Inflow Studies of Propeller-Wing Configurations

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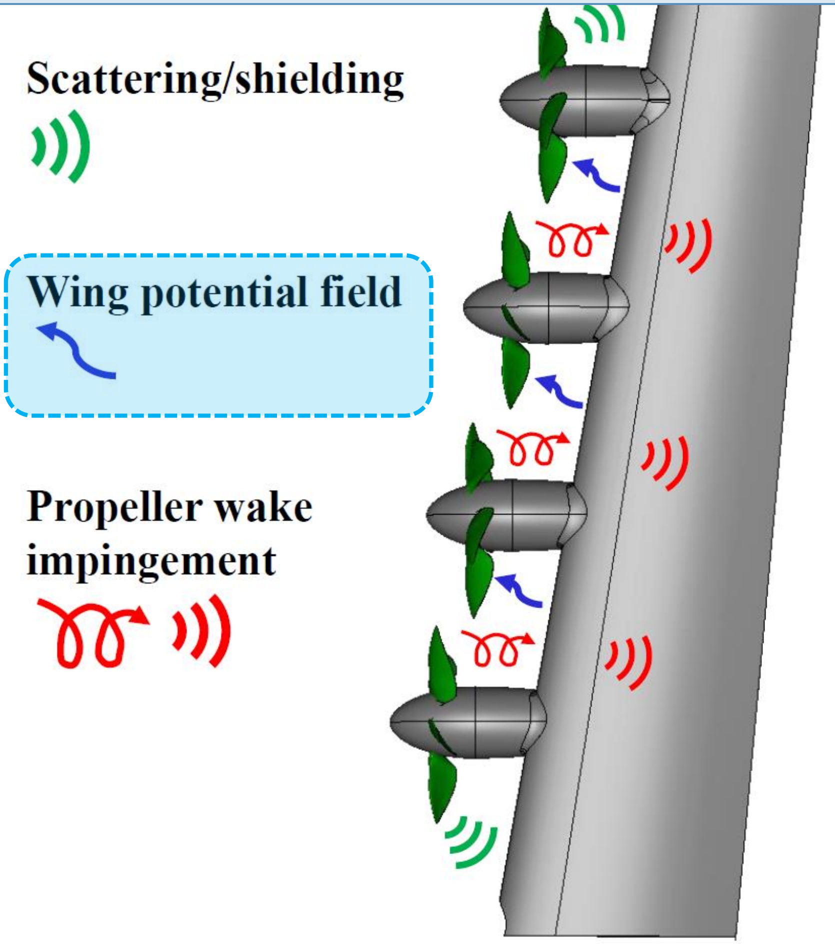
NASA Acoustics Technical Working Group
14 April 2021

Motivation

Urban Air Mobility

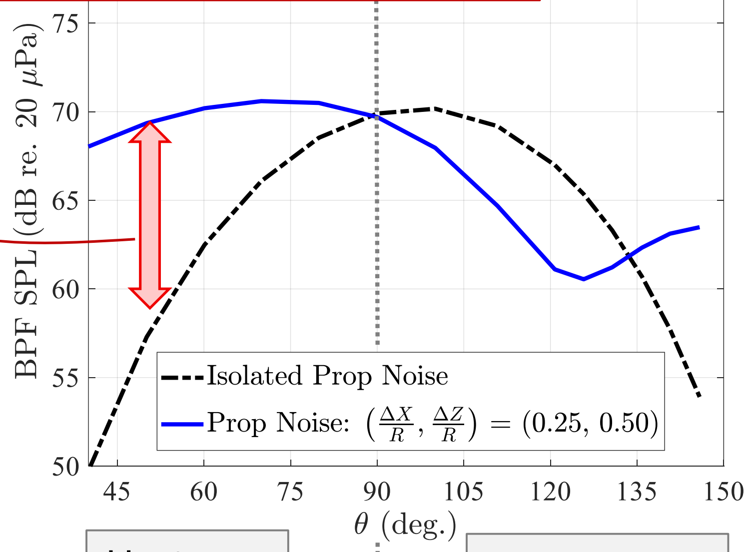
Anticipated Noise Sources from Prop-Wing Interactions



Motivation

Increased propeller noise upstream when wing is present

Simulation

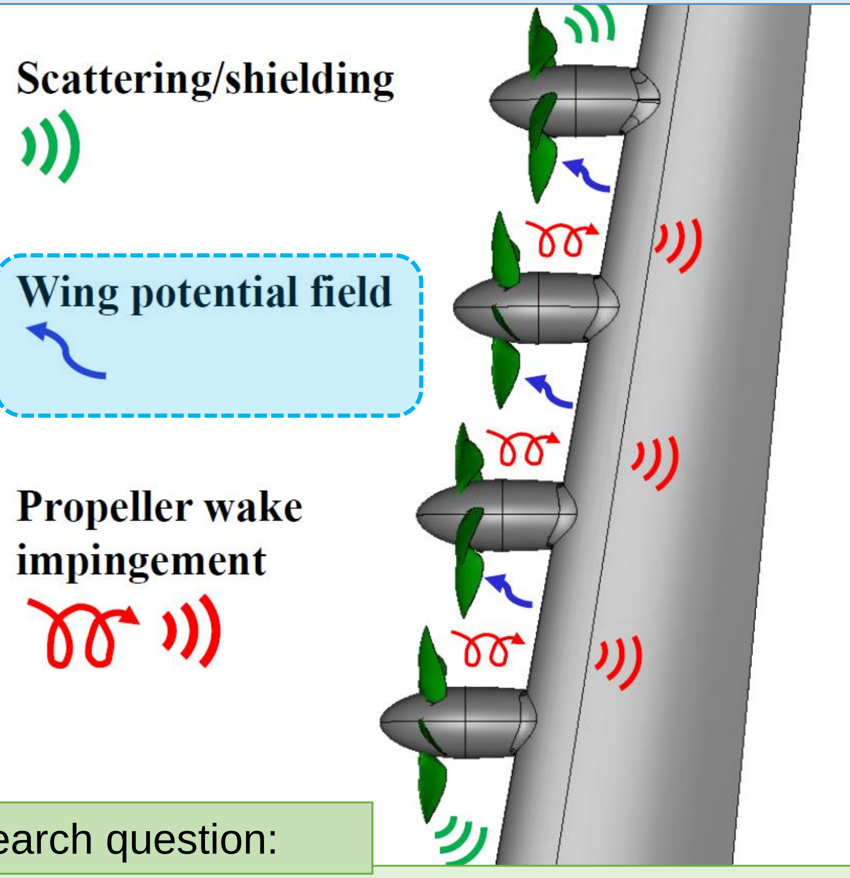


Upstream observers

Downstream observers

Zawodny, N. S., Boyd Jr., D. D., and Nark, D. M., "Aerodynamic and Acoustic Interactions Associated with Inboard Propeller-Wing Configurations," AIAA Scitech Forum, virtual event, 11–15 & 19—21 January 2021.

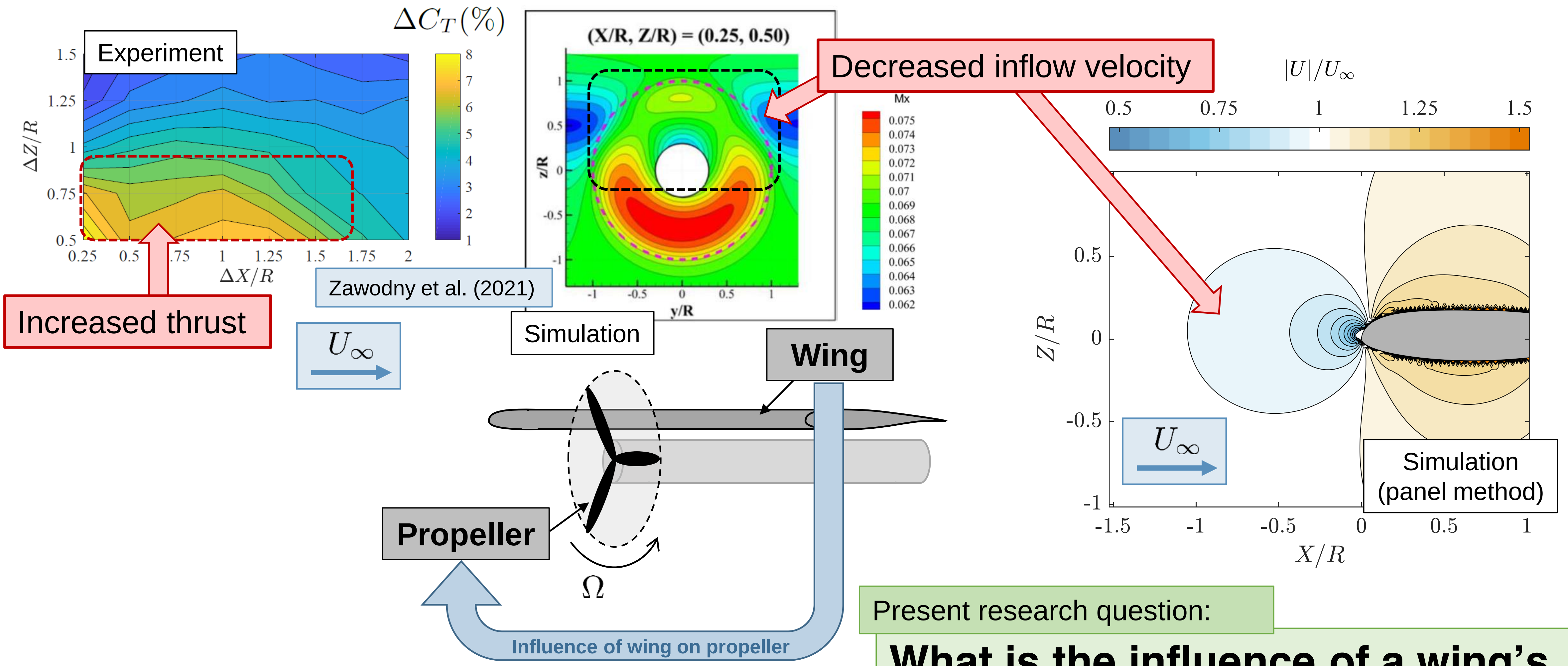
Anticipated Noise Sources from Prop-Wing Interactions



Present research question:

What is the influence of a wing's potential field on propeller inflow?

Motivation



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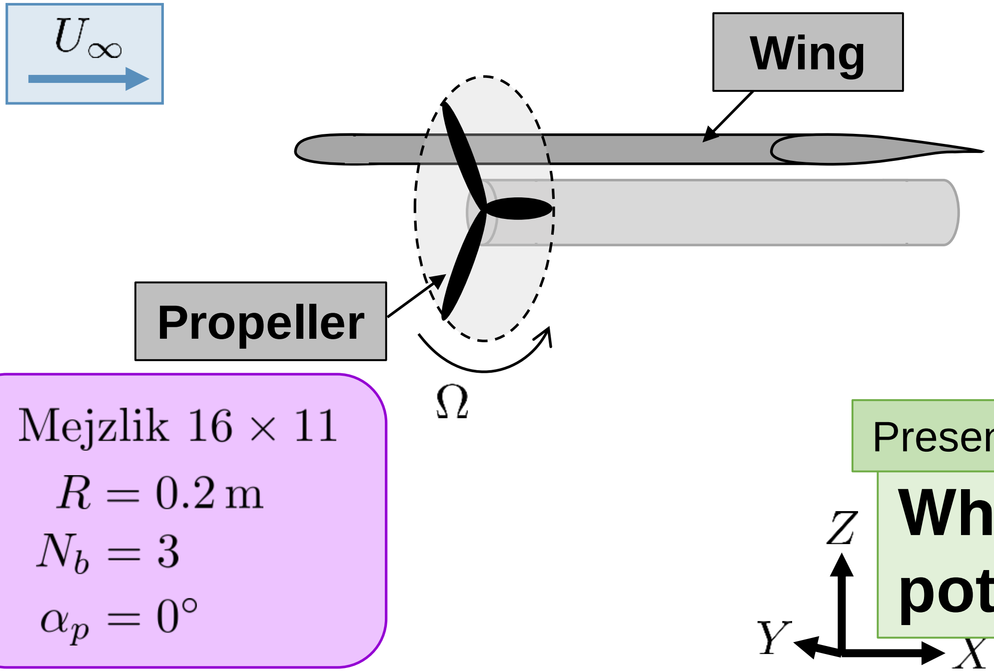
Research Approaches

Experiment

- Measure flow through a cross-stream plane ahead of propeller using stereoscopic particle image velocimetry
- Collect three velocity components, including inflow velocity
- Demonstrate SPIV in LSAWT

Simulation

- OVERFLOW2 (URANS)
- Capture velocities and surface pressures (flow field and acoustics)
- Compare to SPIV data, validate simulation techniques, and gain additional insight



NACA 63(2)-215 Mod. B
$c = 0.406\,\text{m}$
$\alpha_w = 0°$

Mejzlik 16×11
$R = 0.2\,\text{m}$
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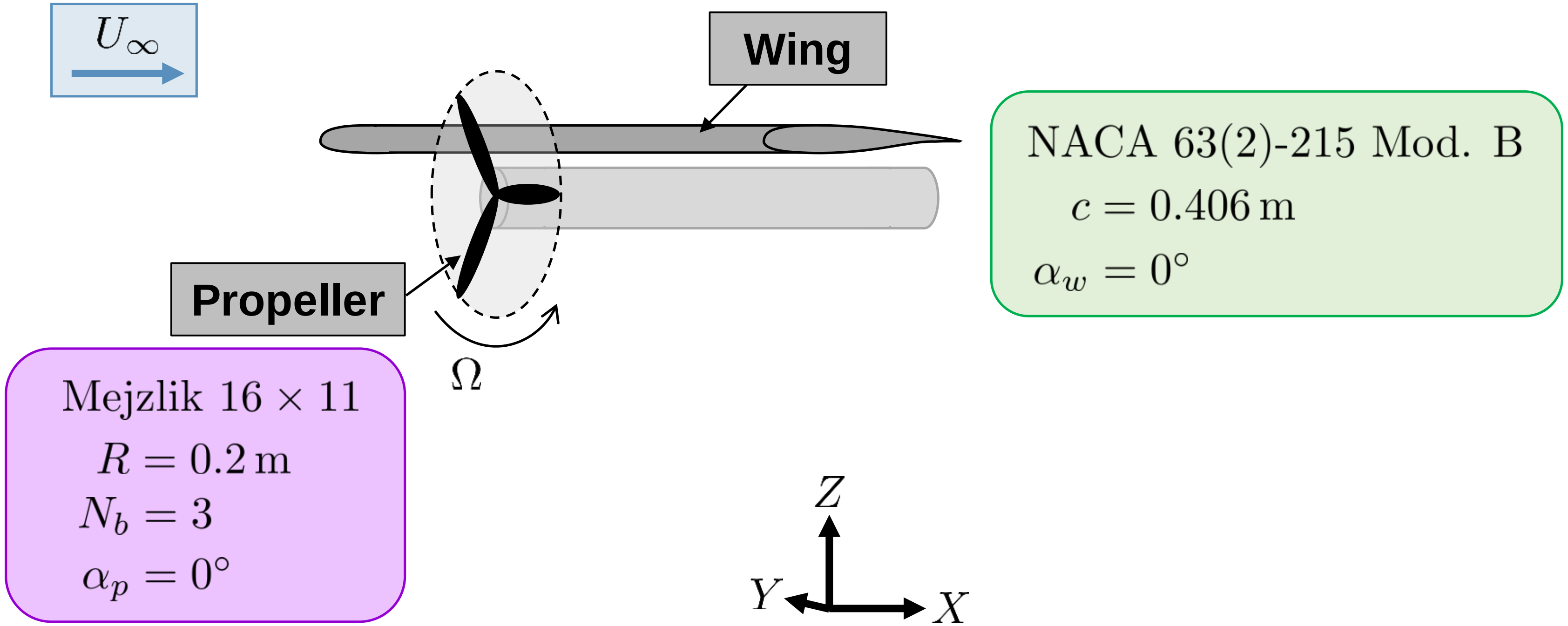
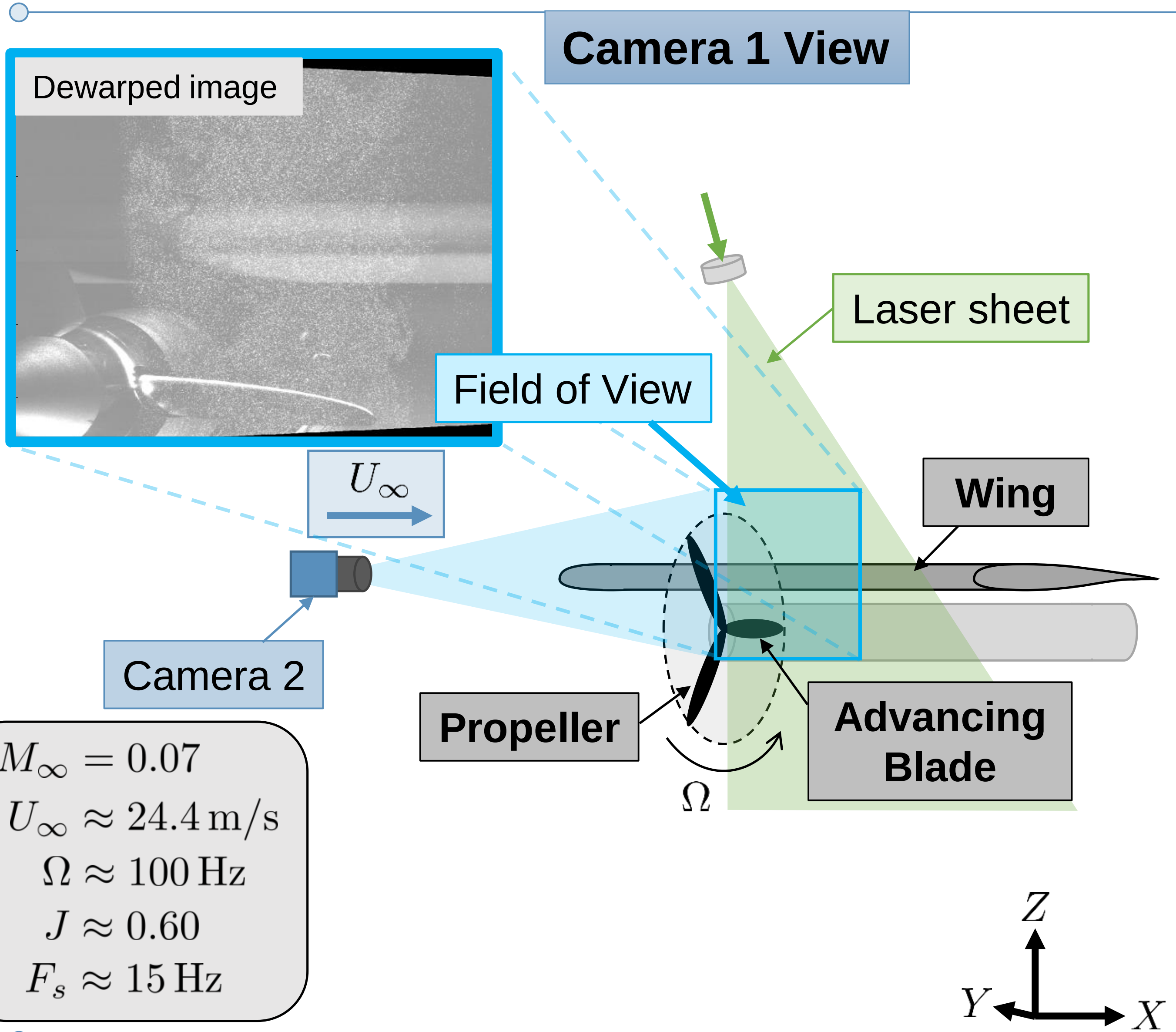


