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Vortex Particle Method for Electric Ducted Fan in Non-Axisymmetric Flow

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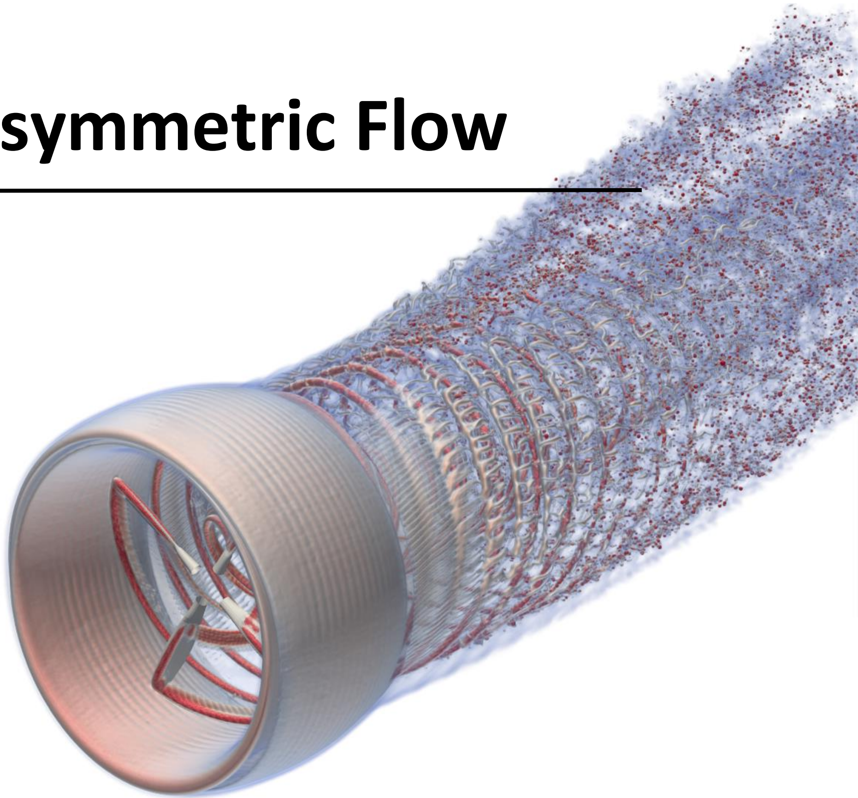
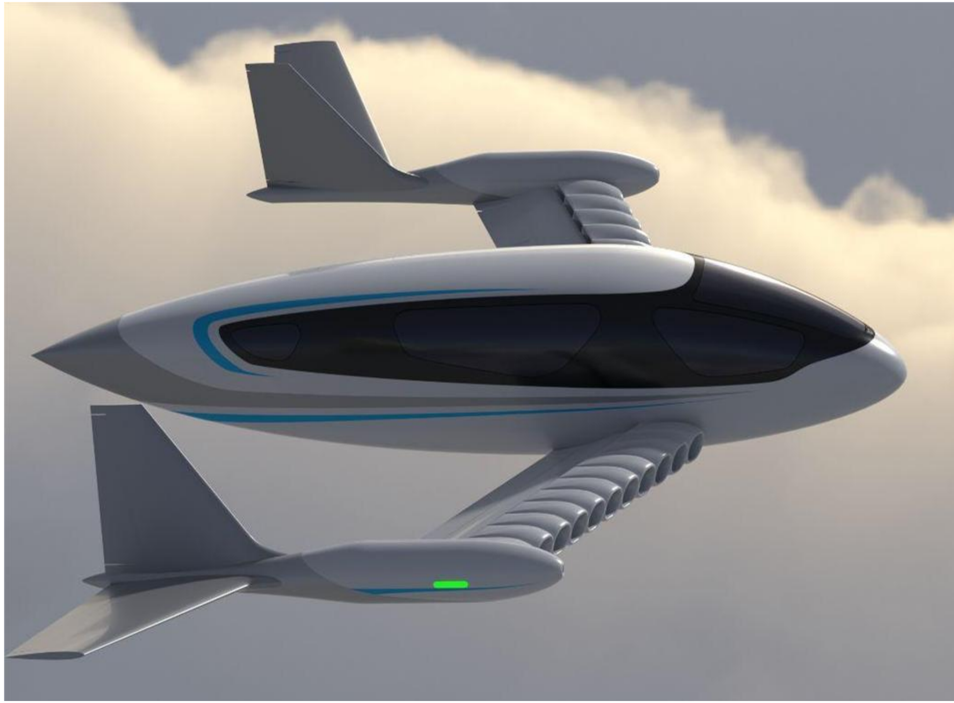


AVIATION Forum, June 12-16, 2023

Ducted fans are the next generation of DEP



Ducted fans are the next generation of DEP

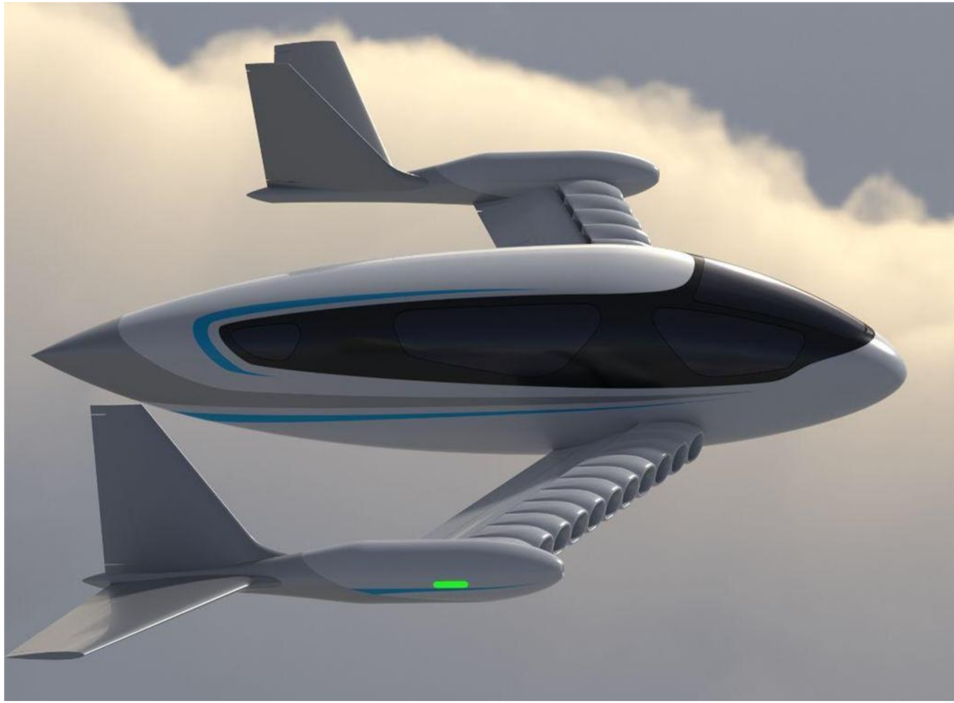
Related presentations

- **The Business Case for Regional Air Mobility at Scale**
  Monday 9:50pm, Harbor E

- **Distributed Electric Propulsion and Vehicle Integration with Ducted Fans**
  Monday 1:20pm, Harbor E

- **Unlocking Low-Cost Regional Air Mobility through Whisper Aero-Propulsive Coupling**
  Monday 1:40pm, Harbor E

- **Mark Moore's keynote:**
  How Whisper Aero Propels the Future of Aviation
  Thursday 8am, Grand Hall A-C



Fundamentals

Meshless LES through the reformulated VPM

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

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

Fundamentals

Meshless LES through the reformulated VPM

Navier-Stokes Eq.

