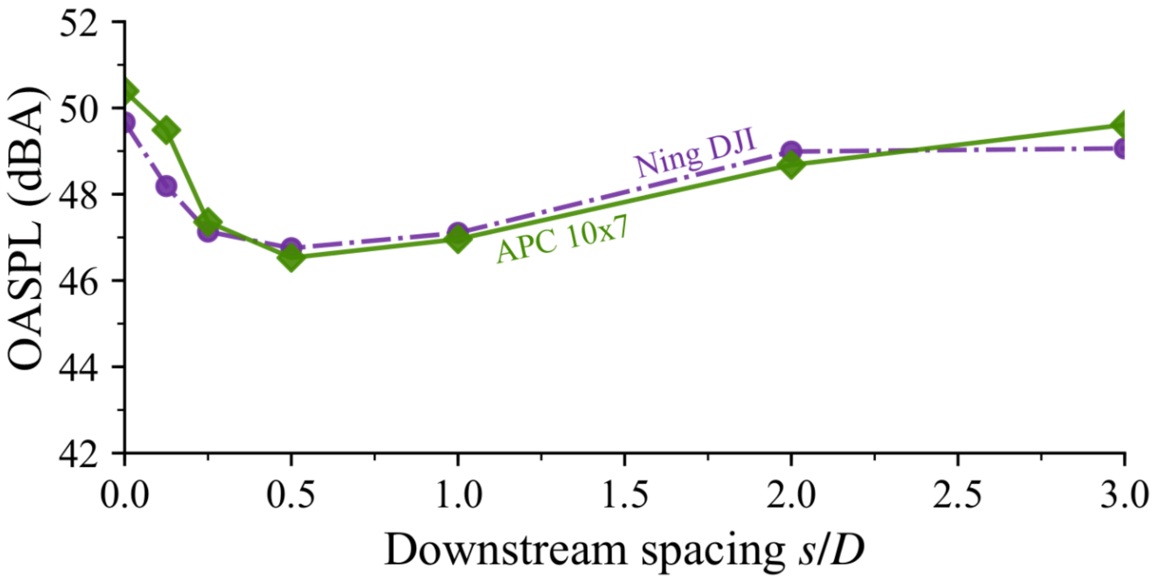
~7 dBA **increase**
as rotors are closer together



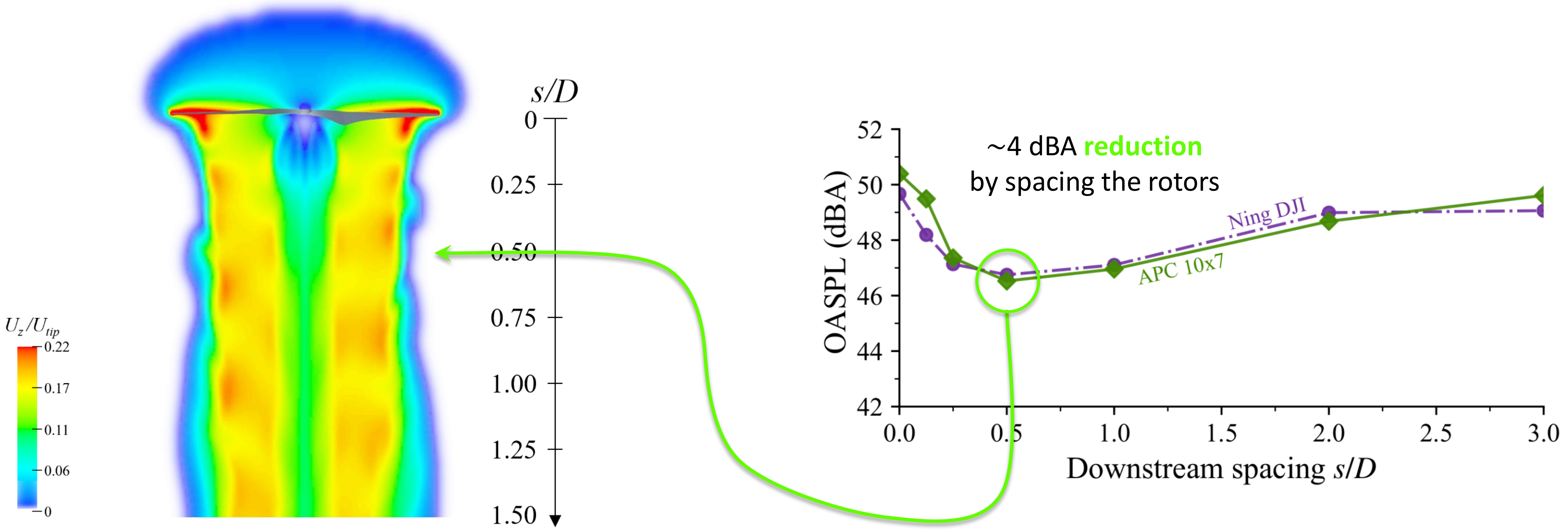
RESULTS

Effects of Downstream Spacing





Effects of Downstream Spacing



CONCLUSIONS

- VPM is 100x faster than URANS with comparable accuracy.
- 7 dBA noise **increase** as rotors are brought closer together.
- 4 dBA noise **reduction** by spacing the rotors downstream.
- Multirotor interactions are not alleviated with a lighter tip loading.

FLOW Lab

flow.byu.edu

github.com/byuflowlab

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