Experimental Setup



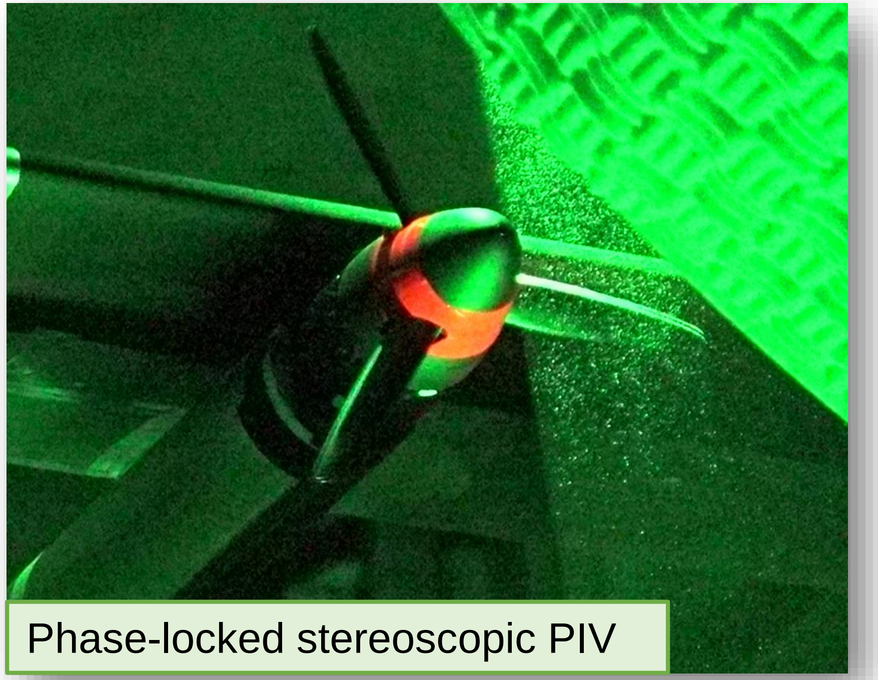
$M_\infty = 0.07$

$U_\infty \approx 24.4\,\mathrm{m/s}$

$\Omega \approx 100\,\mathrm{Hz}$

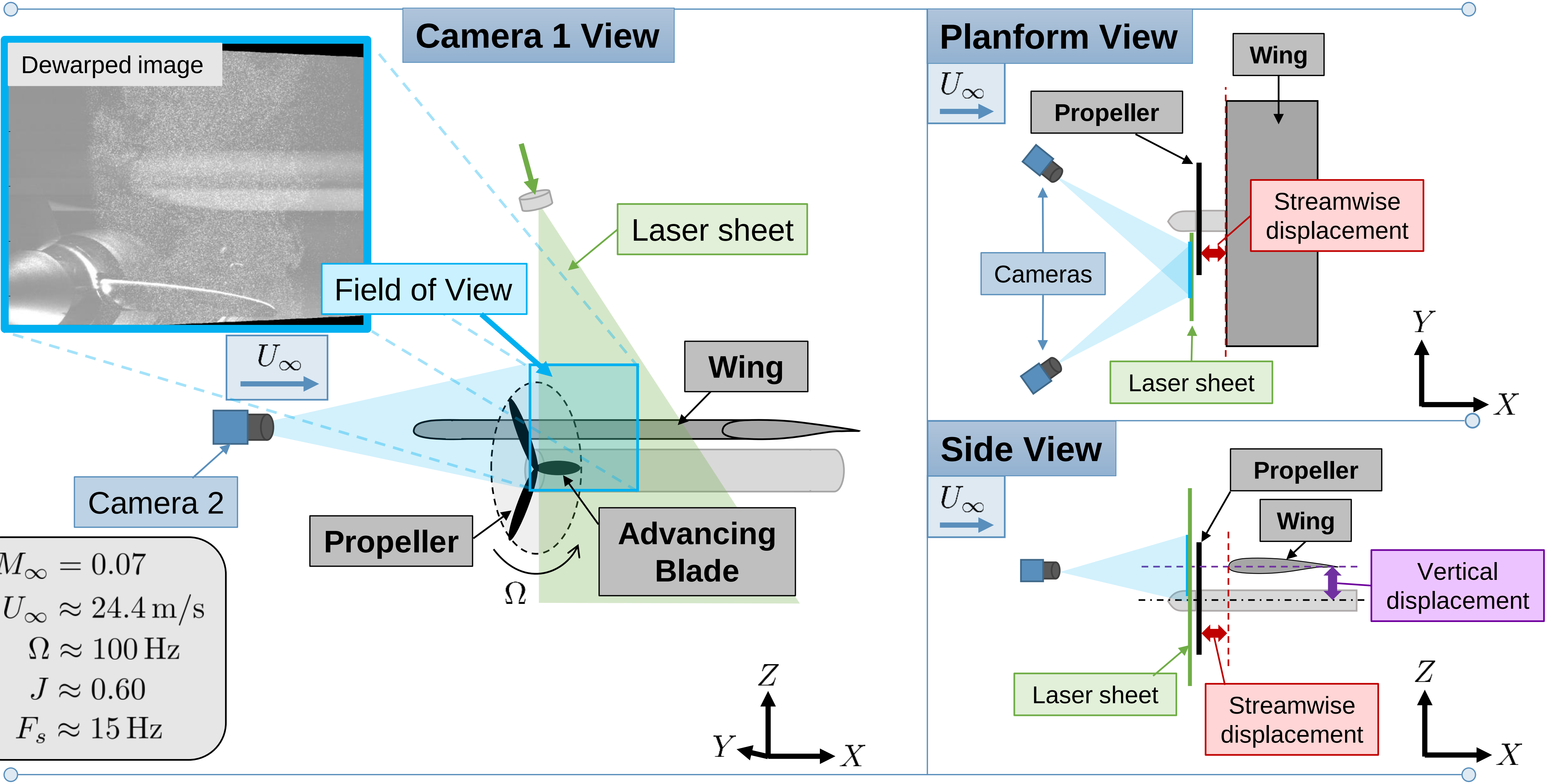
$J \approx 0.60$

$F_s \approx 15\,\mathrm{Hz}$



Phase-locked stereoscopic PIV

Experimental Setup



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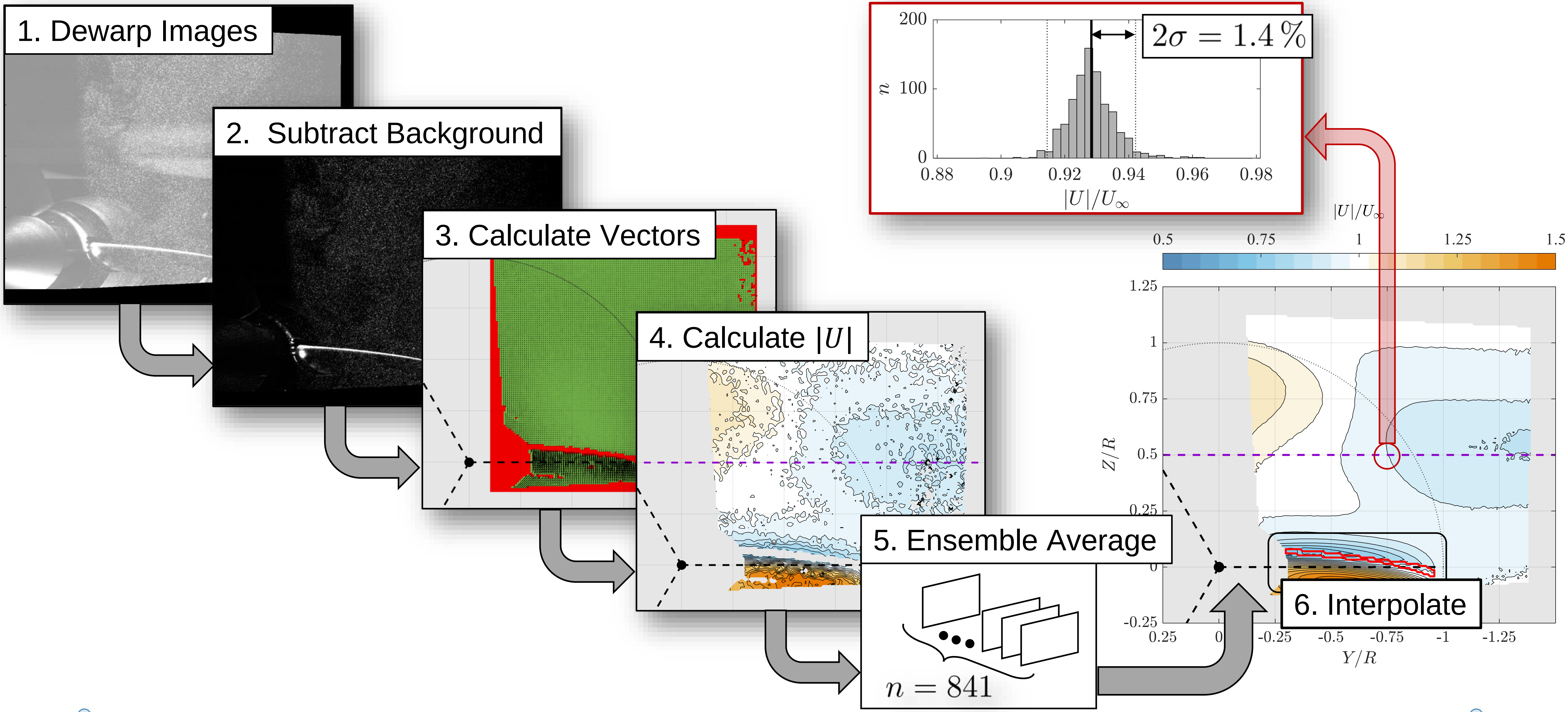
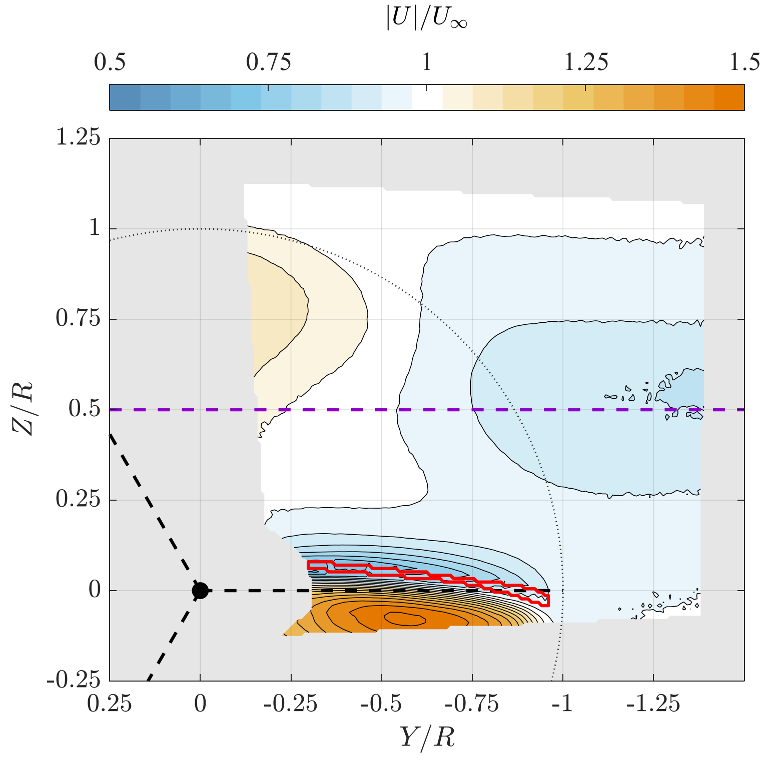
PIV Data Processing



Flow Features



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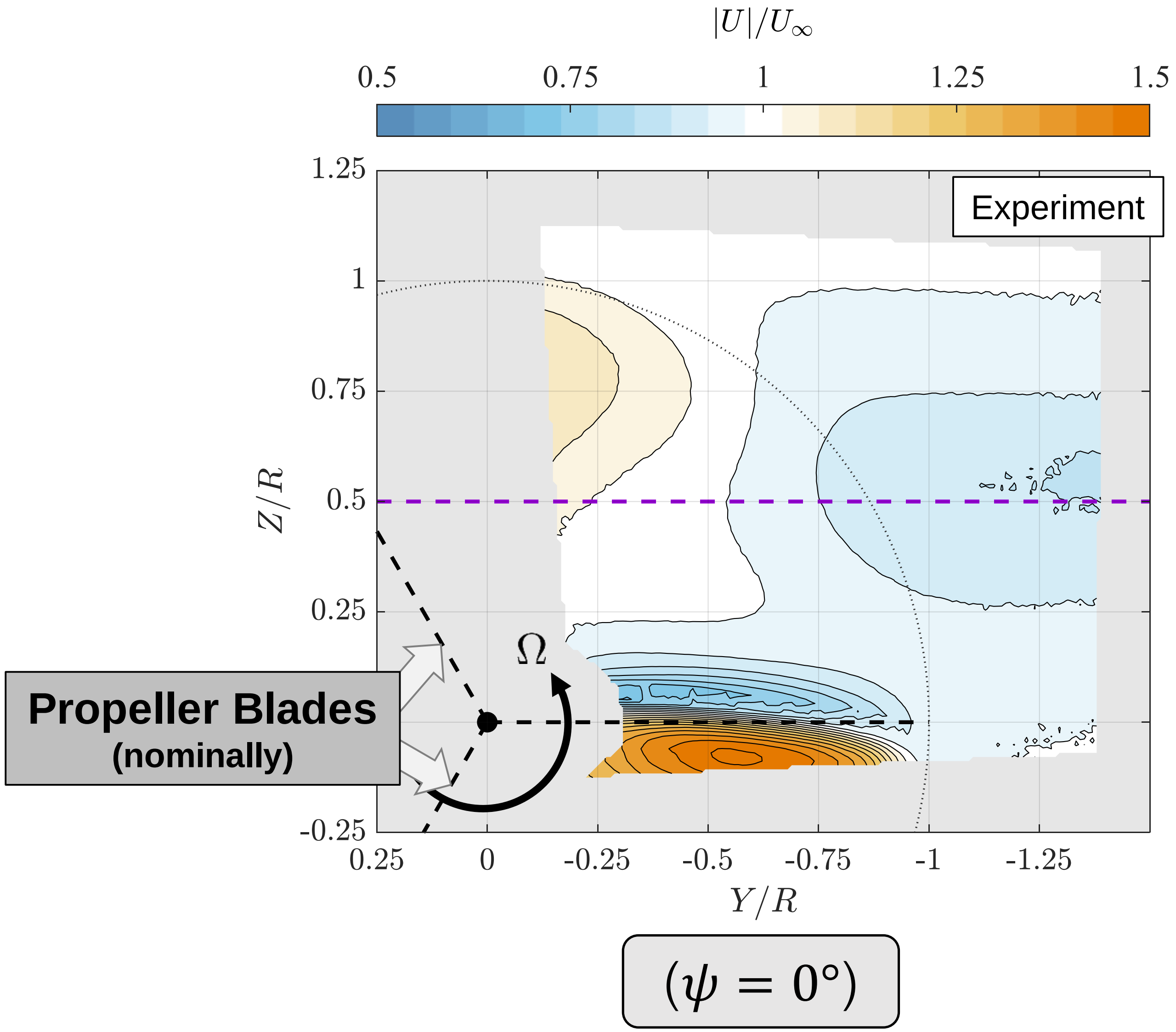