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

Particle Discretization

$$\overline{\boldsymbol{\omega}}(\mathbf{x}) = \sum_p \boldsymbol{\Gamma}_p \zeta_{\sigma_p}\left(\mathbf{x}-\mathbf{x}_p\right)$$

LES-Filtered Navier-Stokes Eq.

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

Filter operator

$$\overline{\phi}\left(\mathbf{x}\right) \equiv \int_{-\infty}^{\infty} \phi(\mathbf{y})\zeta_\sigma(\mathbf{x}-\mathbf{y})\,\mathrm{d}\mathbf{y}$$

ζ_σ *Filter kernel*
σ *Cutoff length*

Subfilter-scale (SFS) stress tensor

$$T_{ij} \equiv \overline{u_i\omega_j} - \overline{u_i}\,\overline{\omega_j}$$

SFS advection

$$\left(\mathbf{E}_{\mathrm{adv}}\right)_i \equiv \frac{\partial T'_{ij}}{\partial x_j}$$

SFS stretching

$$\left(\mathbf{E}_{\mathrm{str}}\right)_i \equiv -\frac{\partial T_{ij}}{\partial x_j}$$

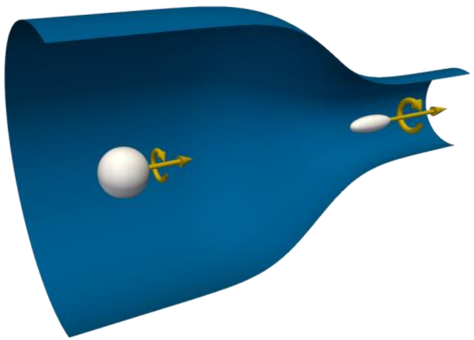
Reformulated VPM Governing Eqs.

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{x}_p = \overline{\mathbf{u}}(\mathbf{x}_p)$$

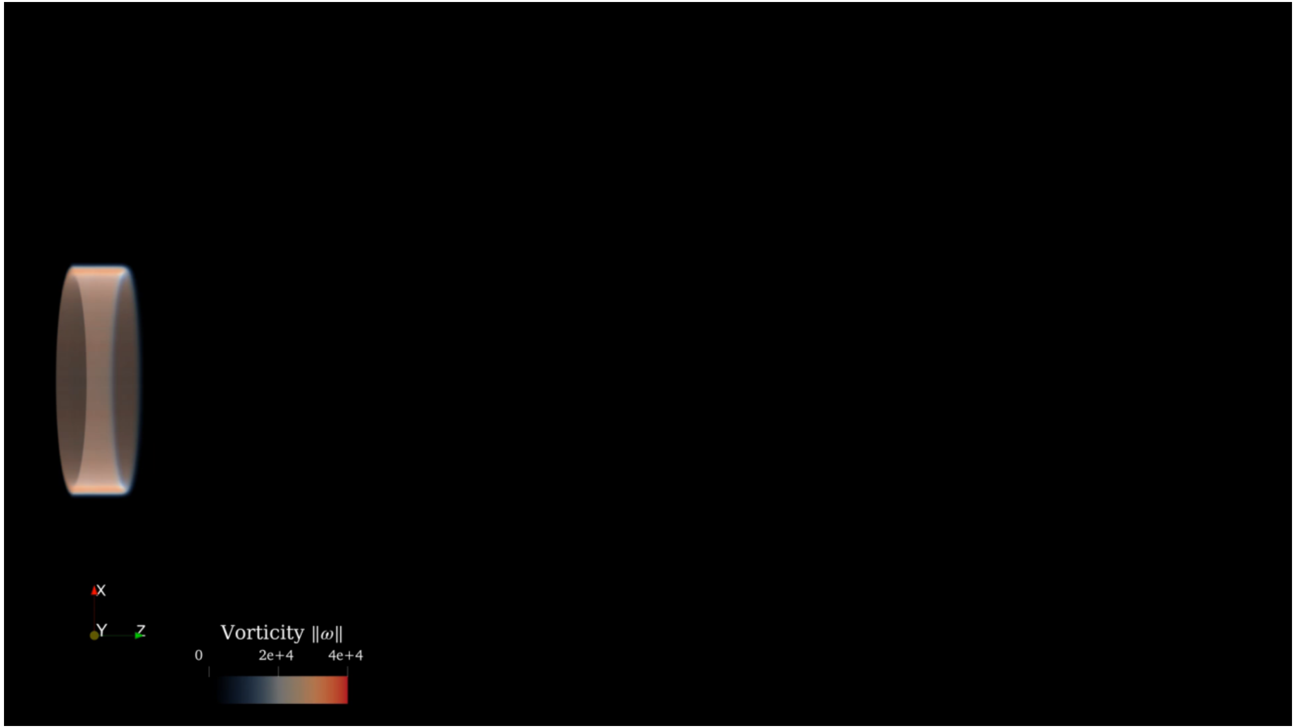
$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\Gamma}_p = \left(\boldsymbol{\Gamma}_p\cdot\nabla\right)\overline{\mathbf{u}}(\mathbf{x}_p) - \frac{3}{5}\left\{\left[\left(\boldsymbol{\Gamma}_p\cdot\nabla\right)\overline{\mathbf{u}}(\mathbf{x}_p)\right]\cdot\hat{\boldsymbol{\Gamma}}_p\right\}\hat{\boldsymbol{\Gamma}}_p - \frac{C_d}{\zeta_{\sigma_p}(\mathbf{0})}\mathbf{E}_{\mathrm{str}}(\mathbf{x}_p)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\sigma_p = -\frac{1}{5}\frac{\sigma_p}{\|\boldsymbol{\Gamma}_p\|}\left[\left(\boldsymbol{\Gamma}_p\cdot\nabla\right)\overline{\mathbf{u}}(\mathbf{x}_p)\right]\cdot\hat{\boldsymbol{\Gamma}}_p,$$

$$\left(\frac{\mathrm{d}}{\mathrm{d}t}\overline{\boldsymbol{\omega}}\right)_{\mathrm{viscous}} = \nu\nabla^2\overline{\boldsymbol{\omega}}$$



rVPM works well for unbounded flows but how can we introduce boundary conditions?



rVPM works well for unbounded flows but how can we introduce boundary conditions?