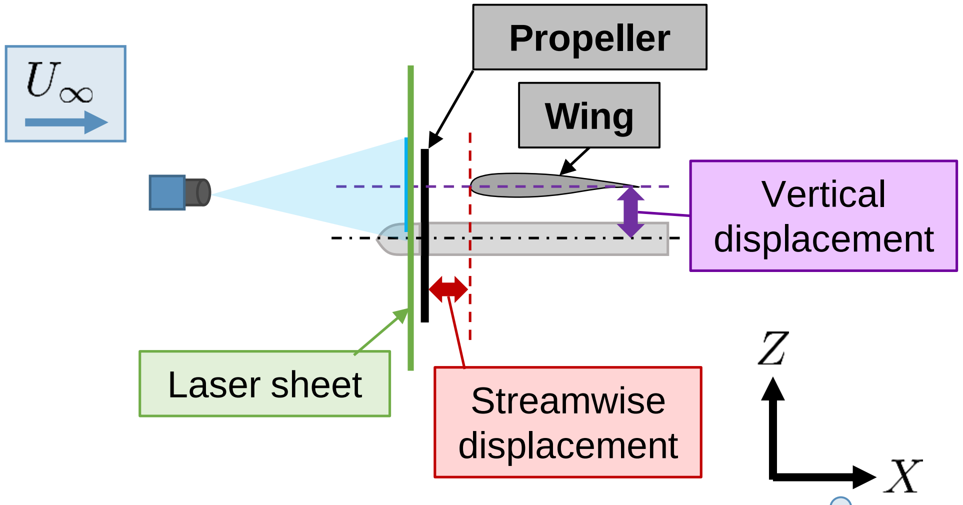

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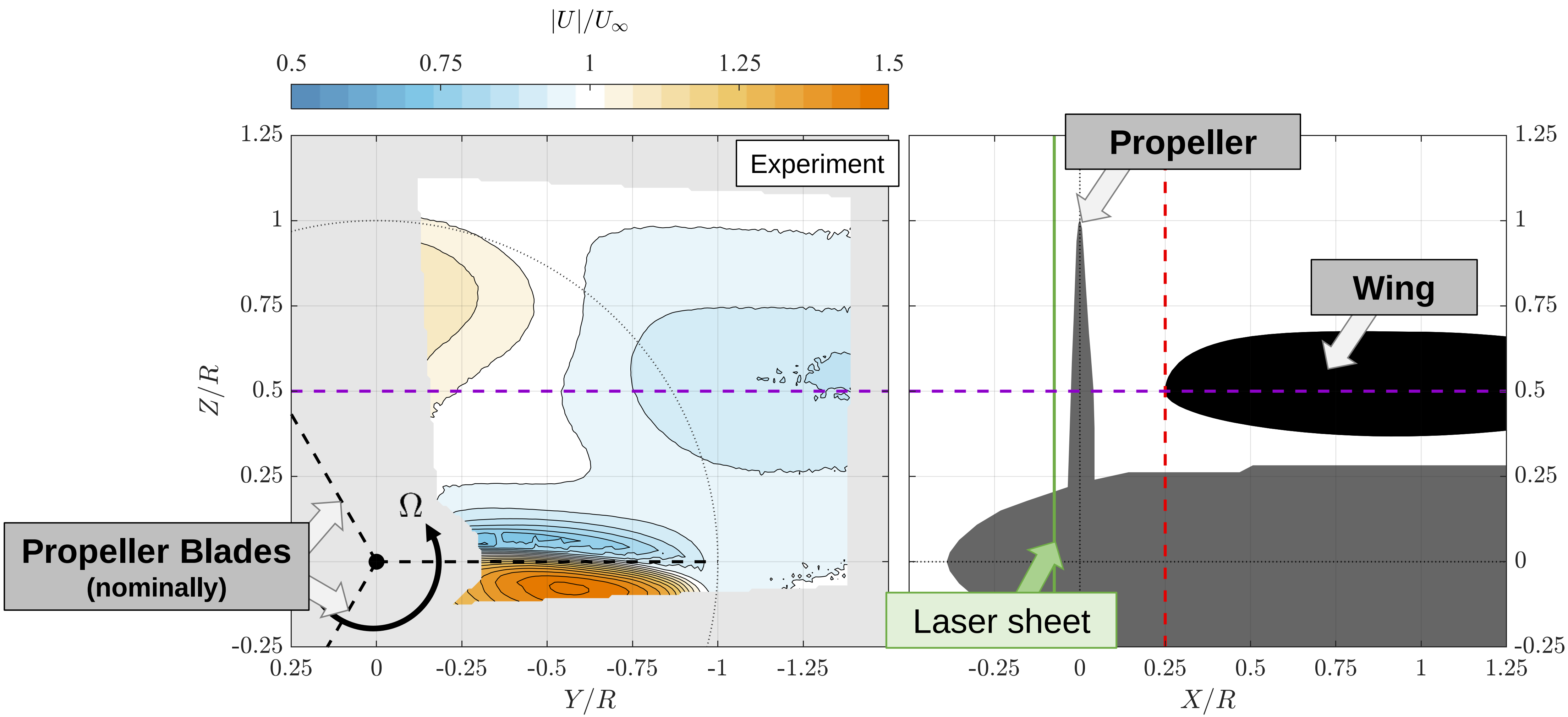
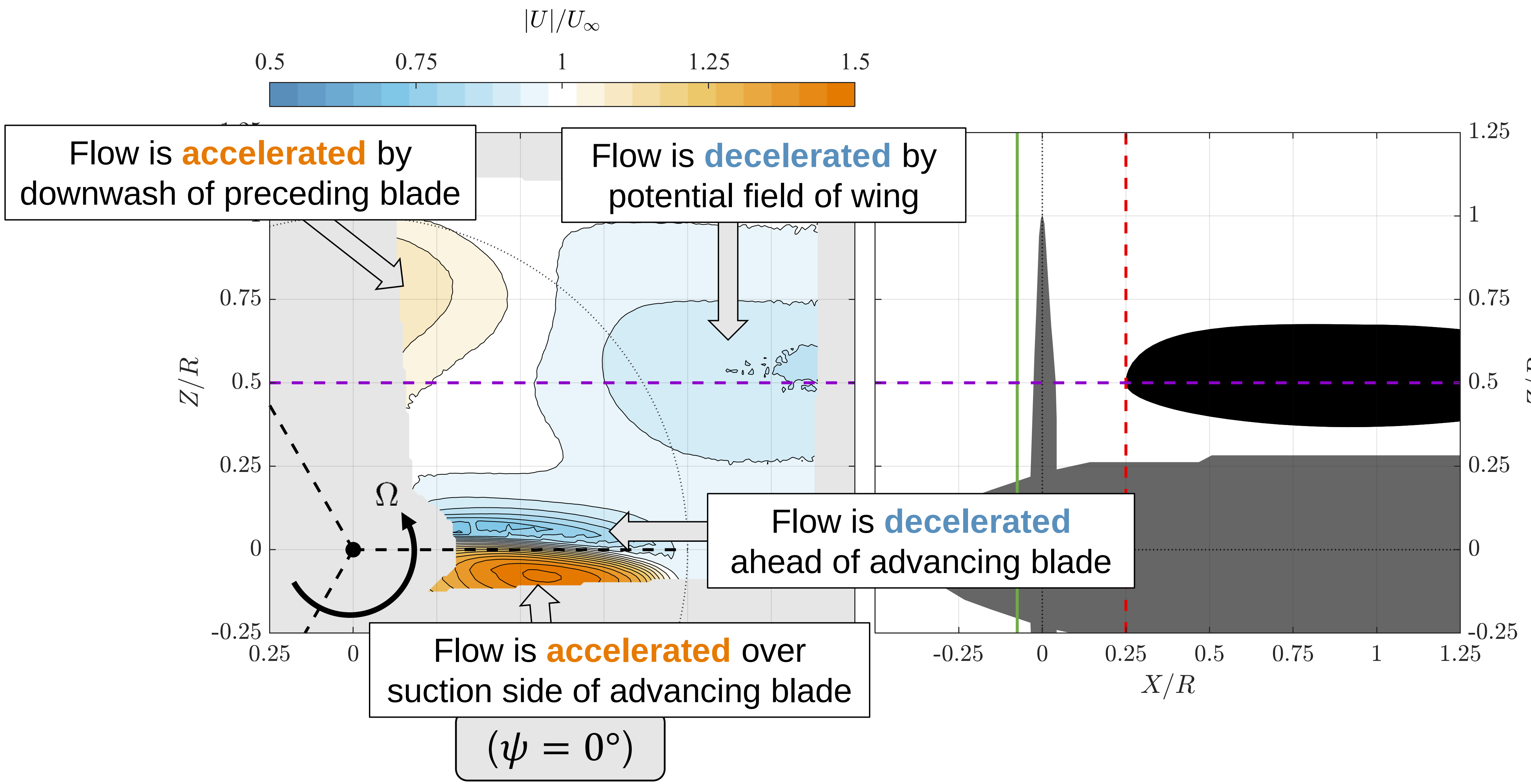
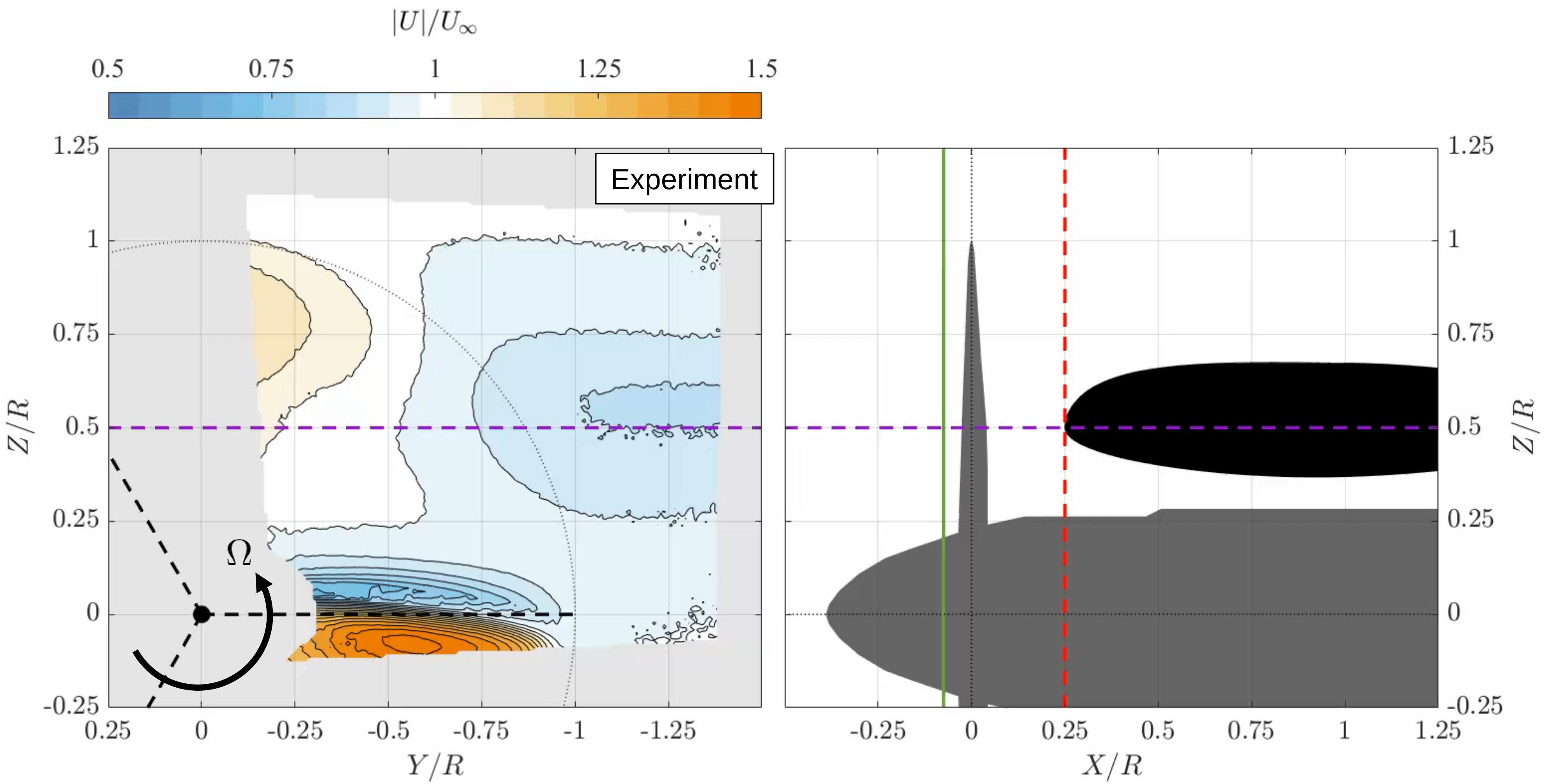


$(\psi = 0°)$

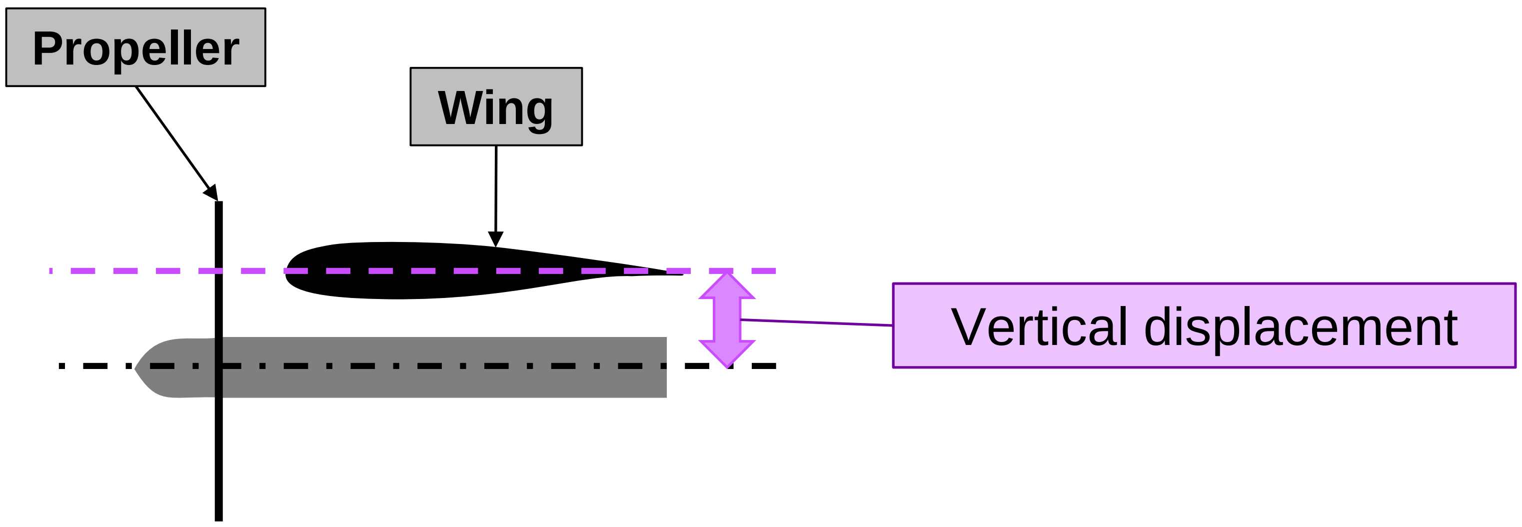
Flow Features



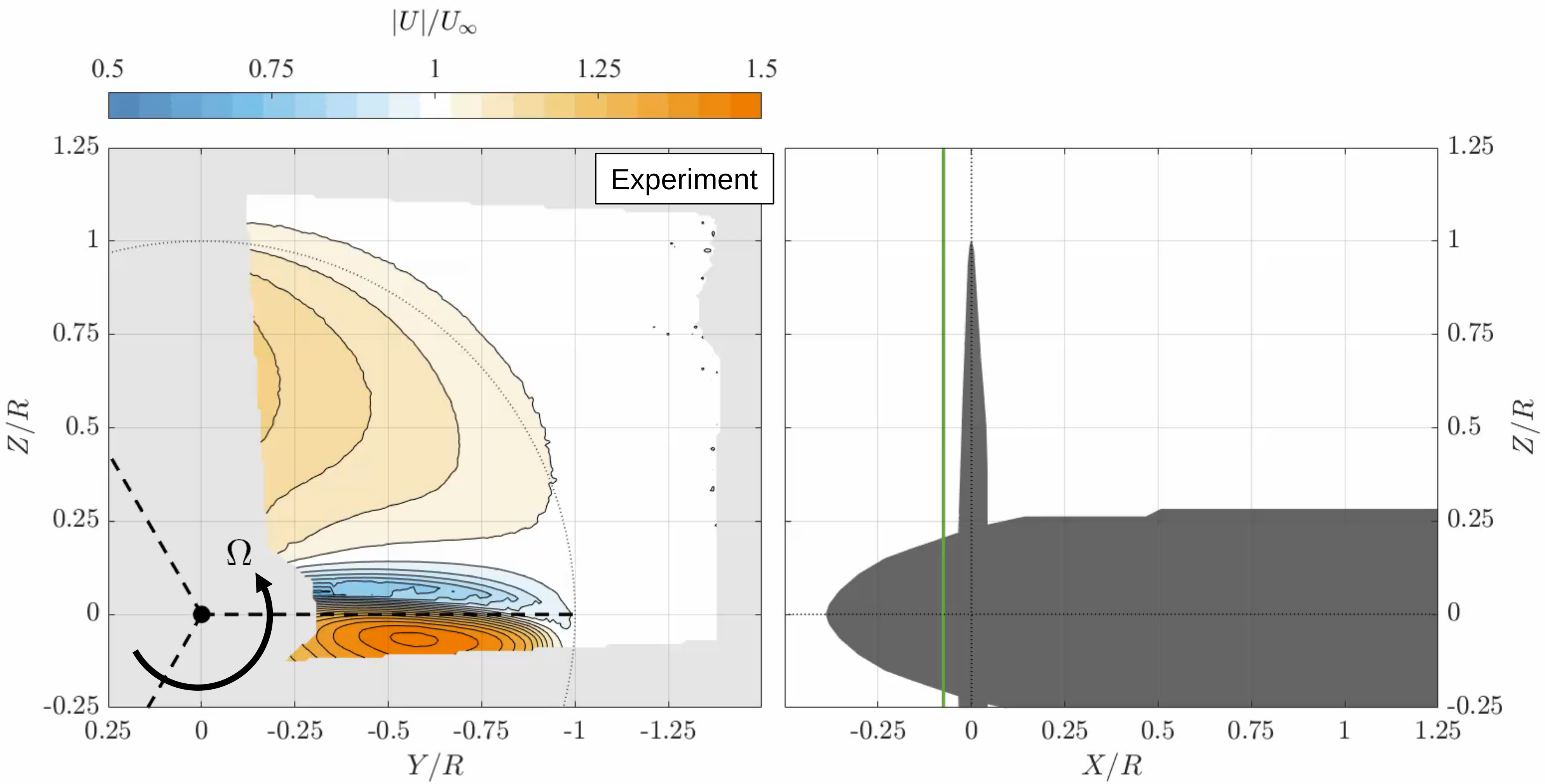
Advancing Blade Passage



Vertical Wing Displacement

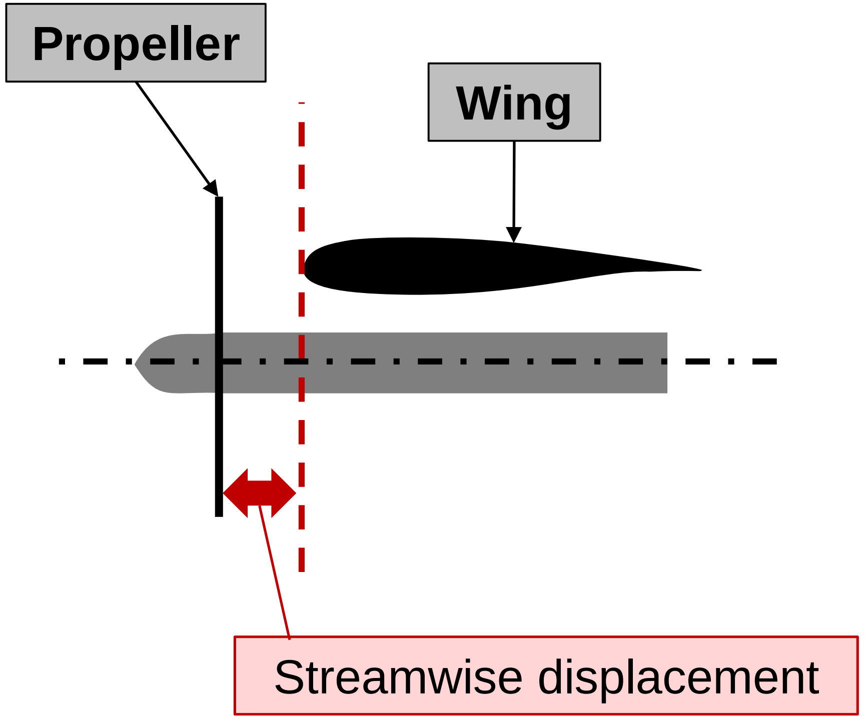


Vertical Wing Displacement



$(\psi = 0°)$

Streamwise Wing Displacement



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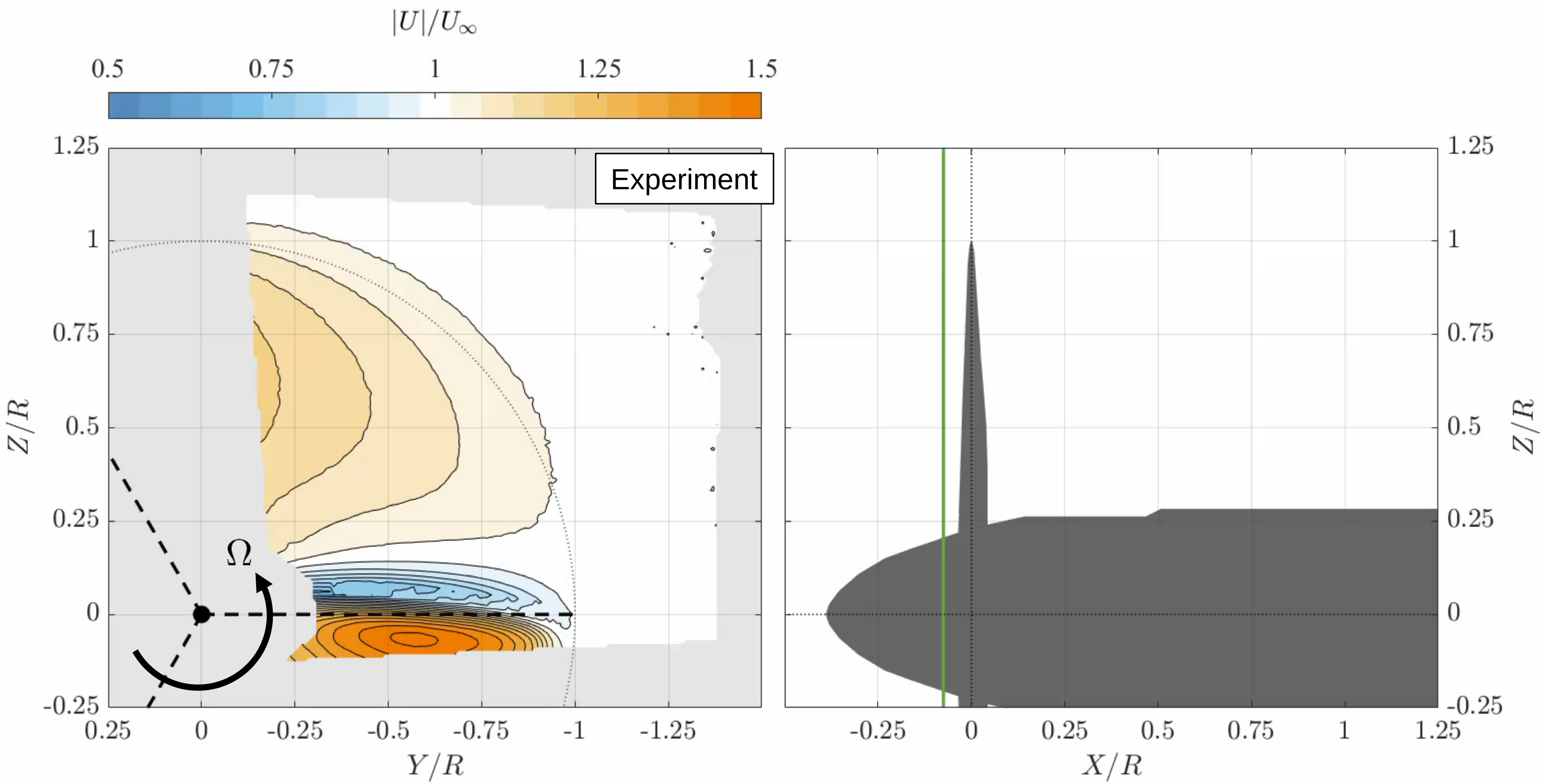

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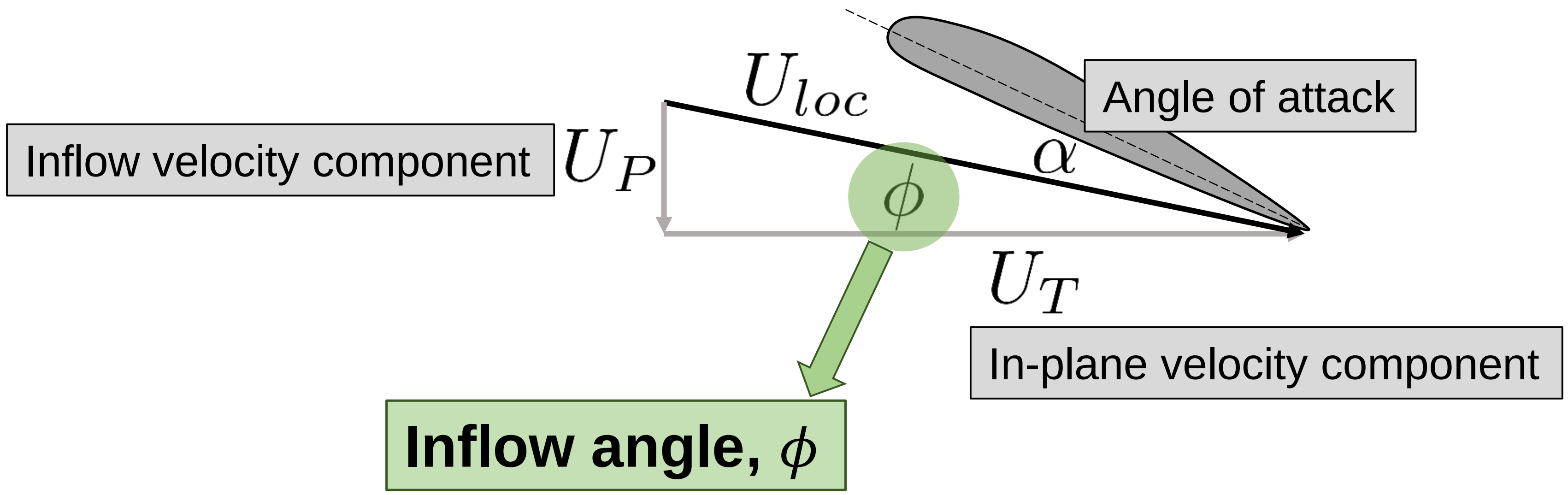
Blade Element Inflow Angle



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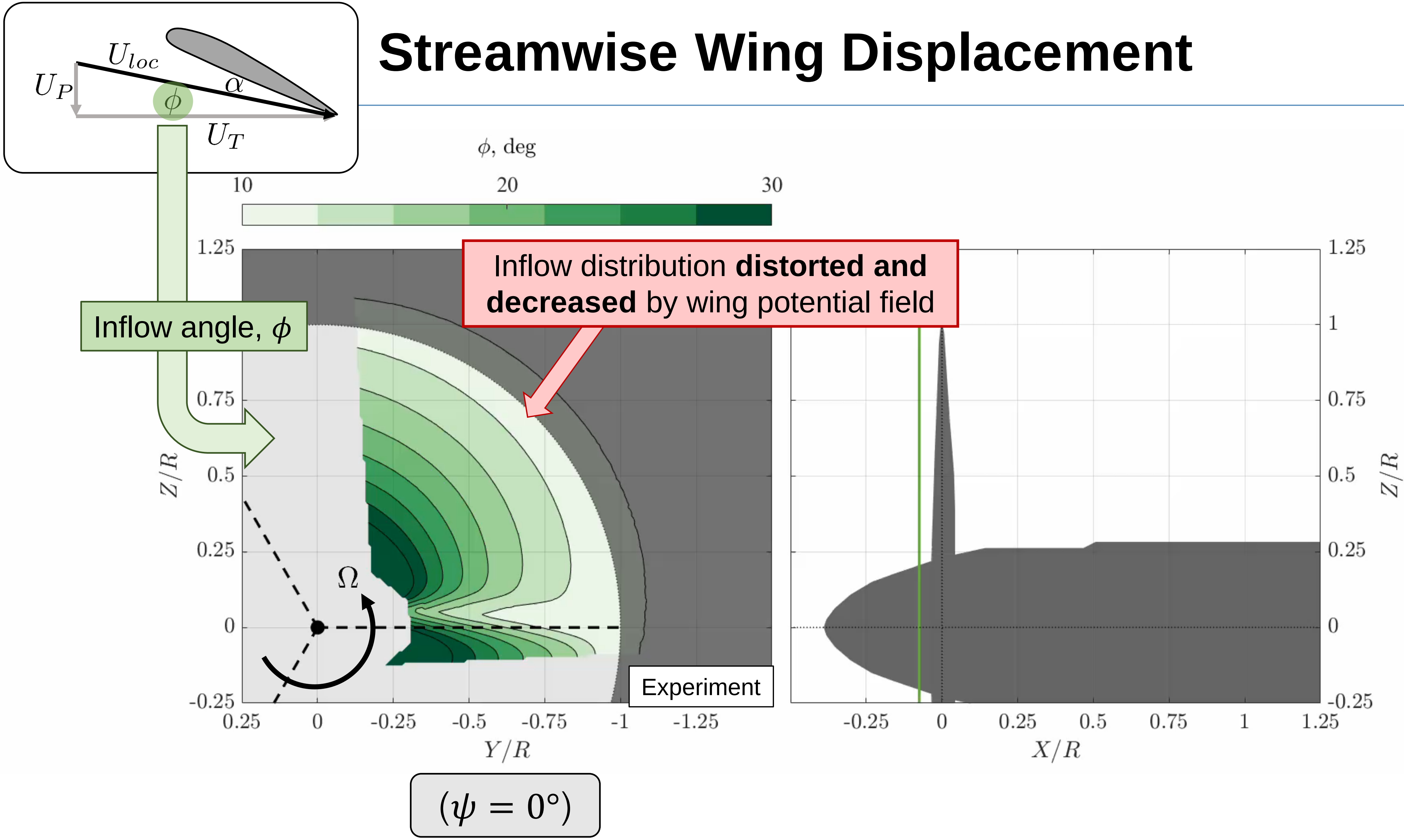

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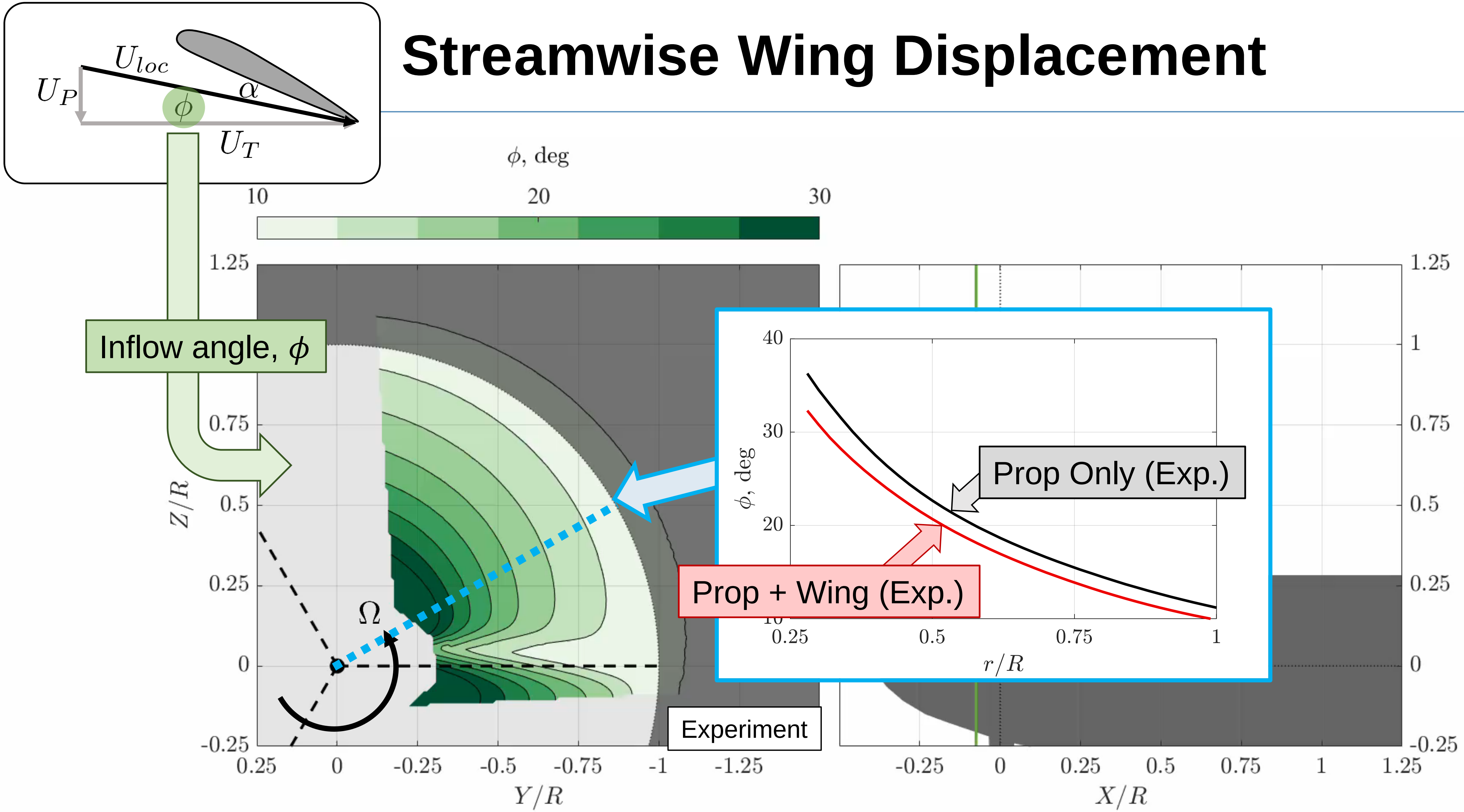
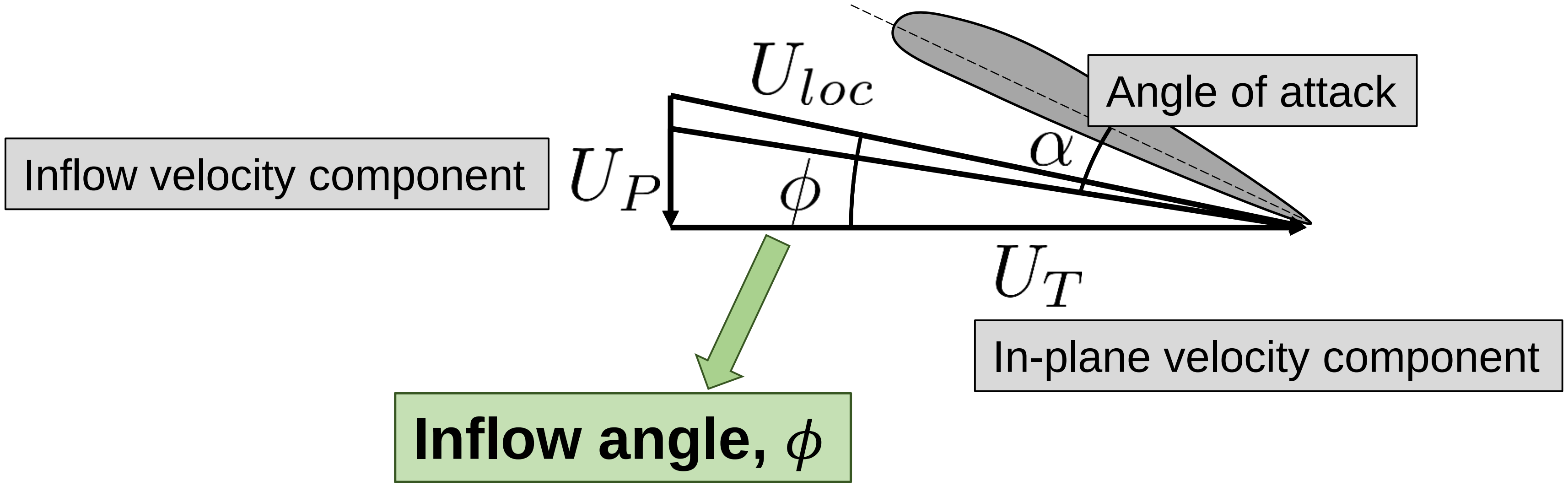


The wing's potential field **decreases** inflow angles

Blade Element Inflow Angle



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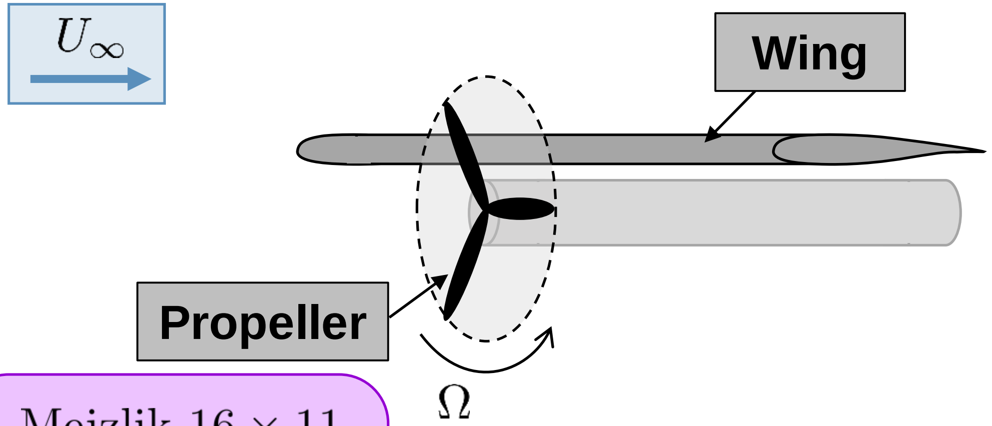

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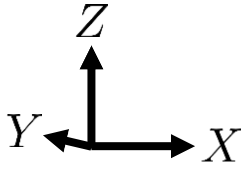
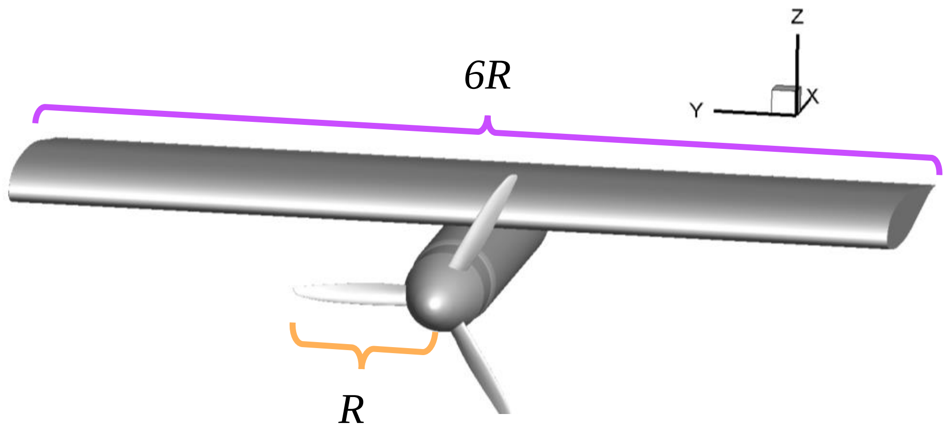
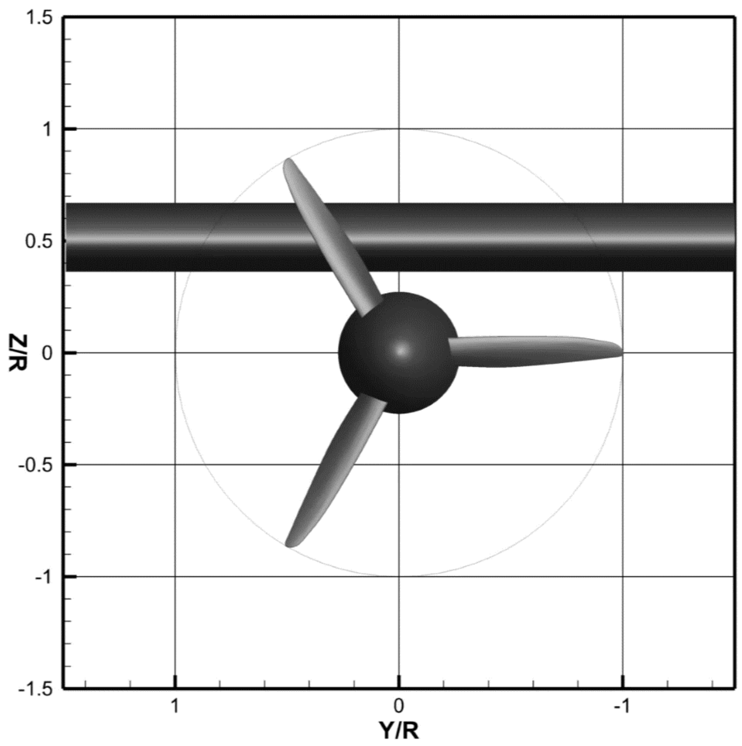


CFD Overview

Flow field (OVERFLOW2)

- Navier-Stokes equations solved on overset meshes
- Unsteady in time (~15 revolutions)
- URANS: SA-DDES turbulence model
- Run time ~ 1 day / rev. on 560 processors



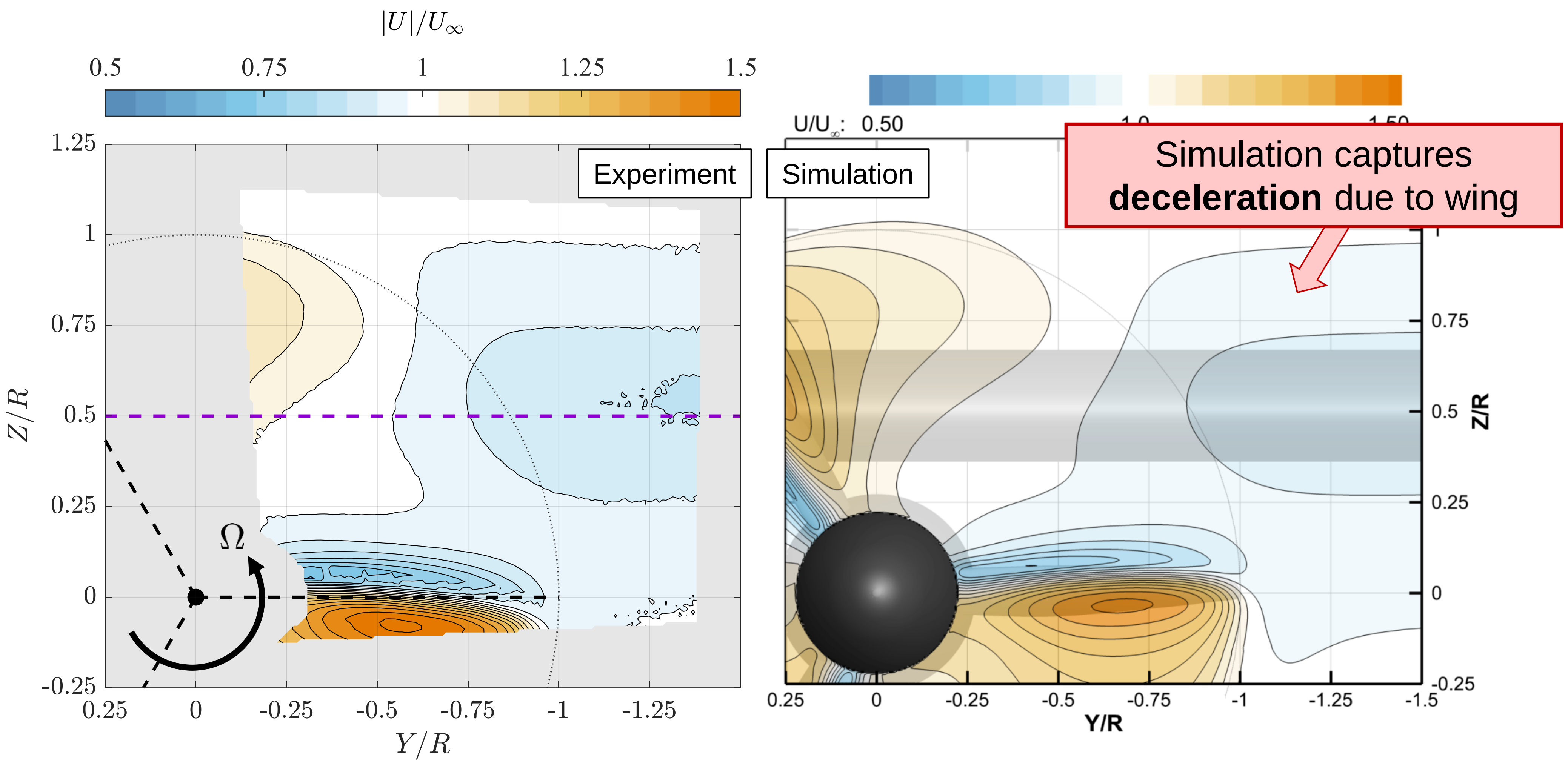


Acoustic field (PSU-WOPWOP)

- Ffowcs Williams-Hawkings equation
- Thickness and loading noise from surface pressure