Meshless LES with Immersed Vorticity

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

rVPM solver — *actuator model*

$$\overline{\boldsymbol{\omega}} = \boxed{\overline{\boldsymbol{\omega}}_{\mathrm{free}}} + \boxed{\overline{\boldsymbol{\omega}}_{\mathrm{bound}}}$$

free particles — *bound particles*

$$\overline{\boldsymbol{\omega}}(\mathbf{x}) = \underbrace{\sum_p \boldsymbol{\Gamma}_p \zeta_{\sigma_p}\left(\mathbf{x} - \mathbf{x}_p\right)}_{\overline{\boldsymbol{\omega}}_{\mathrm{free}}} + \underbrace{\sum_b \boldsymbol{\Gamma}_b \zeta_{\sigma_b}\left(\mathbf{x} - \mathbf{x}_b\right)}_{\overline{\boldsymbol{\omega}}_{\mathrm{bound}}}$$

$$\overline{\mathbf{u}}\left(\mathbf{x}\right) = \underbrace{\sum_p g_{\sigma_p}\left(\mathbf{x} - \mathbf{x}_p\right)\mathbf{K}\left(\mathbf{x} - \mathbf{x}_p\right) \times \boldsymbol{\Gamma}_p}_{\overline{\mathbf{u}}_{\mathrm{free}}} + \underbrace{\sum_b g_{\sigma_b}\left(\mathbf{x} - \mathbf{x}_b\right)\mathbf{K}\left(\mathbf{x} - \mathbf{x}_b\right) \times \boldsymbol{\Gamma}_b}_{\overline{\mathbf{u}}_{\mathrm{bound}}}$$

Fundamentals

rVPM works well for unbounded flows
but how can we introduce boundary conditions?

Meshless LES with Immersed Vorticity

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

rVPM solver *actuator model*

$$\overline{\boldsymbol{\omega}} = \overline{\boldsymbol{\omega}}_{\mathrm{free}} + \overline{\boldsymbol{\omega}}_{\mathrm{bound}}$$

"FLOWUnsteady: An Interactional Aerodynamics Solver for Multirotor Aircraft and Wind Energy."
E. J. Alvarez & A. Ning (2022). AIAA AVIATION Forum.

Rotor — Actuator Line Model (ALM)

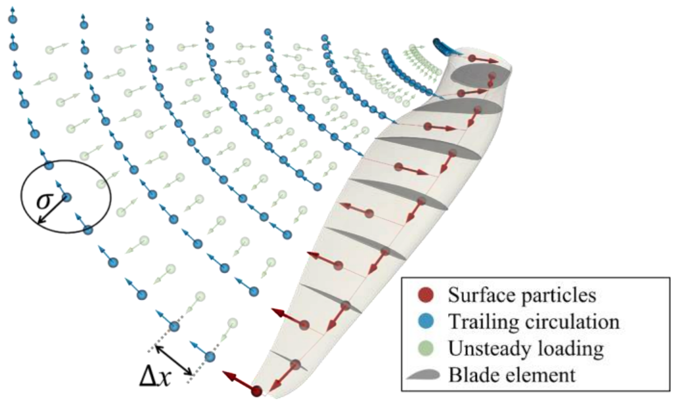
Force Calculation

- Effective AOA from LES
- Airfoil lookup tables (c_l, c_d, vs AOA)
- 3D drag and stall delay due to centrifugal forces
- Prandtl loss correction for tip and hub

Circulation

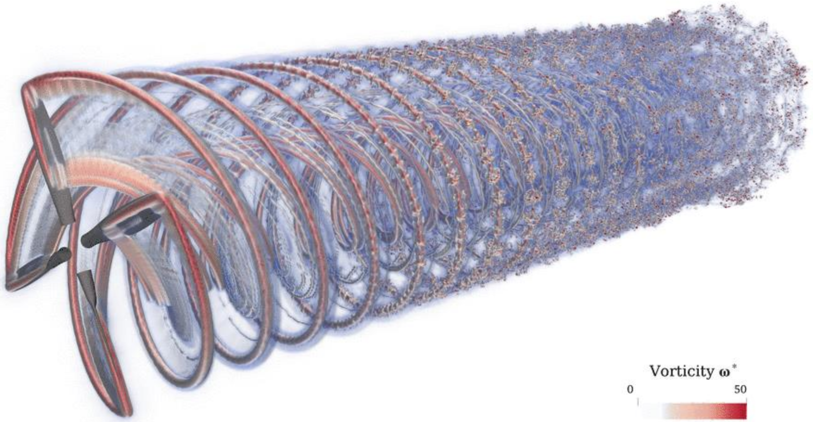
$$\Gamma = C_l \frac{Vc}{2}$$

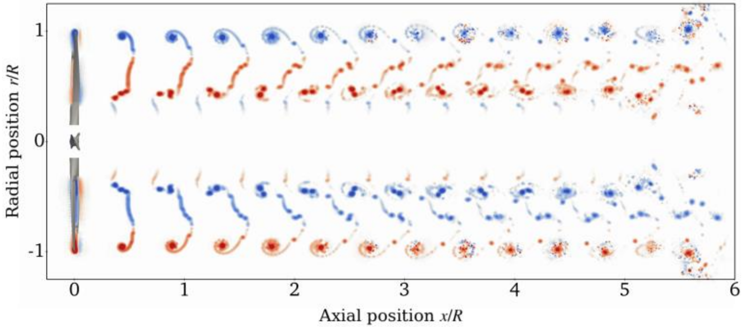
Immersed Vorticity



"Meshless Large Eddy Simulation of Rotor-Wing Interactions Through the Reformulated Vortex Particle Method."
E. J. Alvarez & A. Ning (2022). *In review.*

Rotor — Actuator Line Model (ALM)





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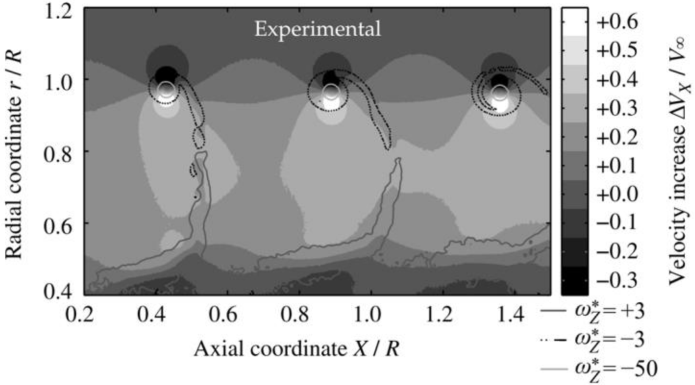
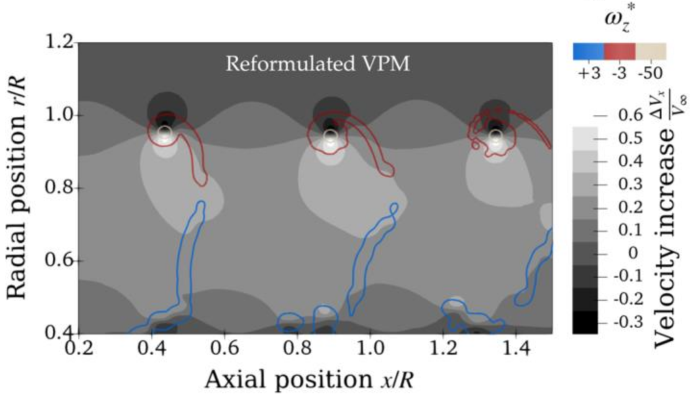