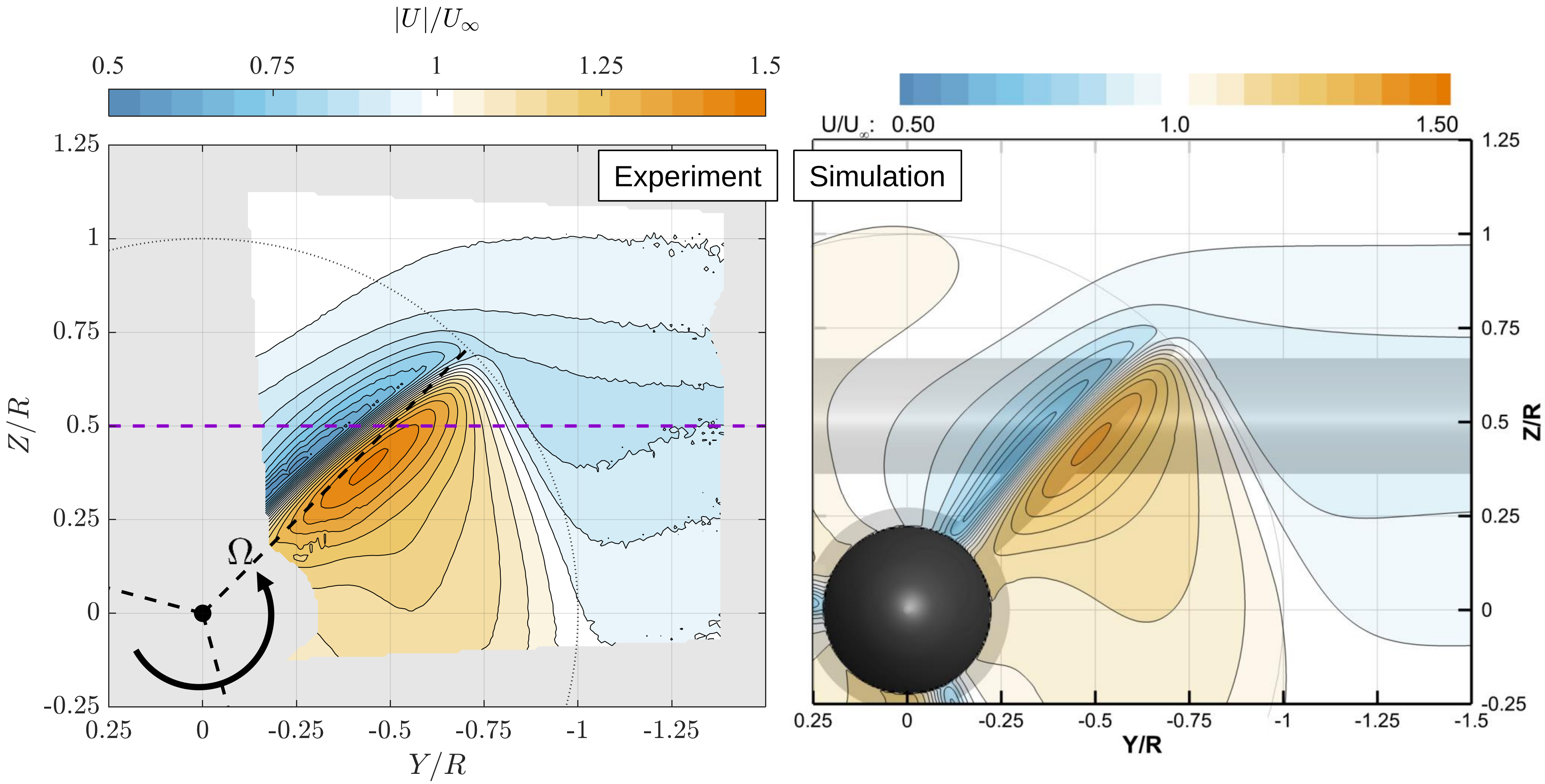
*More details in backup slides

Total Velocity



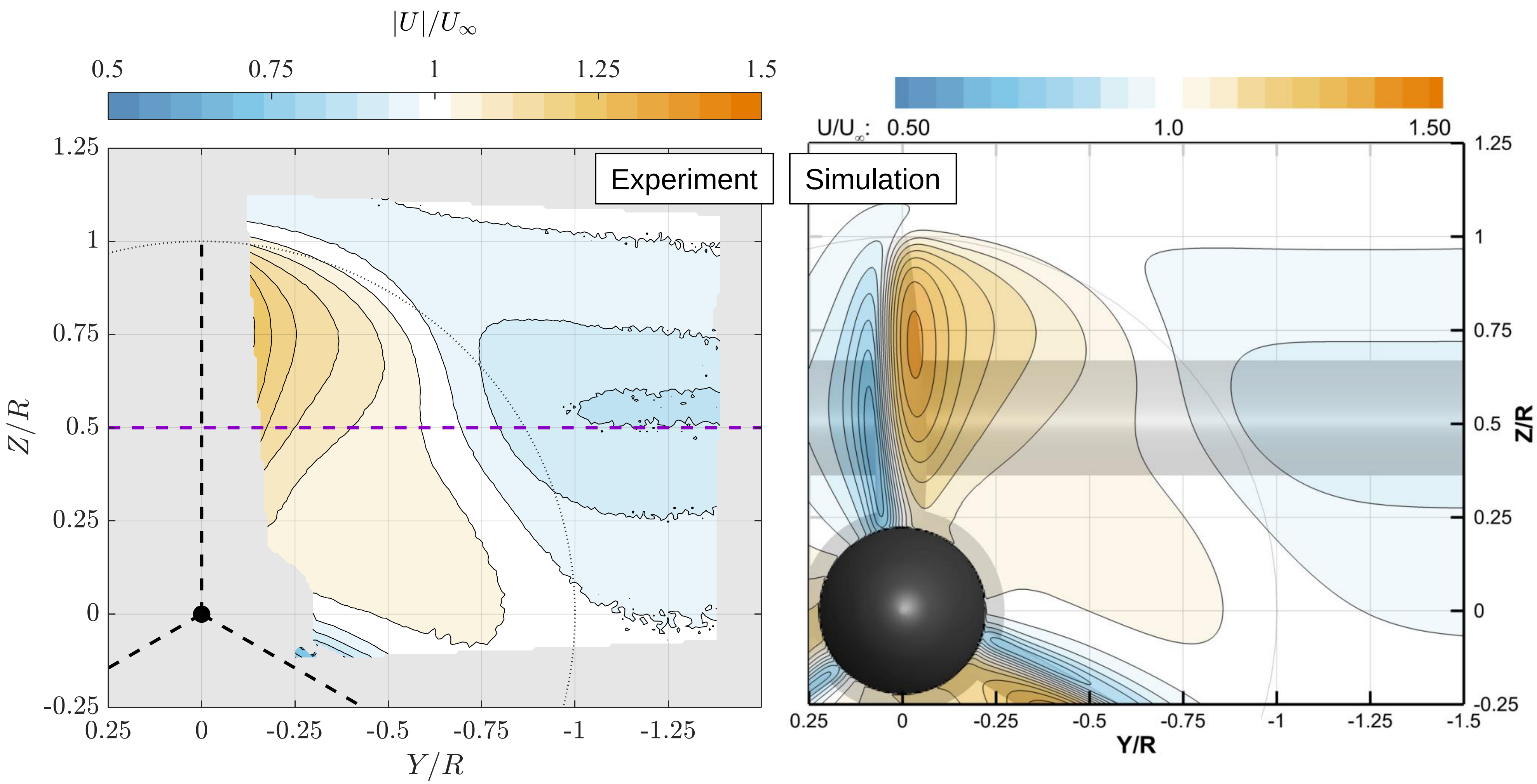
$(\psi = 0°)$

Total Velocity

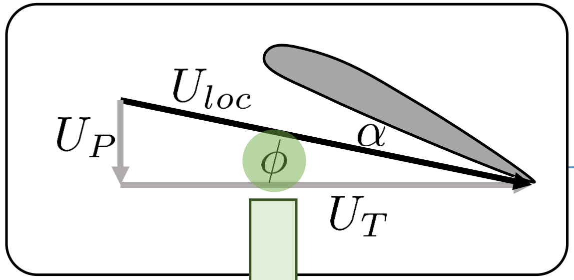


$(\psi = 45°)$

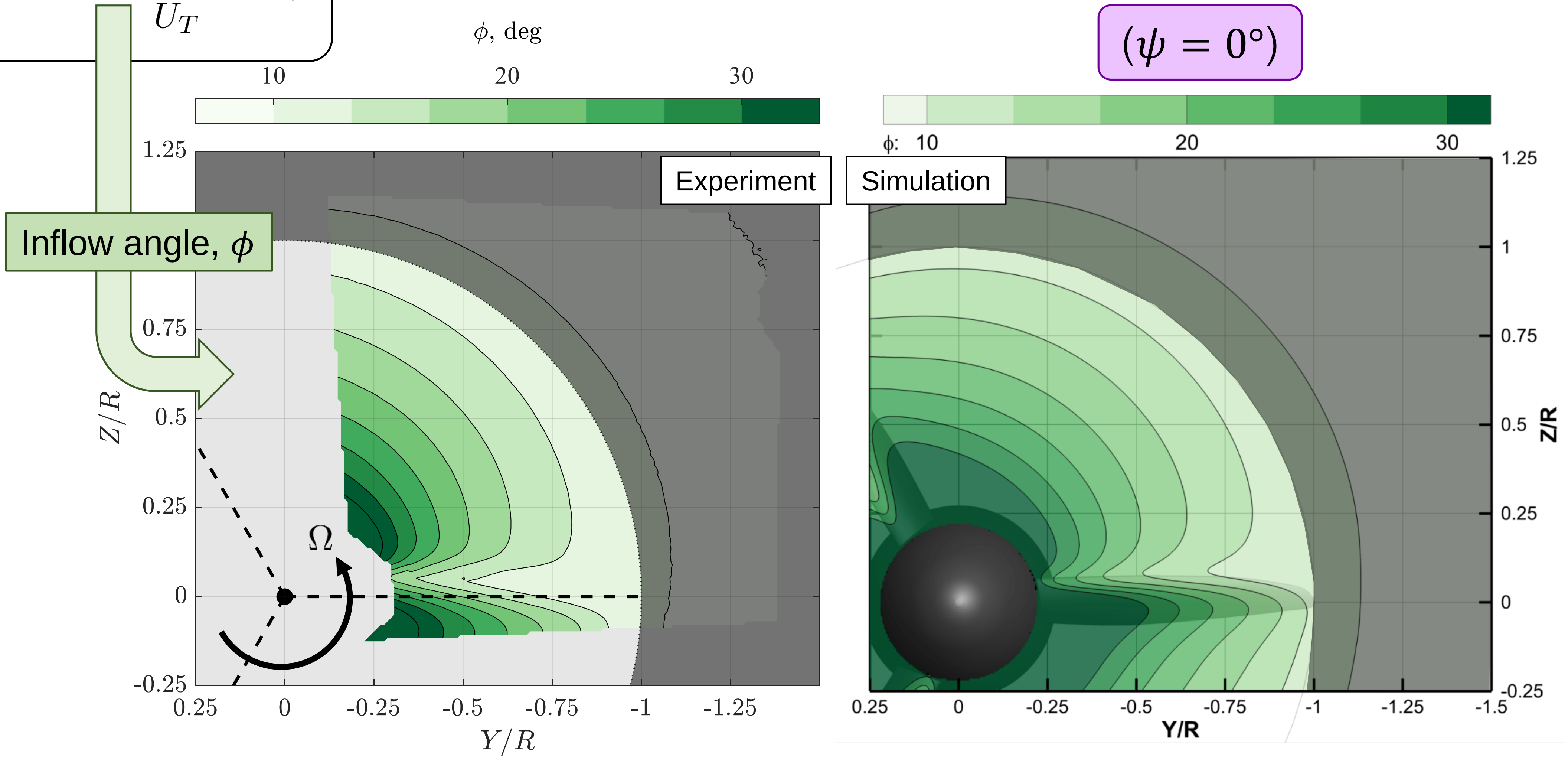
Total Velocity



$(\psi = 90°)$

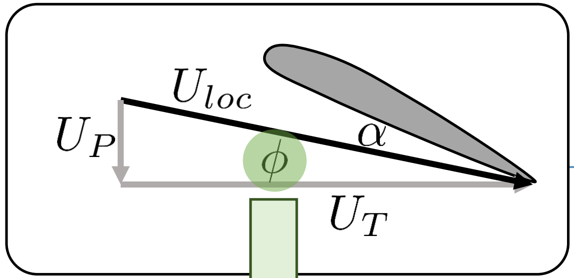


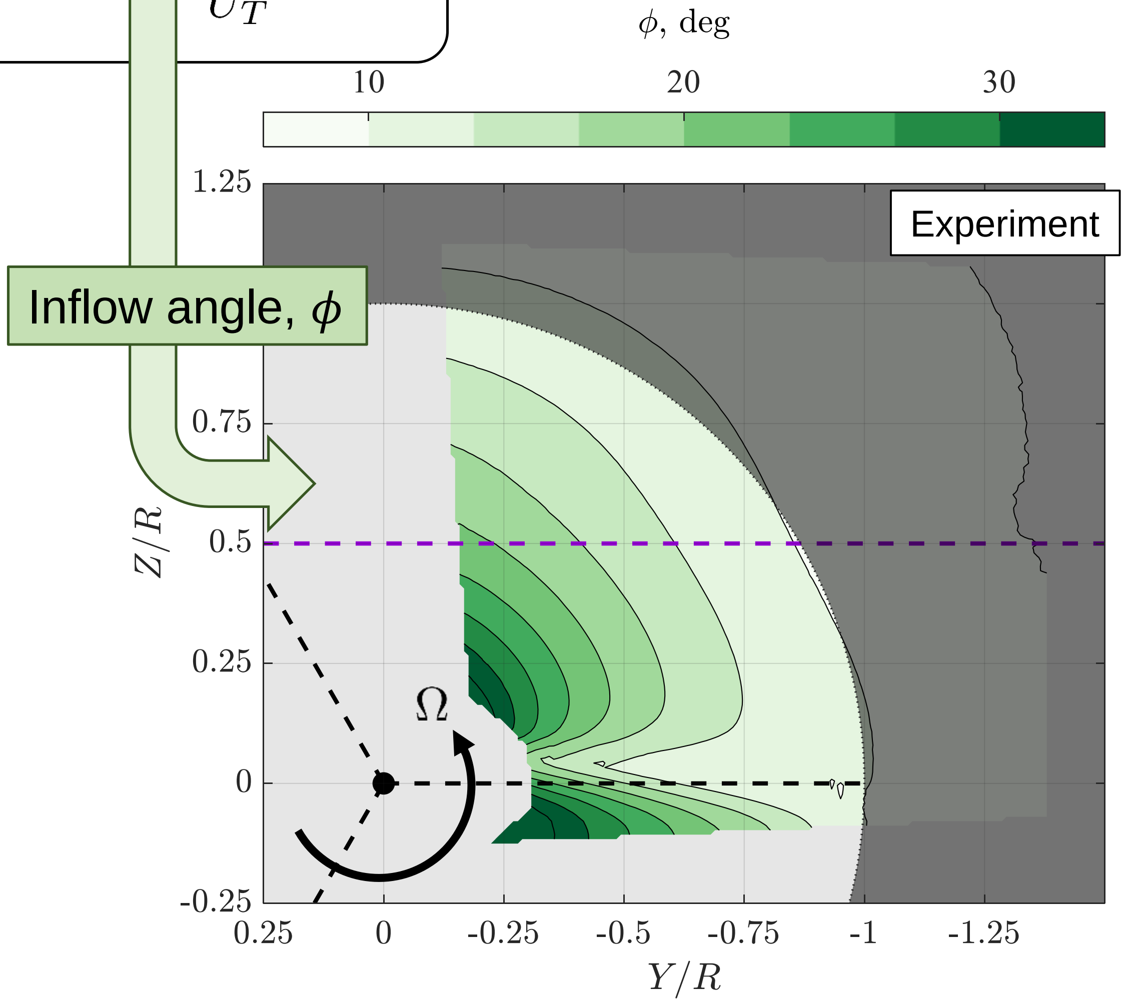
Inflow Comparison



Isolated Propeller

Inflow Comparison





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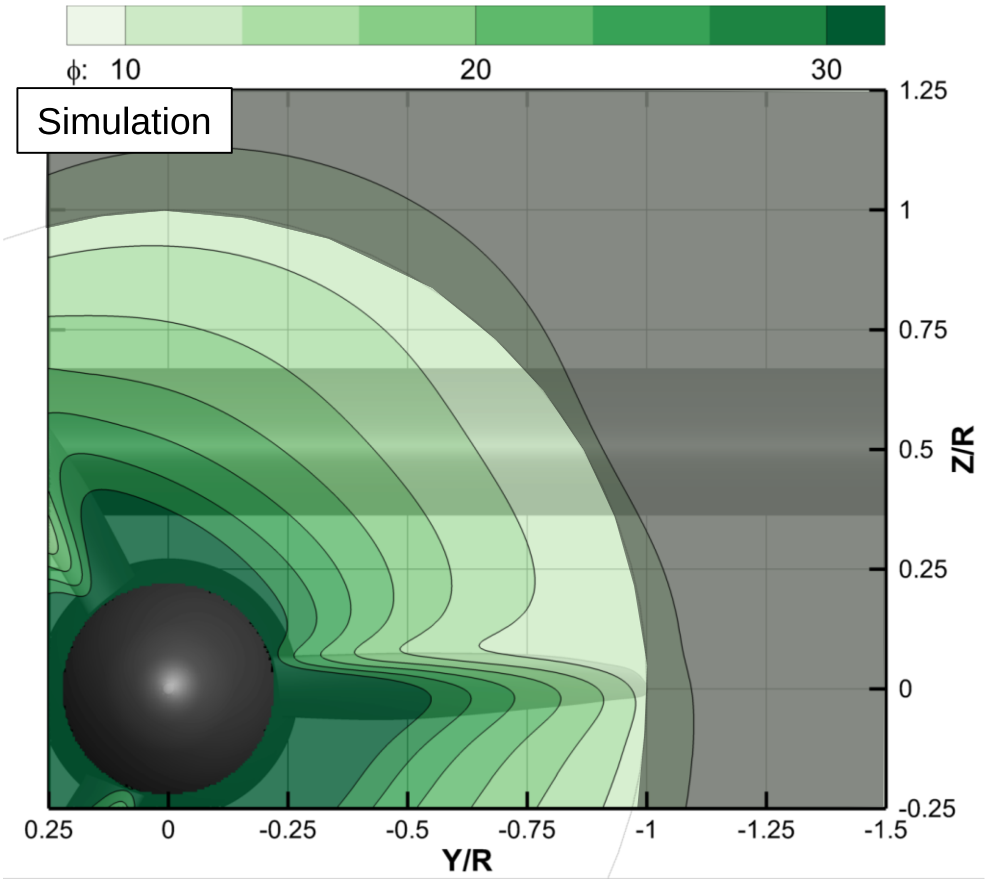

Propeller + Wing

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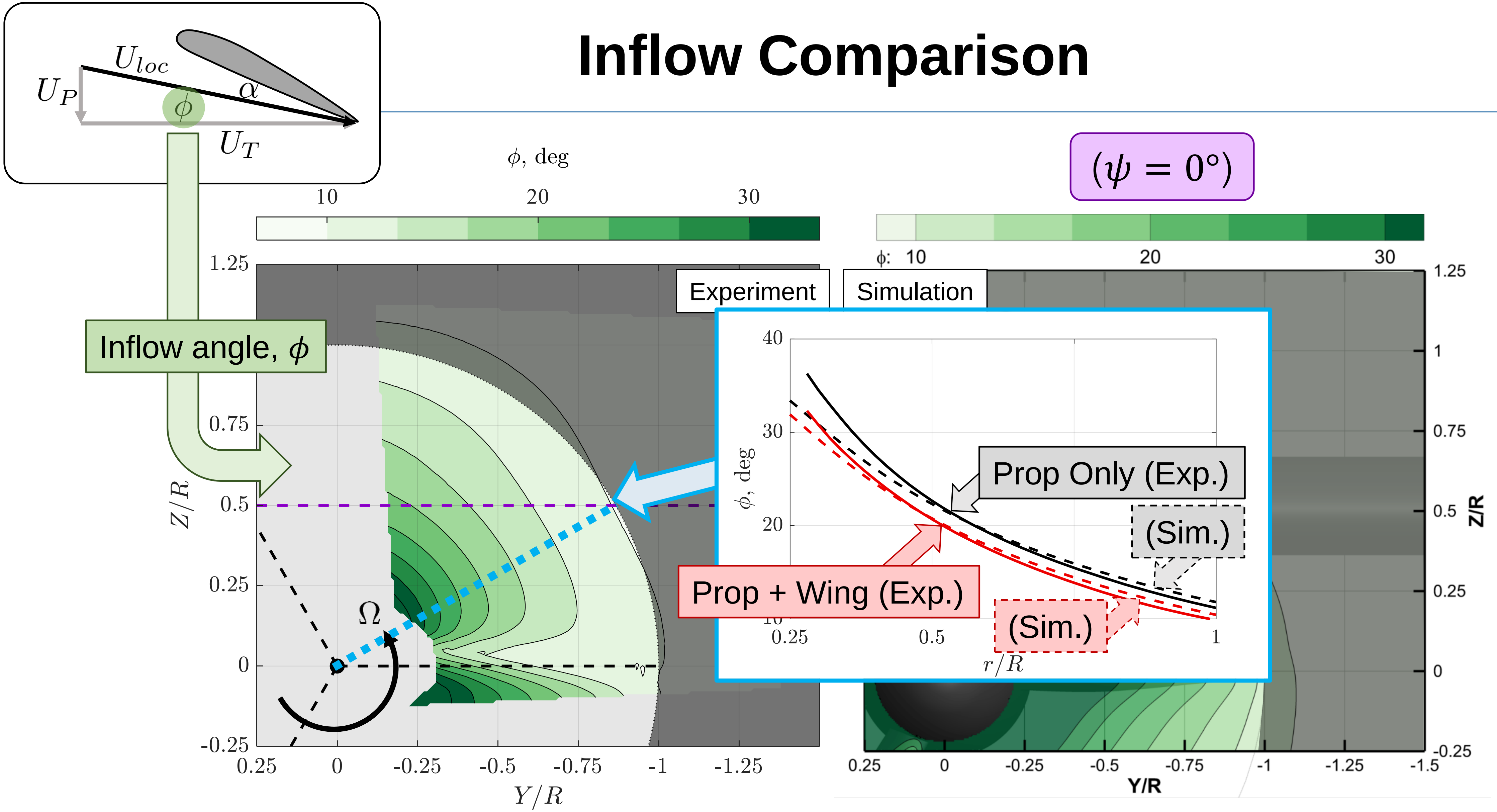
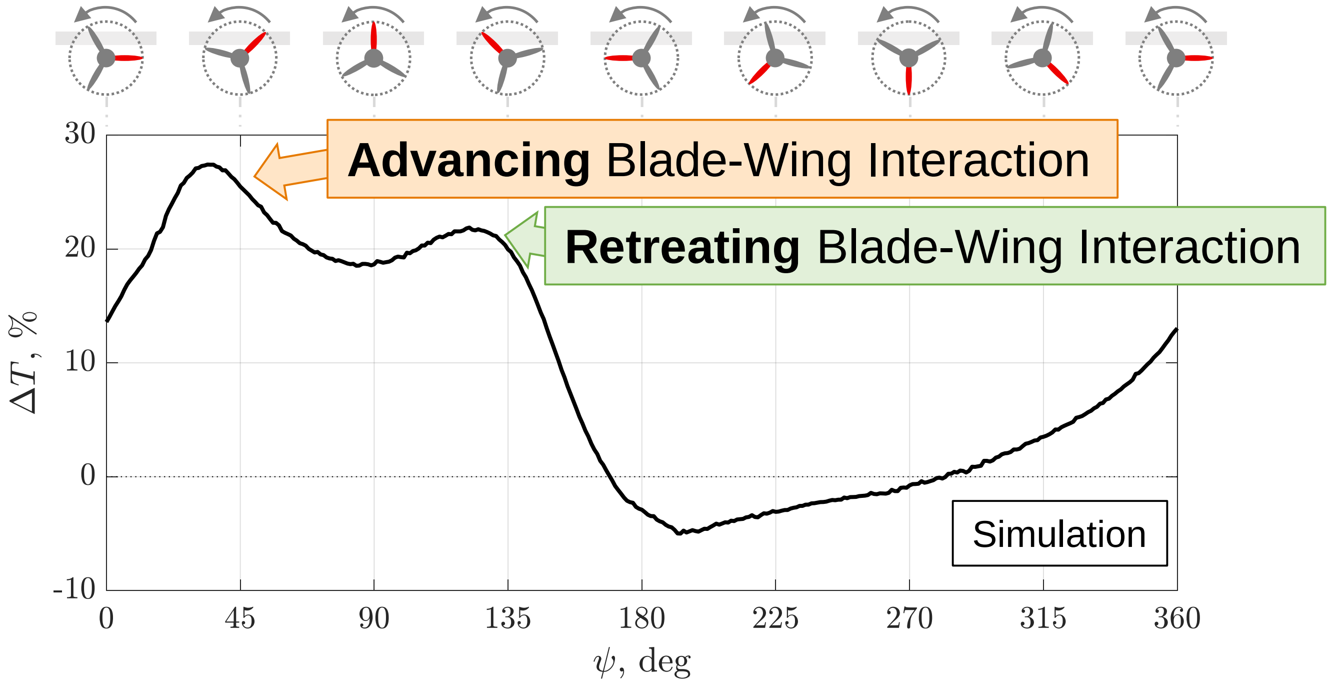


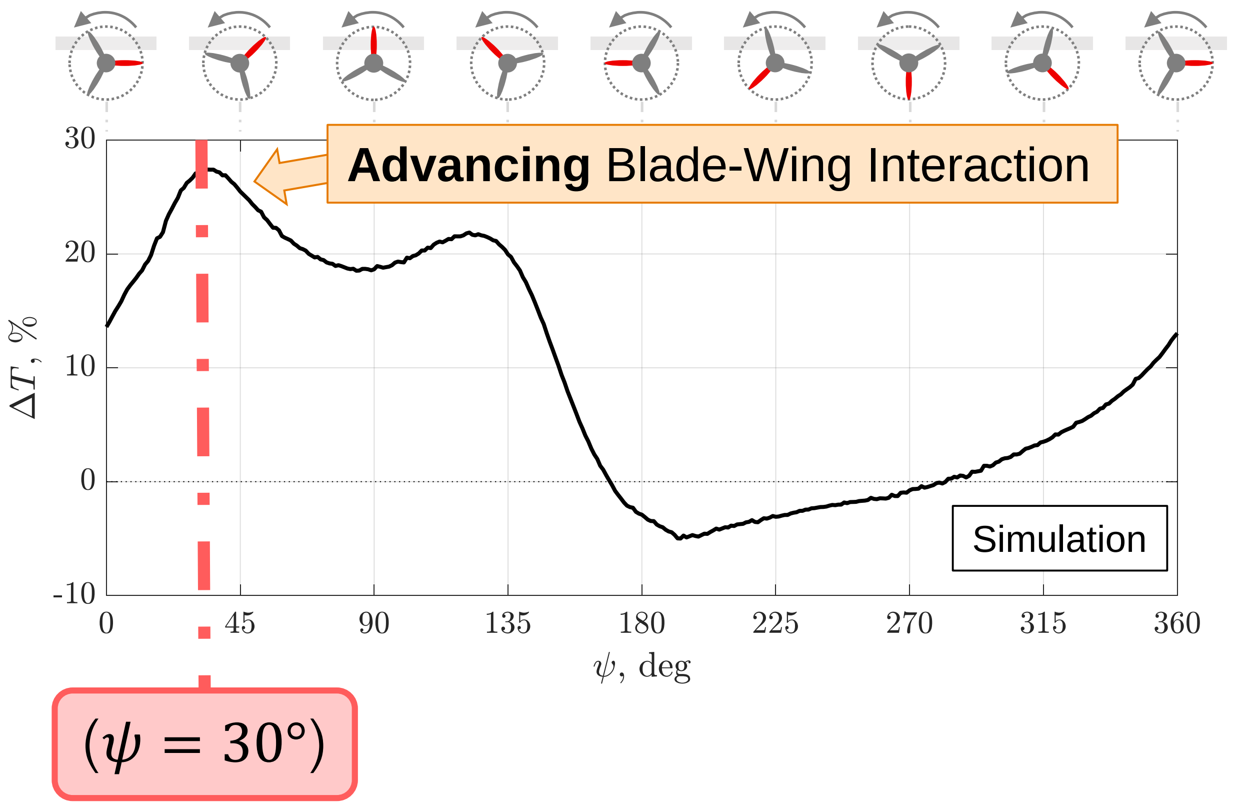
Propeller + Wing

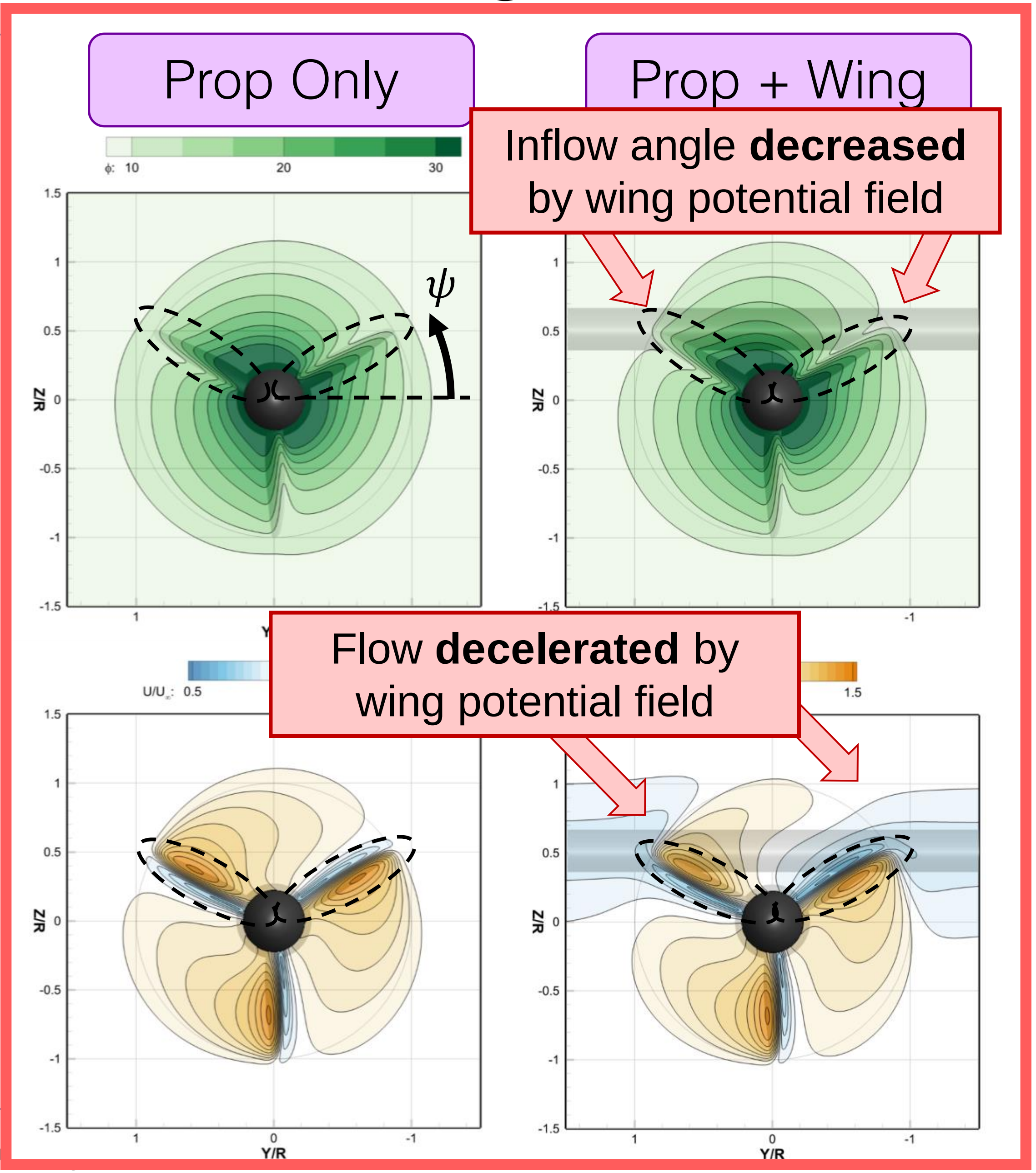
Azimuthally Varying Blade Loading



$$\Delta T = \frac{T_{\mathrm{p,\,w}} - \overline{T_{\mathrm{p}}}}{\overline{T_{\mathrm{p}}}}$$

Azimuthally Varying Blade Loading





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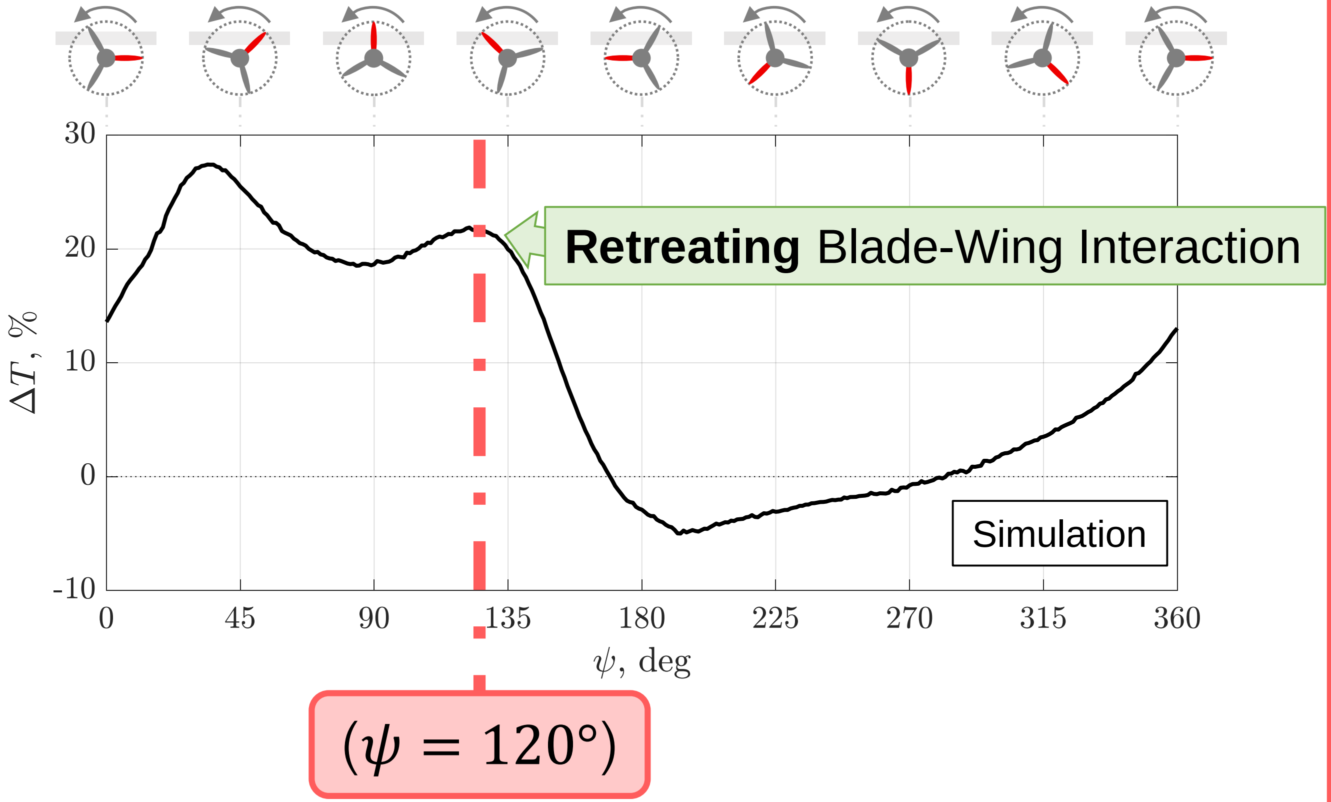
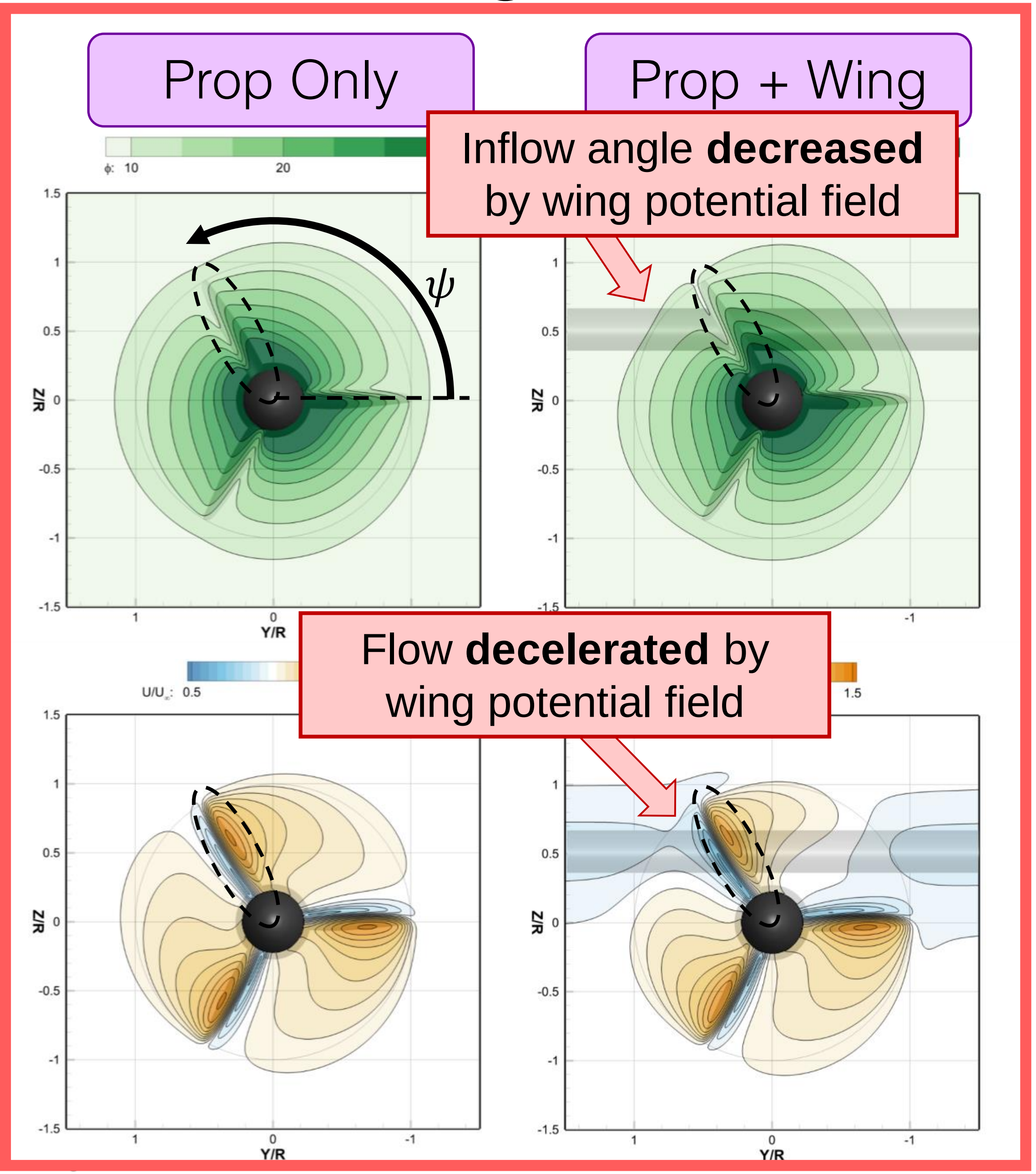
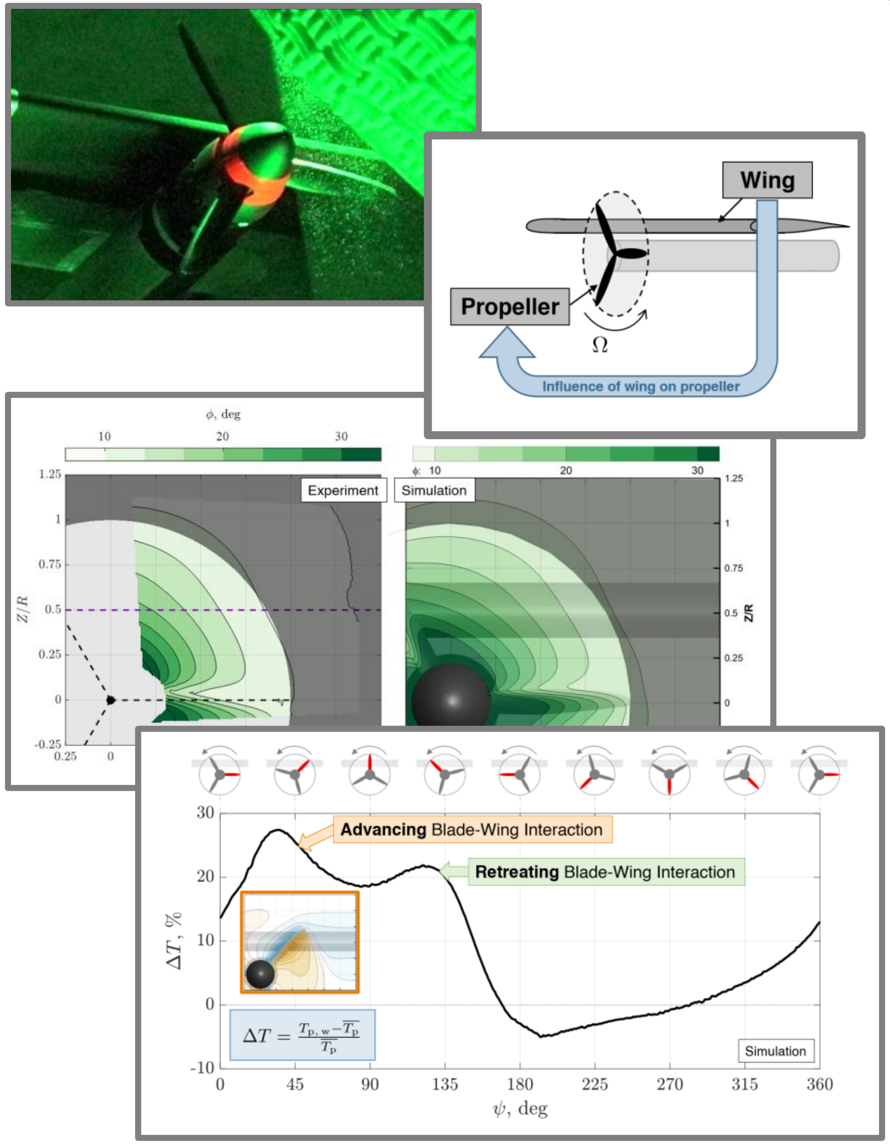




Conclusions

- Demonstrated **stereoscopic PIV** in LSAWT
- The potential field of the **wing reduces total velocity and inflow angles**
- The simulation showed **azimuthally varying blade thrust** as blades pass ahead of the wing
- Unsteady blade loading is believed to result in increased **vibrations** and **additional periodic loading noise**
- Recommendation is to **install propellers far upstream of wing** to reduce wing-on-prop noise



Acknowledgments

- Computational Support
  - ⇒ Doug Boyd
  - ⇒ Joe Derlaga
  - ⇒ Pieter Buning
- Experimental Support
  - ⇒ Luther Jenkins
  - ⇒ Scott Bartram
- LSAWT team
  - ⇒ John Swartzbaugh
  - ⇒ Stan Mason
  - ⇒ Bryan Lamb
  - ⇒ Jeff Collins
  - ⇒ Mick Hodgins
- Transformative Tools and Technologies (TTT) Project

Thank you.