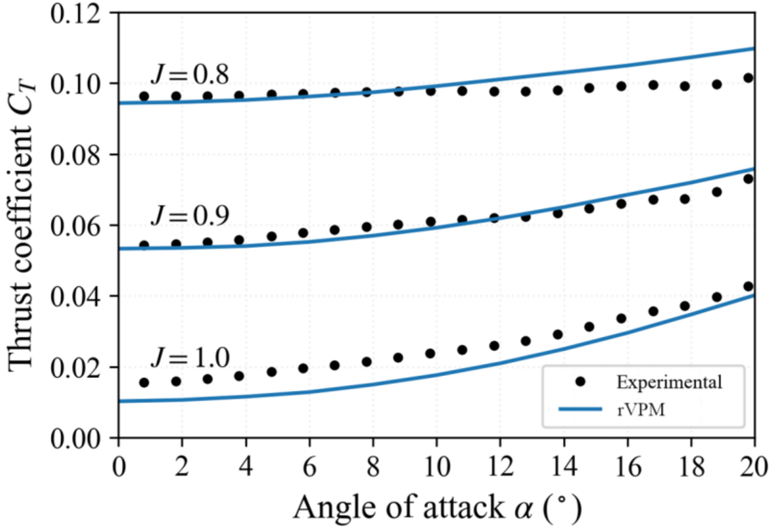


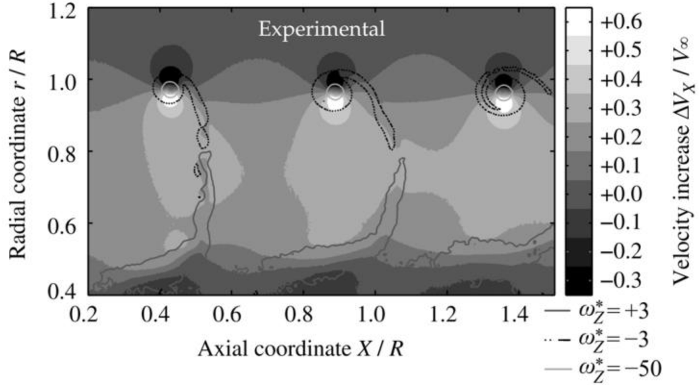
Experimental: *Sinnige et al., "Unsteady Pylon Loading Caused by Propeller-Slipstream Impingement for Tip-Mounted Propellers," Journal of Aircraft, 2018*

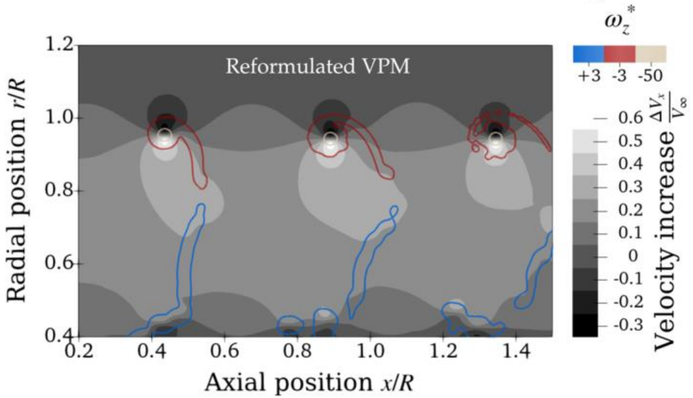
"Meshless Large Eddy Simulation of Rotor-Wing Interactions Through the Reformulated Vortex Particle Method."
E. J. Alvarez & A. Ning (2022). *In review.*

Rotor — Actuator Line Model (ALM)

Rotor at incidence angle





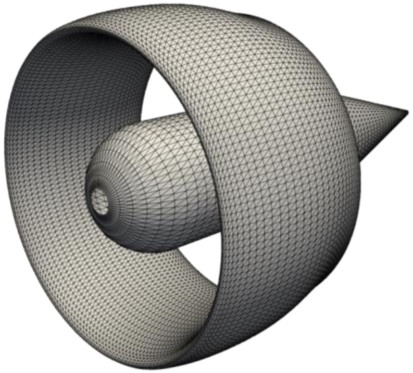


Experimental: *Sinnige et al., "Unsteady Pylon Loading Caused by Propeller-Slipstream Impingement for Tip-Mounted Propellers," Journal of Aircraft, 2018*

Duct and Centerbody — Actuator Surface Model (ASM)

Panel Method

- Constant doublet elements (vortex rings)
- Imposes no-flow-through along walls
- Computes surface vorticity
- Computes surface velocity