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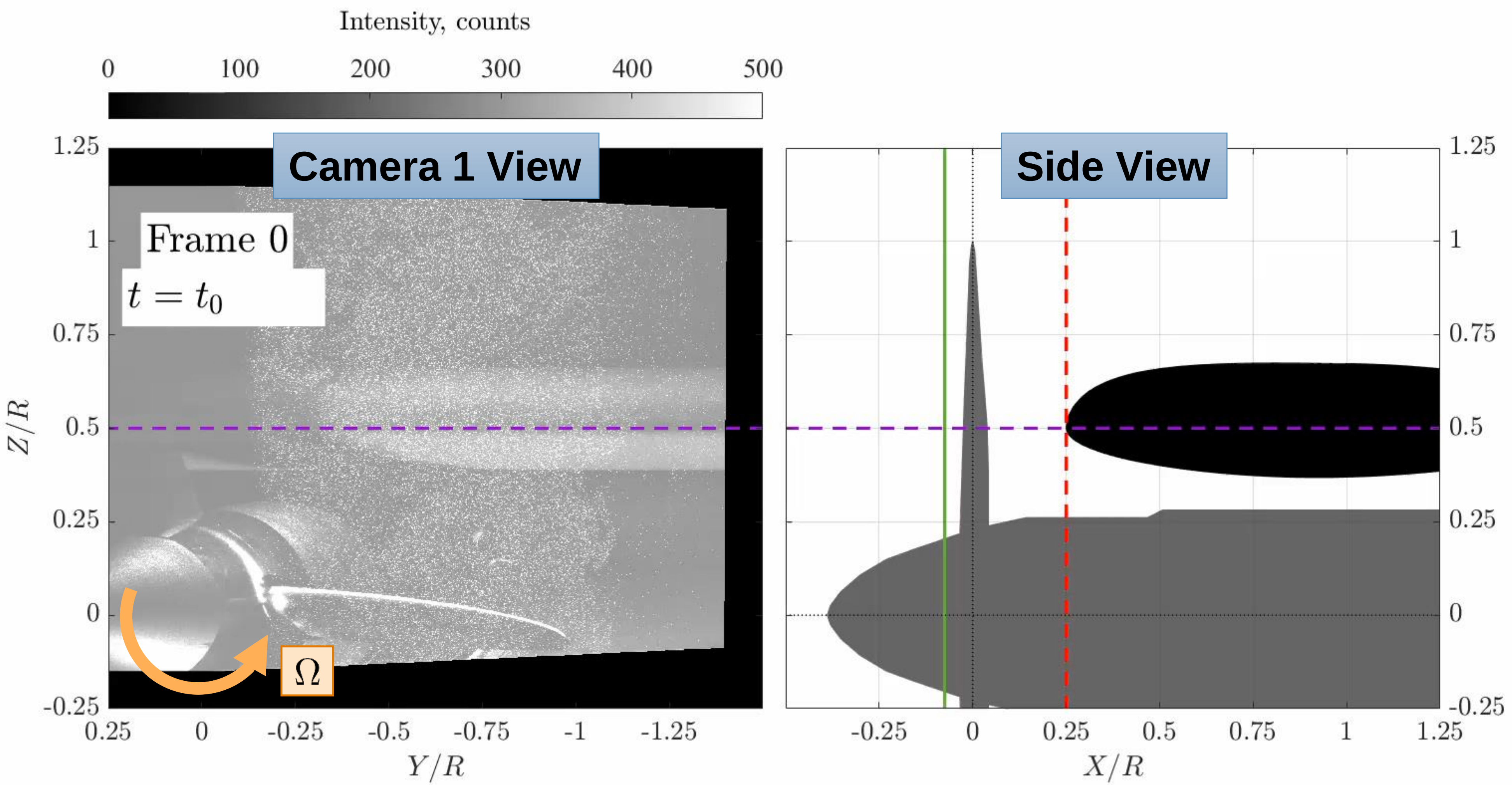
Experiment Challenges and Limitations

- Uncertainty in propeller azimuth and position
  - ⇒ Time synchronization between 1/rev laser tachometer and programmable timing unit (PTU)
    - variation across run conditions (e.g., bias)
    - variation during each run (e.g., jitter)
  - ⇒ Observed some lateral and vertical displacement of propeller spinner due to stand vibrations
- Laser reflections
  - ⇒ reflections can lead to camera saturation, thus limiting the laser power that can be used
  - ⇒ bandpass optical filters were used on cameras
  - ⇒ spinner was treated with orange reflective tape to shift wavelength of laser reflection
  - ⇒ laser sheet was intentionally clipped to provide sufficient illumination of seeding near spinner
  - ⇒ attempted to mitigate reflection off propeller using sharpie, did not work
  - ⇒ plan to investigate other optical treatment options for future test activities
- Intermittent flow seeding
  - ⇒ The LSAWT is an open-circuit tunnel, challenging for uniform seeding
  - ⇒ Seeding was introduced in settling chamber, targeting a streamtube through the field of view
  - ⇒ A smoke rake will be considered in future tests to encourage more homogenious flow seeding
- Sheet optics
  - ⇒ LaVision's "variable divergent standard sheet optics" are specified to provide a maxiumum working distance of 2 meters. This proved challenging as it was required that the laser and sheet optics be positioned outside of the core flow in the LSAWT.
  - ⇒ The gaussian intensity distribution of the laser sheet resulted in less illumination of seeding in the outer flow region
- Calibration
  - ⇒ Installation of the calibration target required partial disassembly of the model (e.g., spinner and propeller)

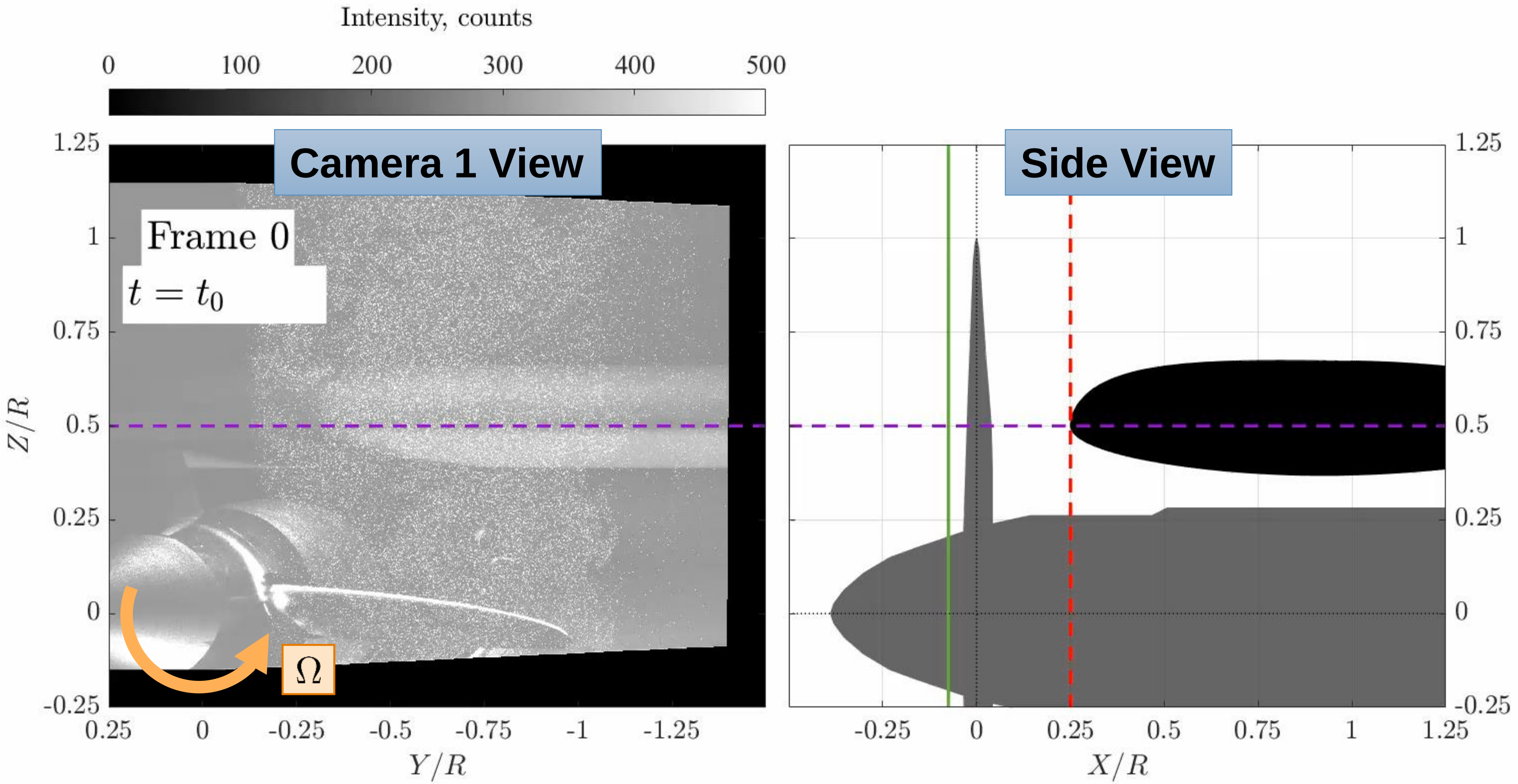
Experiment Successes

- Demonstrated stereoscopic PIV with interrogation plane perpendicular to flow direction with good correlation between image pairs
- Installed two cameras near nozzle on tall support structures; cameras did not vibrate appreciably
- Laser head was mounted on support structure; did not vibrate appreciably
- The two laser beams were aligned and similar in intensity; no need to realign or tune the laser head

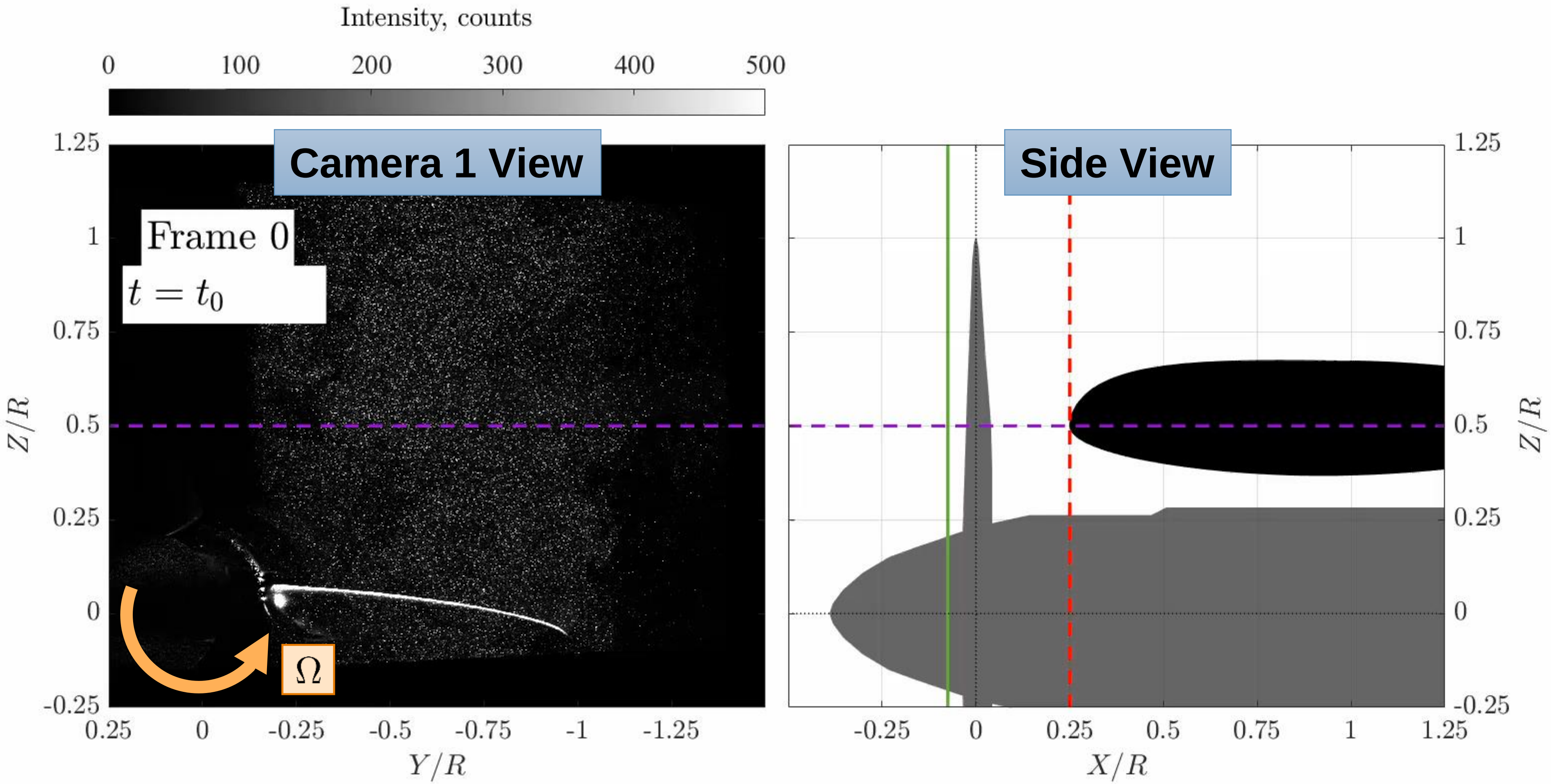
Sample Image Pair



Propeller Azimuth Drift in Background Images

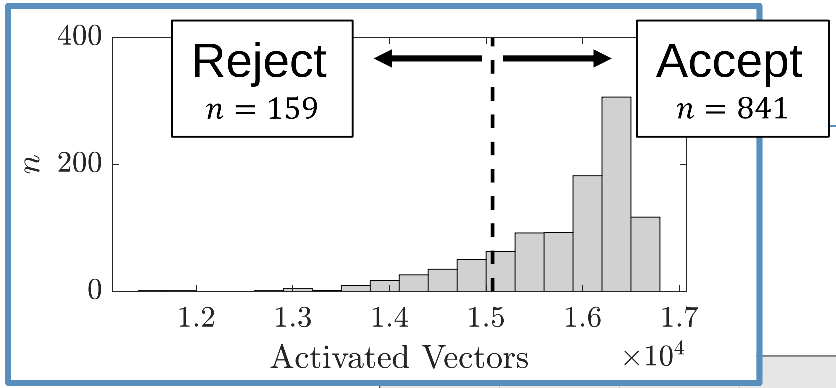


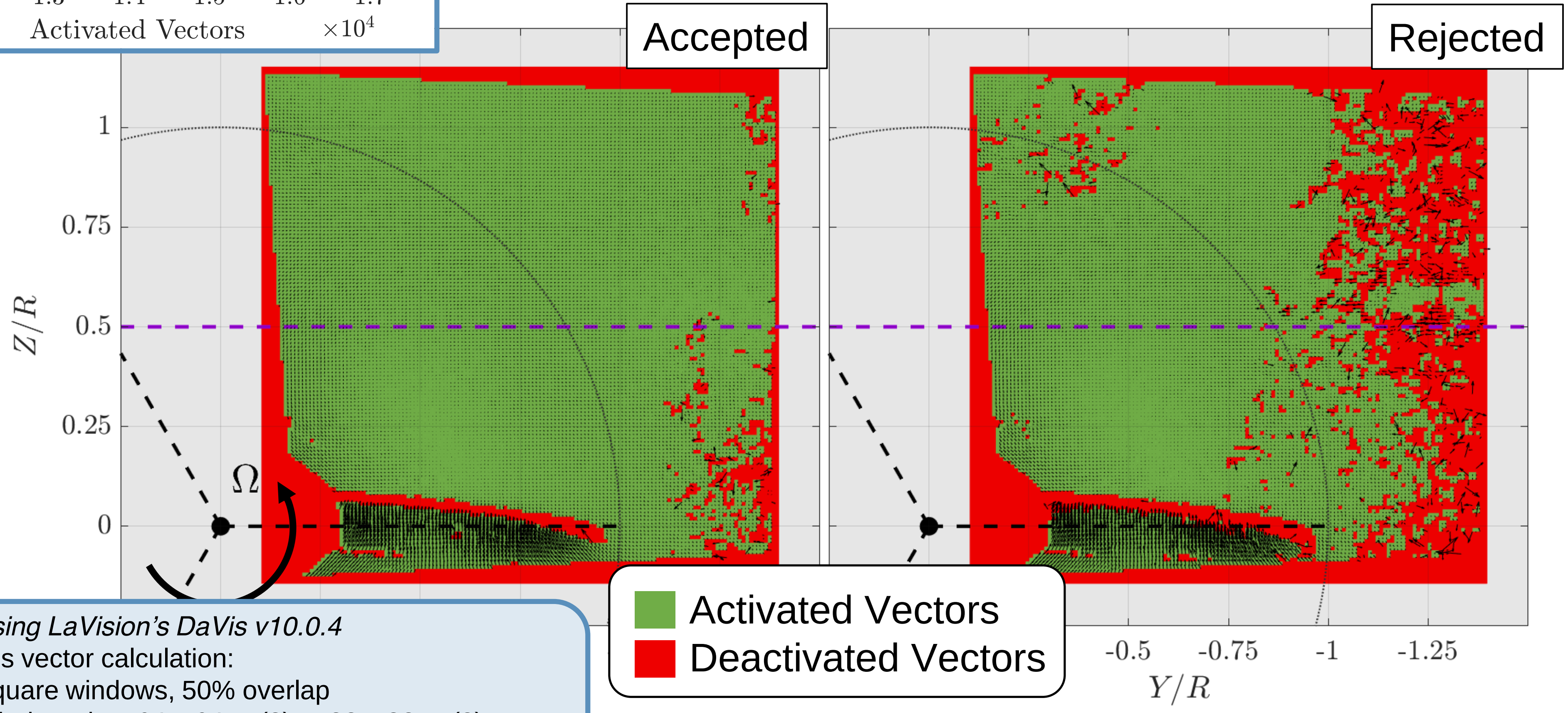
Sample Image Pair with Background Subtracted



n = 1,000 image pairs collected for each run condition

Data Rejection

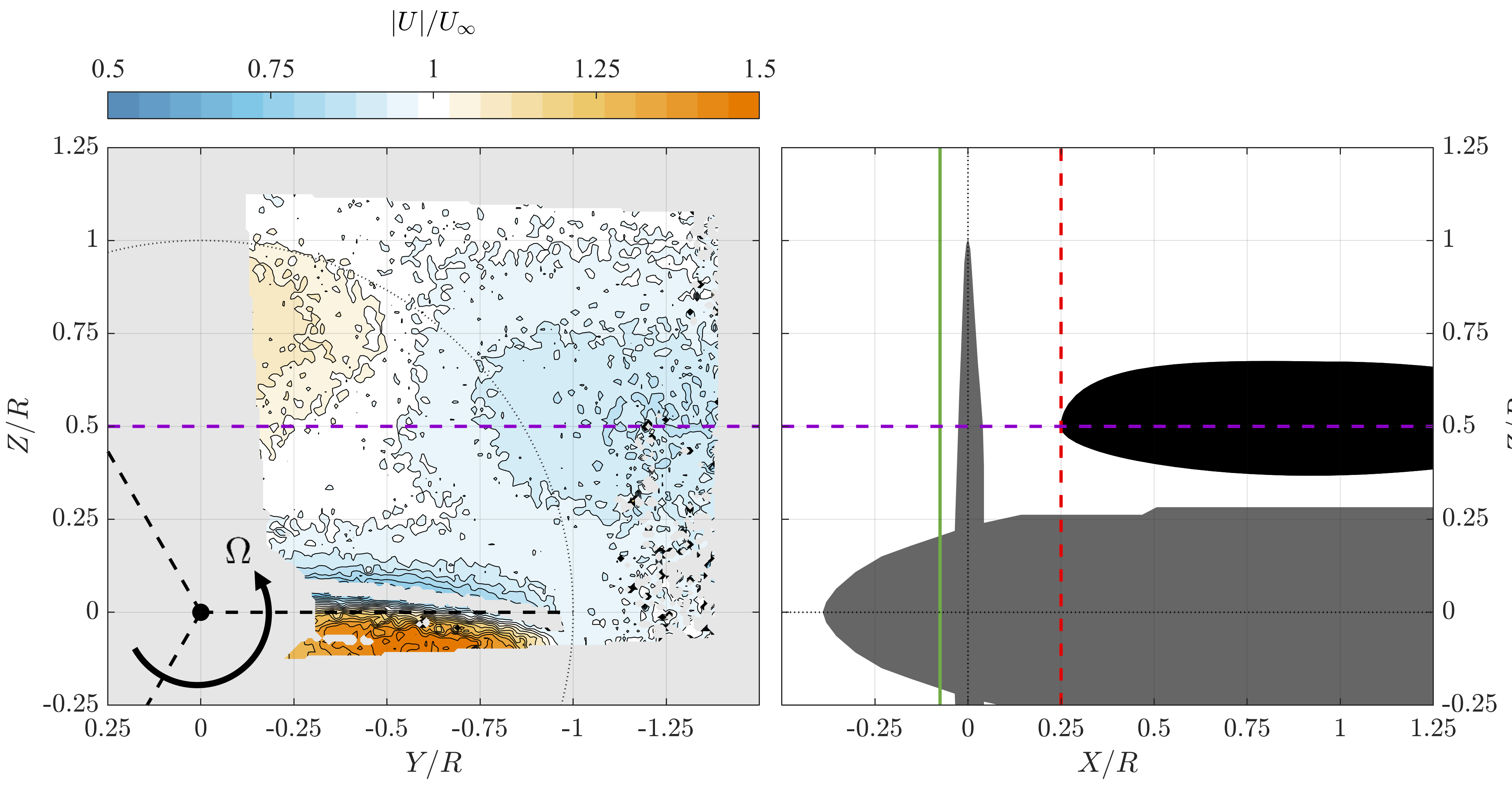




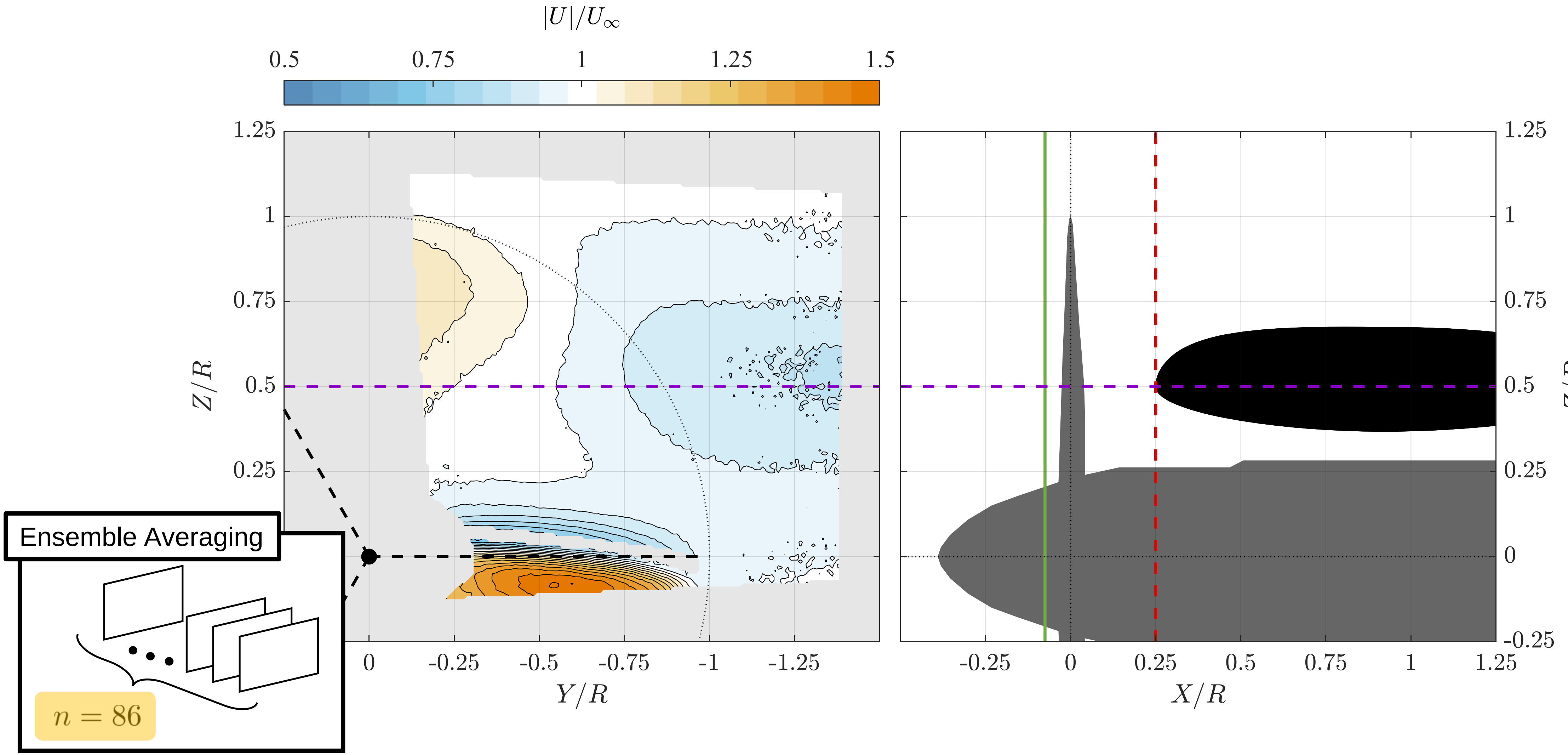
Processed using LaVision's DaVis v10.0.4

- Multi-pass vector calculation:
  - Square windows, 50% overlap
  - Window size: 64 x 64px (2) to 32 x 32px (2)
- Resolution: ~ 0.01R/vec
- Median filter: universal outlier detection

Instantaneous Measurment



Ensemble Average



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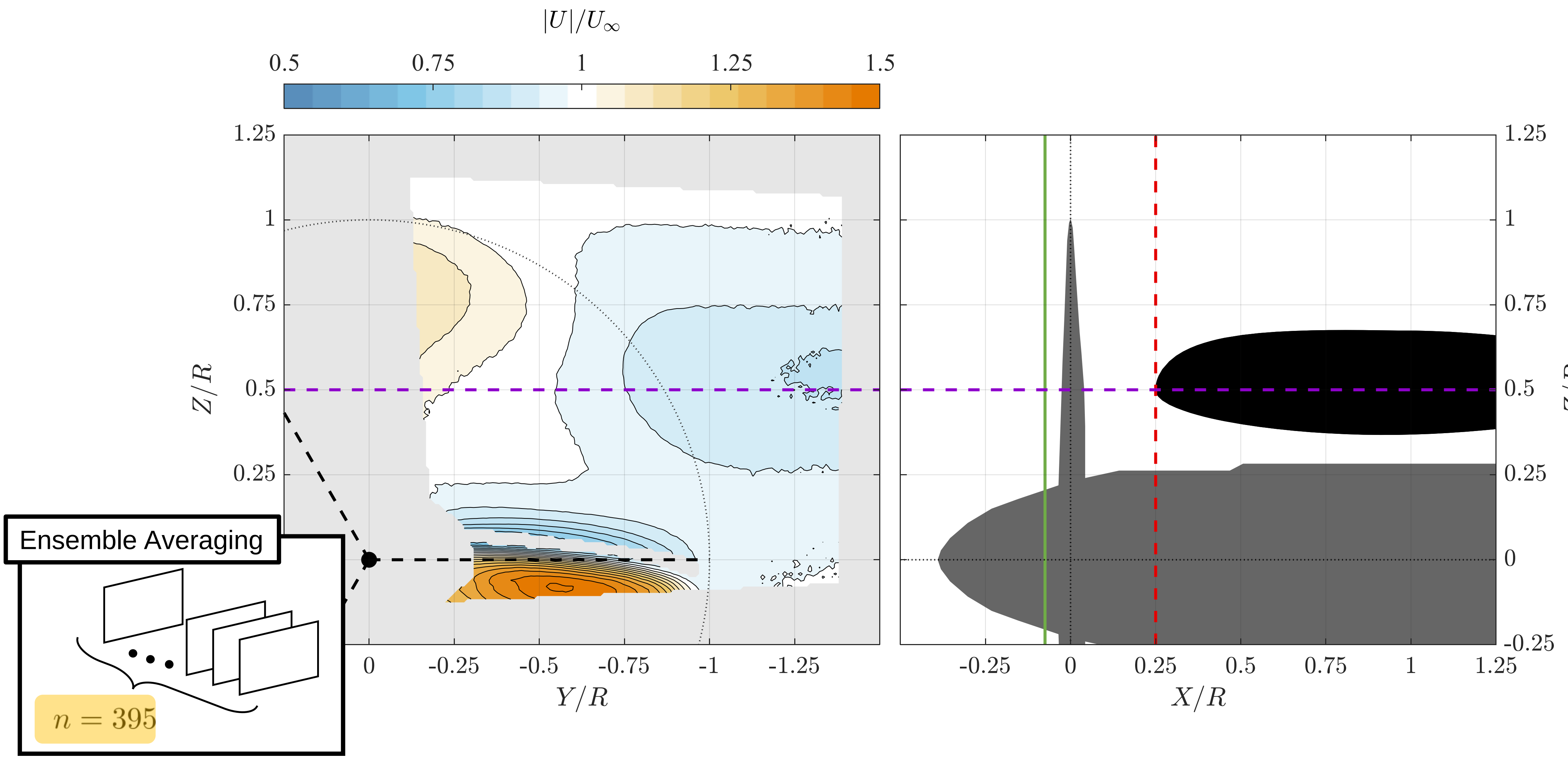

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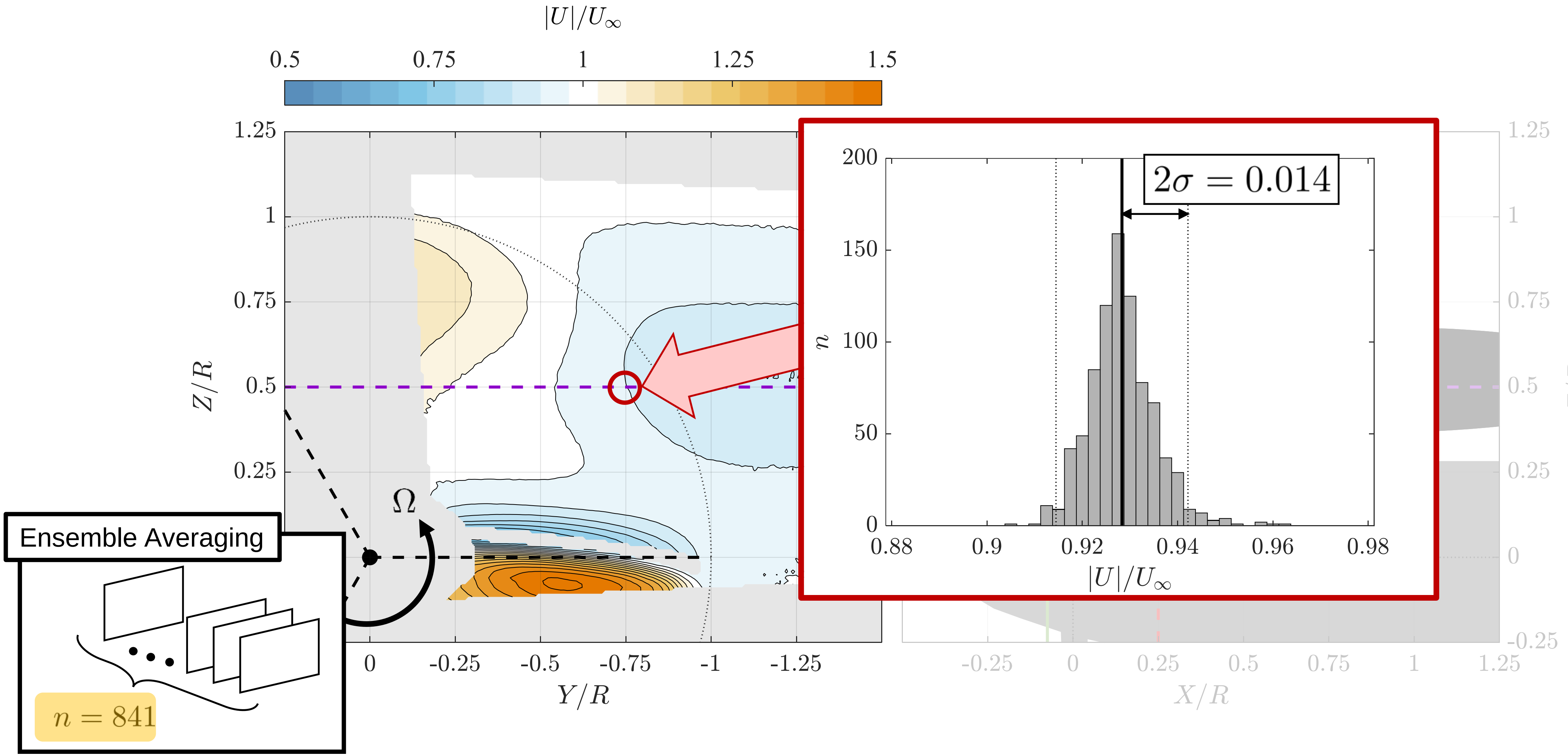
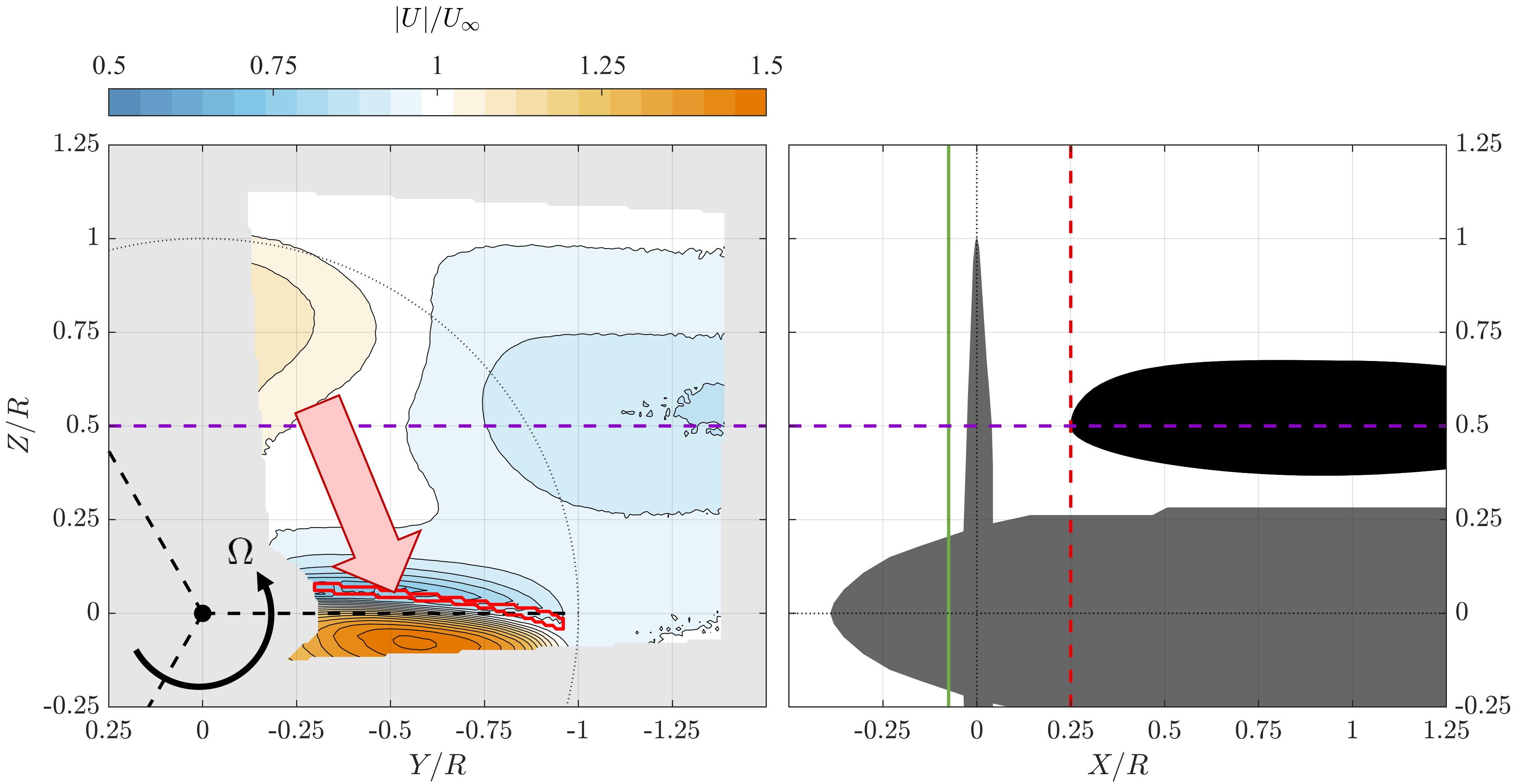


Interpolation



Backup: CFD Methods

- Slight differences in run conditions

Input Value	Experiment	Simulation
M_{∞}	0.07	0.068
U_{∞}	~ 24.4 m/s	23.1 m/s
Ω	~ 100 Hz	97.76 Hz
J	~ 0.60	0.59

- OVERFLOW2 Details
  - ⇒ LHS = Improved SSOR
  - ⇒ RHS = HLLE++ upwind scheme with Newton sub-iterations
  - ⇒ URANS: SA-DDES w/rotation and curvature corrections
- Run Time
  - ⇒ Convergence to oscillatory steady-state = reduction in residuals of two-orders of magnitude at each sub-iteration
  - ⇒ 1 revolution ~27 hrs. on Pleiades with 560 cores (at ¼ deg time steps)
  - ⇒ 15+ revolutions (10 coarse @ 2.5° increments, 5 @ at 1/4° increments)

Azimuthally Varying Blade Loading