Surface Pressure

$$C_p \approx 1 - \left(\frac{u}{u_\infty}\right)^2$$

Immersed Vorticity

- Convert vortex rings into particles
- Shed vorticity from trailing edge

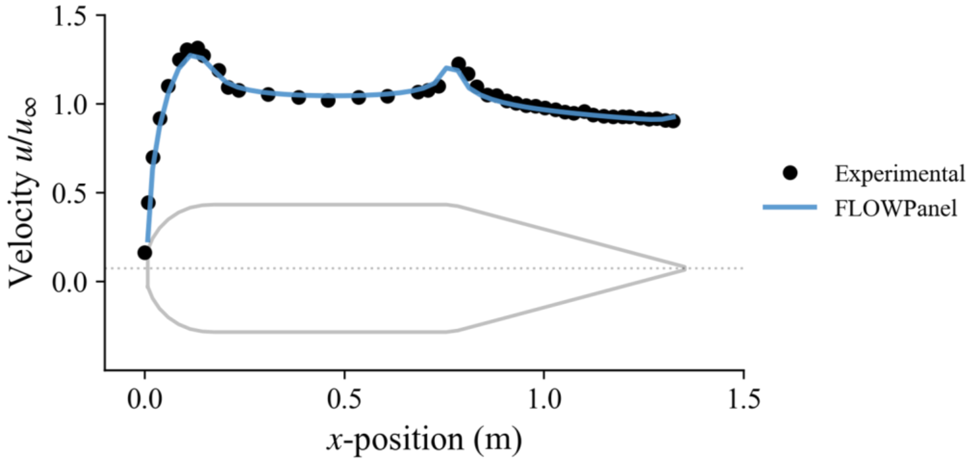
FLOWPanel

github.com/byuflowlab/FLOWPanel.jl

Actuator Surface Model

Preliminary Validation

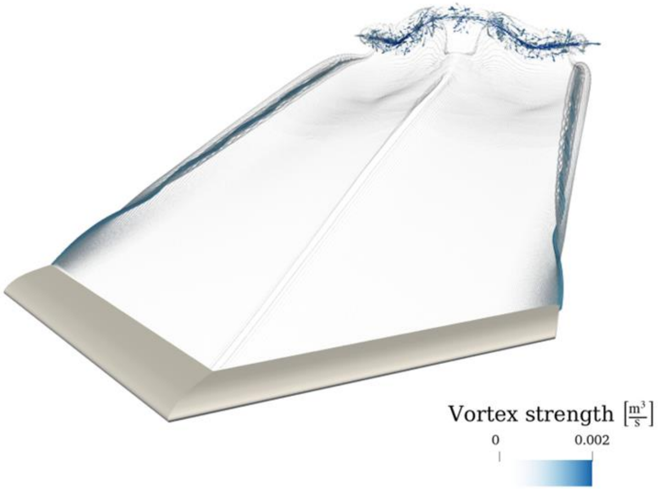
Thick non-lifting centerbody



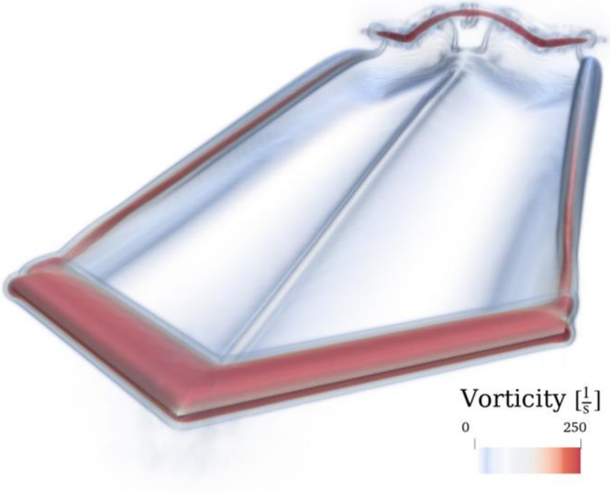
Actuator Surface Model

Preliminary Validation

Lifting body



(a) Computational elements (vortex particles)



(b) Volume rendering of vorticity field

Fig. 4 Swept wing simulation using actuator surface model.

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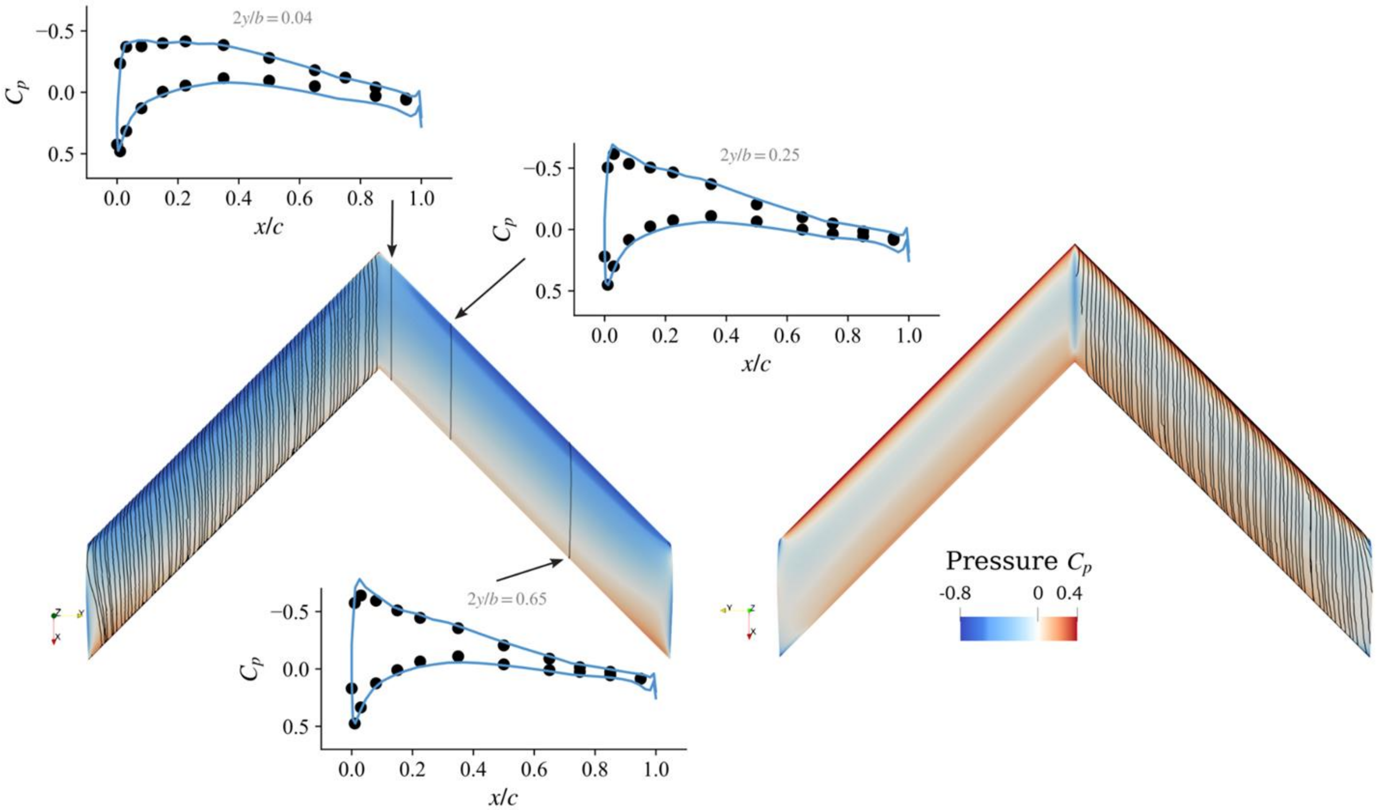
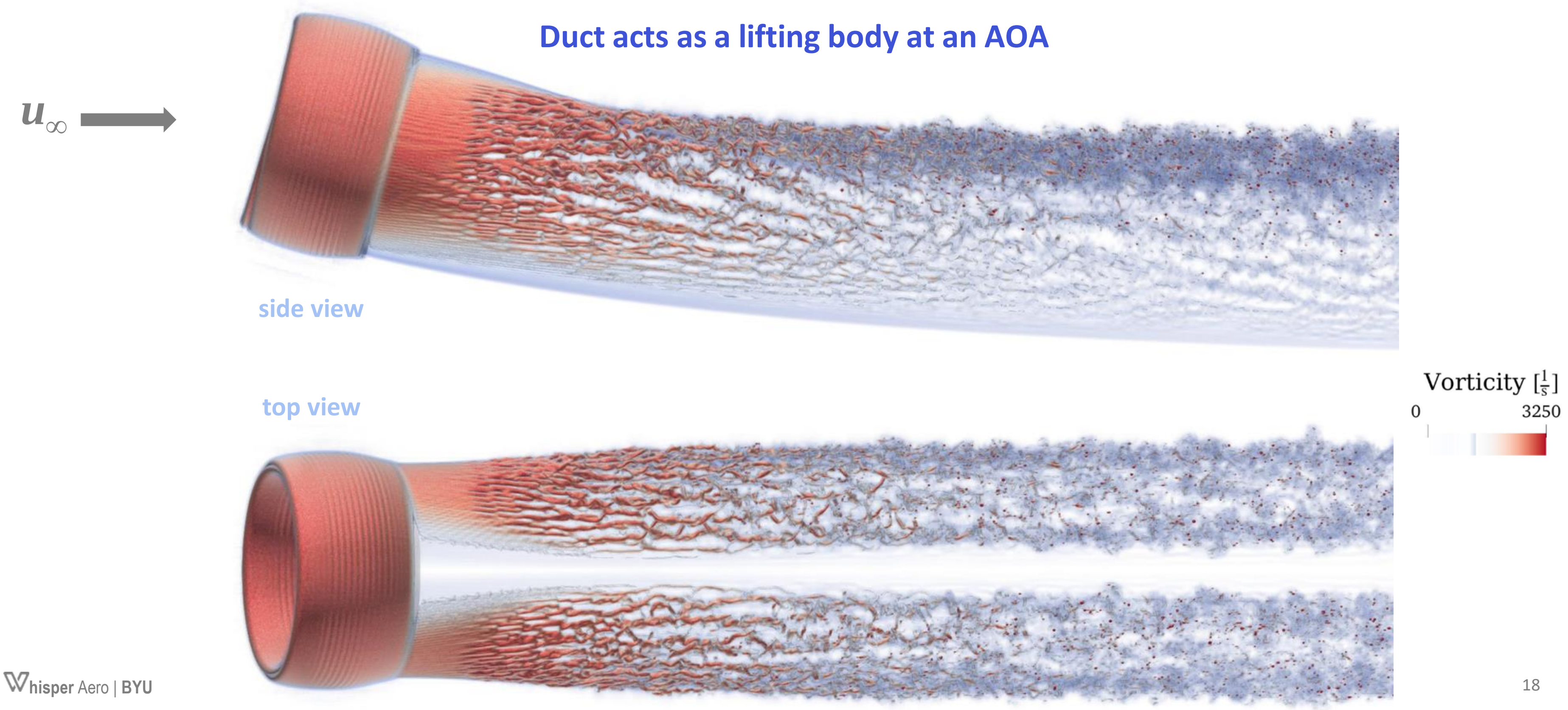
Preliminary Validation

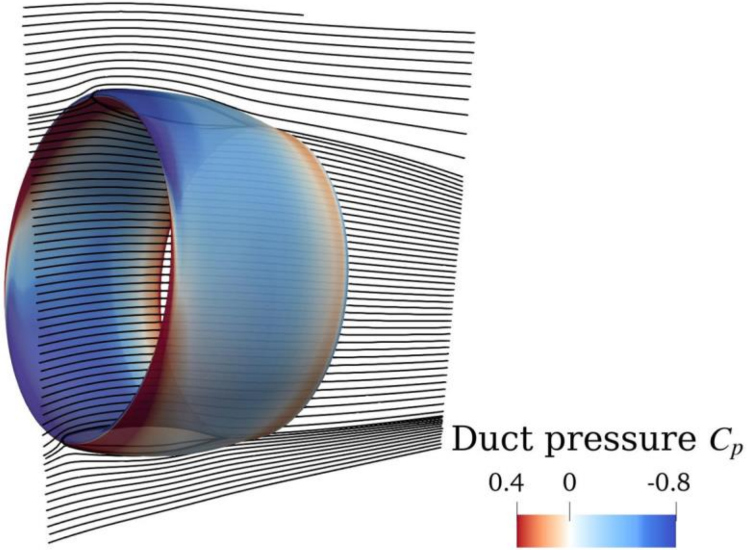


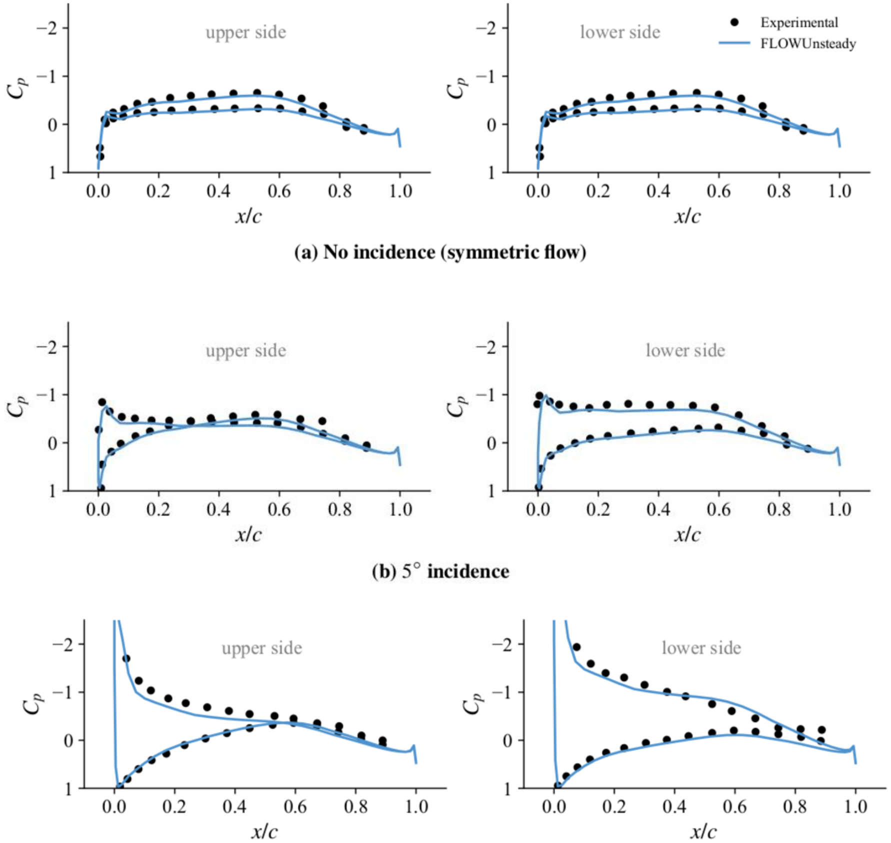
RESULTS

Isolated Duct at Incidence Angle



Isolated Duct at Incidence Angle



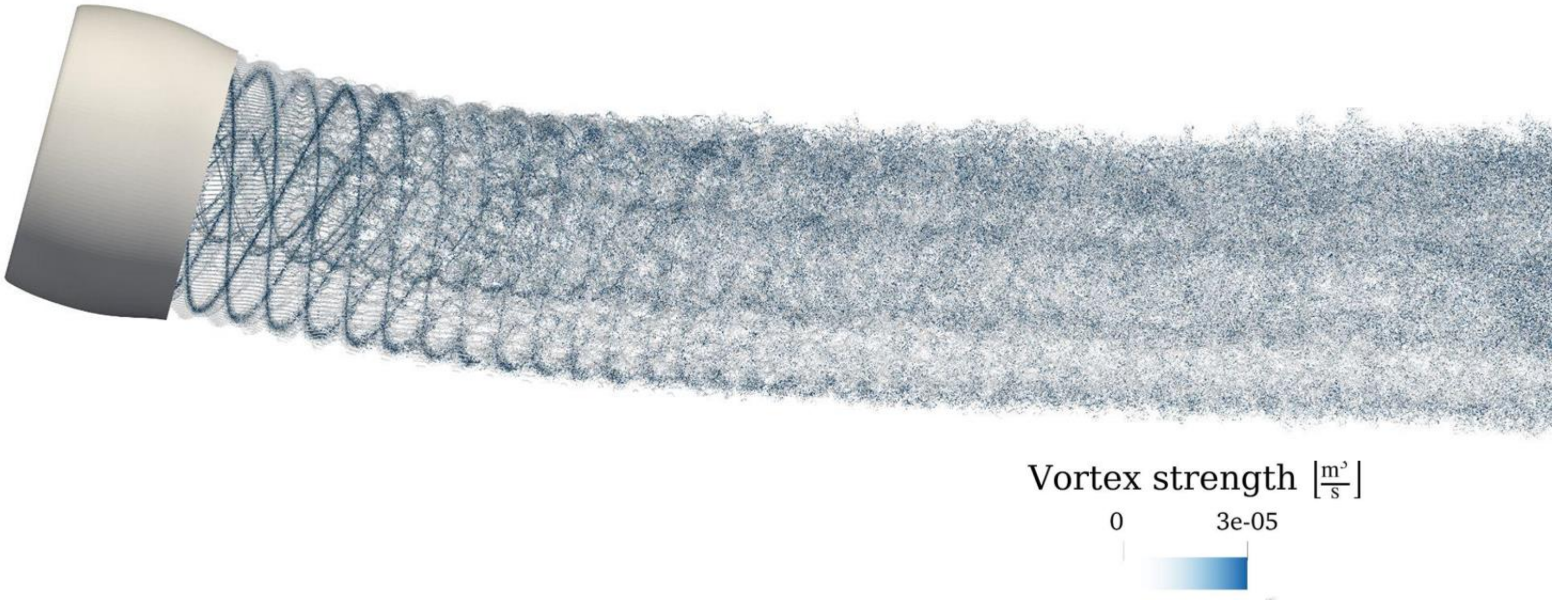


(a) No incidence (symmetric flow)

(b) 5° incidence

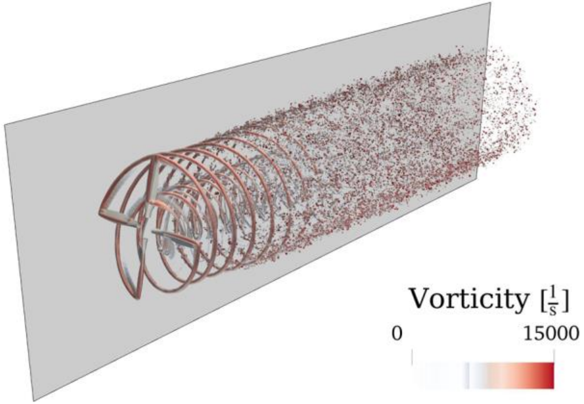
(c) 15° incidence

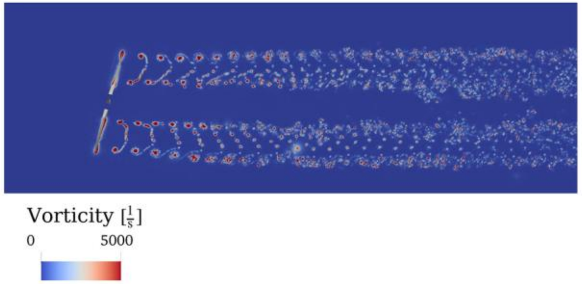
Ducted Fan at Incidence Angle



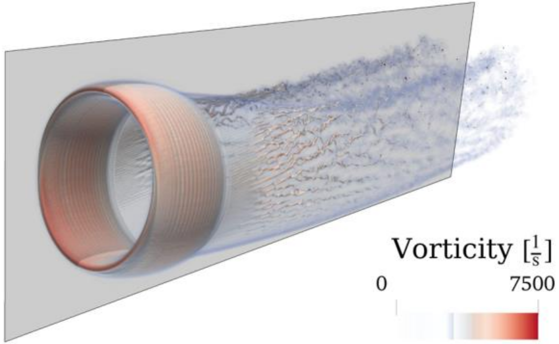
Ducted Fan at Incidence Angle

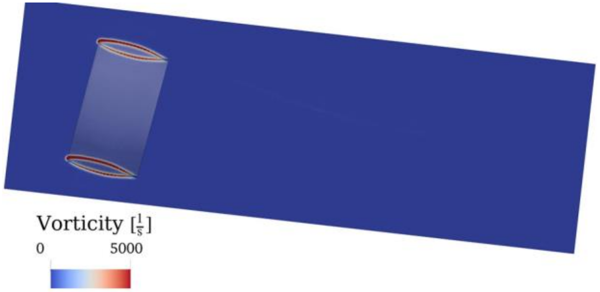
open prop



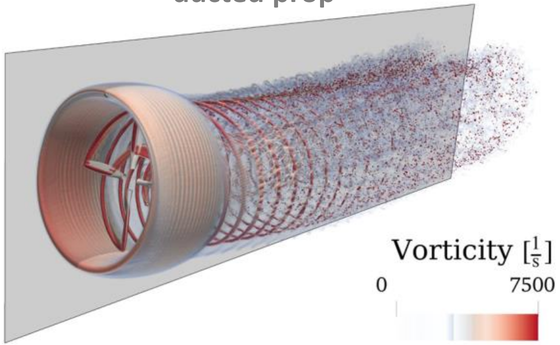


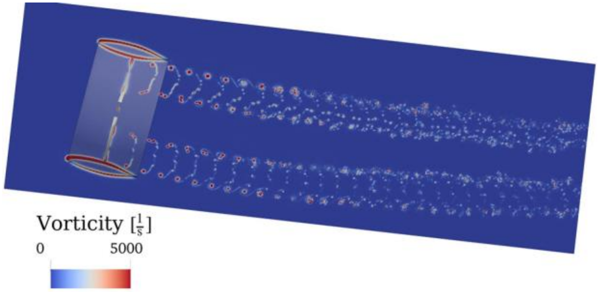
duct





ducted prop





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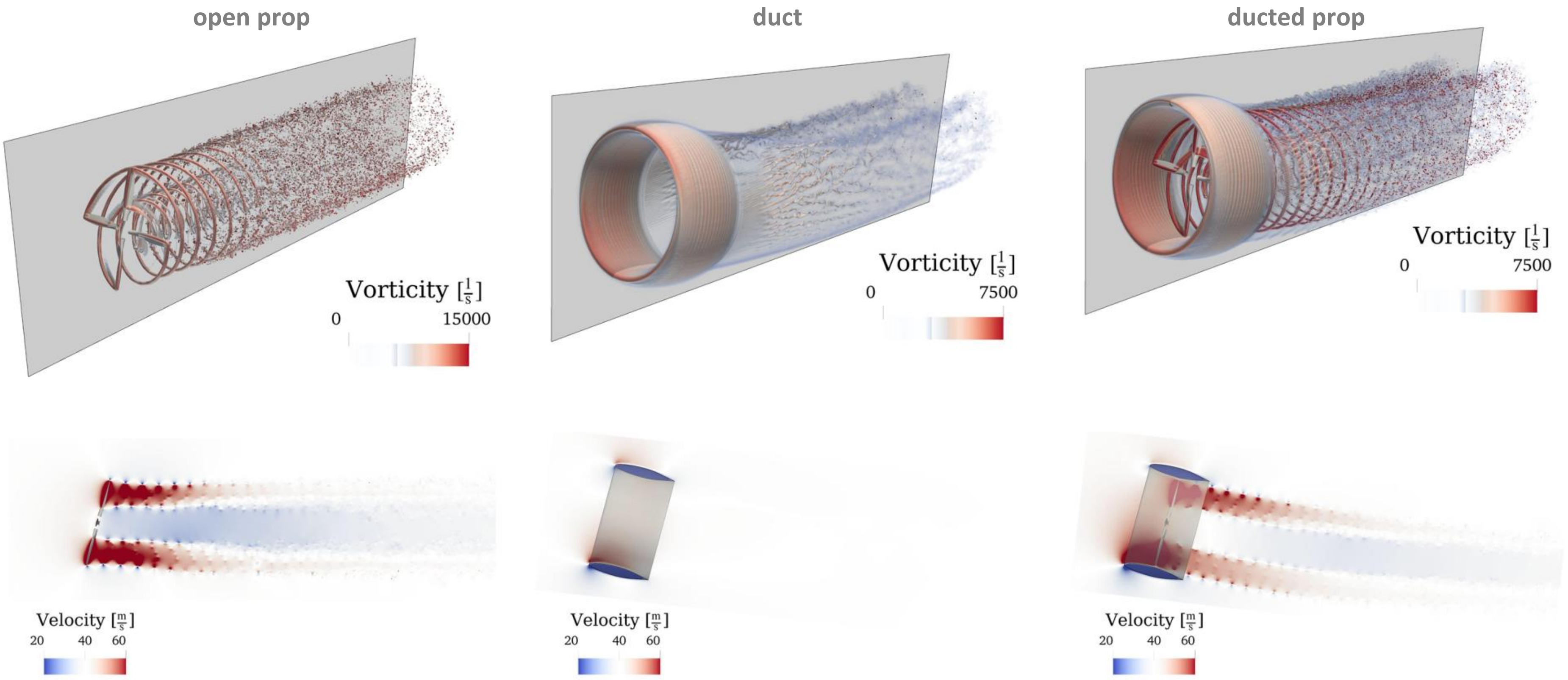
Ducted Fan at Incidence Angle



Ducted Fan at Incidence Angle

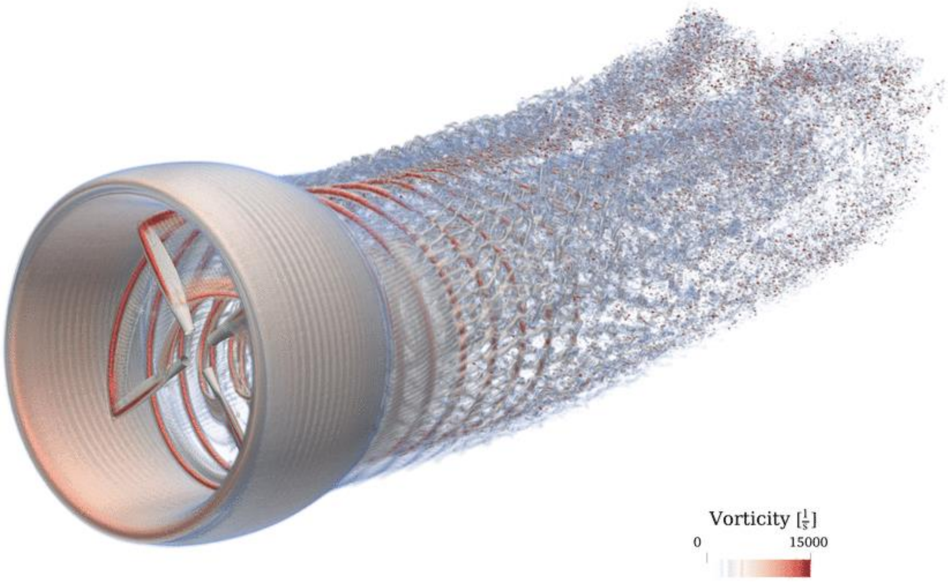


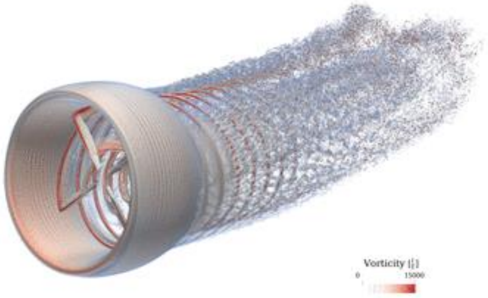
Table 1 Performance of propulsor with and without duct.

	Thrust T	Torque Q	Propulsive Efficiency η
Open propeller	49.1 N (11.0 lbf)	1.73 Nm	0.64
Ducted propeller	37.3 N (8.4 lbf)	1.18 Nm	0.72
Open propeller, $\alpha = 15°$	53.4 N (12.0 lbf)	1.83 Nm	0.66
Ducted propeller, $\alpha = 15°$	43.5 N (9.8 lbf)	1.13 Nm	0.87

Propulsive efficiency defined as $\eta = \frac{T u_\infty}{2\pi n Q}$, where $n = \frac{\text{RPM}}{60}$, RPM = 16.8 kHz, and $u_\infty = 40\,\text{m/s}$.

SUMMARY

- **Developed actuator surface model based on a panel method**
- **ASM was validated for both non-lifting and lifting bodies**
- **Accurately resolves isolated duct at AOA**
- **Preliminary results on a ducted fan at AOA**



FLOWUnsteady

github.com/byuflowlab/FLOWUnsteady

Future Work

- Include stators and centerbody
- Validation of ducted fan comparing to experiment
- Effects of non-axisymmetric flow on structures and noise

FLOWPanel

github.com/byuflowlab/FLOWPanel.jl


Whisper Aero