# Aeroacoustic and Aerodynamic Interaction Effects Between eVTOL Rotors

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# Acknowledgements

This research was supported by Archer Aviation Inc., and the authors are grateful for continual support.

# Outline

- Introduction
- Overview of Study
- Prediction Method
- Experimental Validation
- Results
  - Thrust
  - Acoustics
- Summary and Conclusions

Fig 1. Visualization of the flow around the propeller in hover computed by DUST simulations

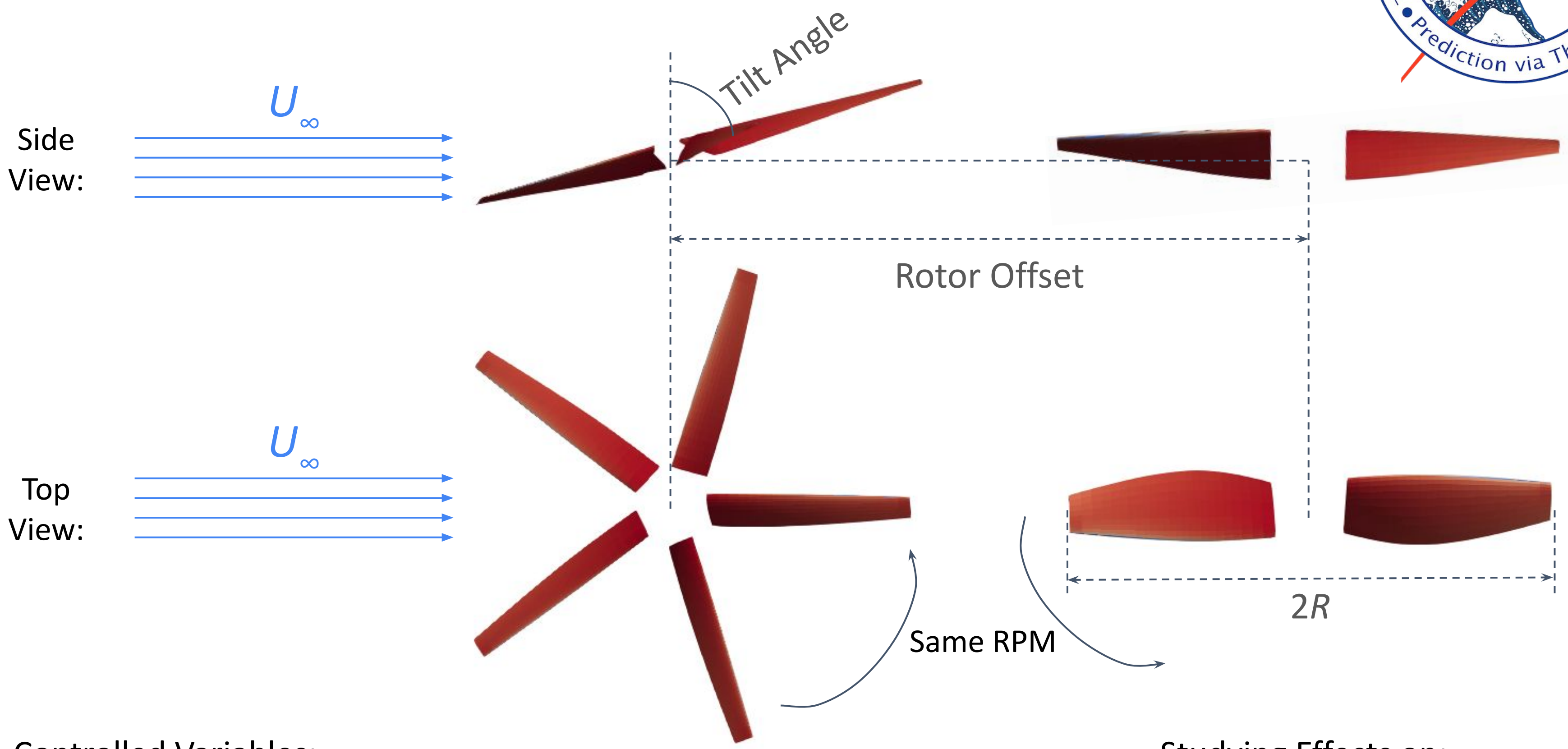
# Growth of eVTOL and sUAS

- Increase in demand for the use of electric motors and propellers to drive propulsors across a range of small air vehicle classes
- Applications of eVTOL and sUAS within urban environments
- Concern for increased urban noise pollution
- Effects of rotor configurations needs to be better understood to lower noise levels while maintaining flight characteristics

Fig 2. Archer's Maker aircraft (via. Archer.com).

Fig 3. Archer's Midnight aircraft (via. Archer.com).

# Overview of Study



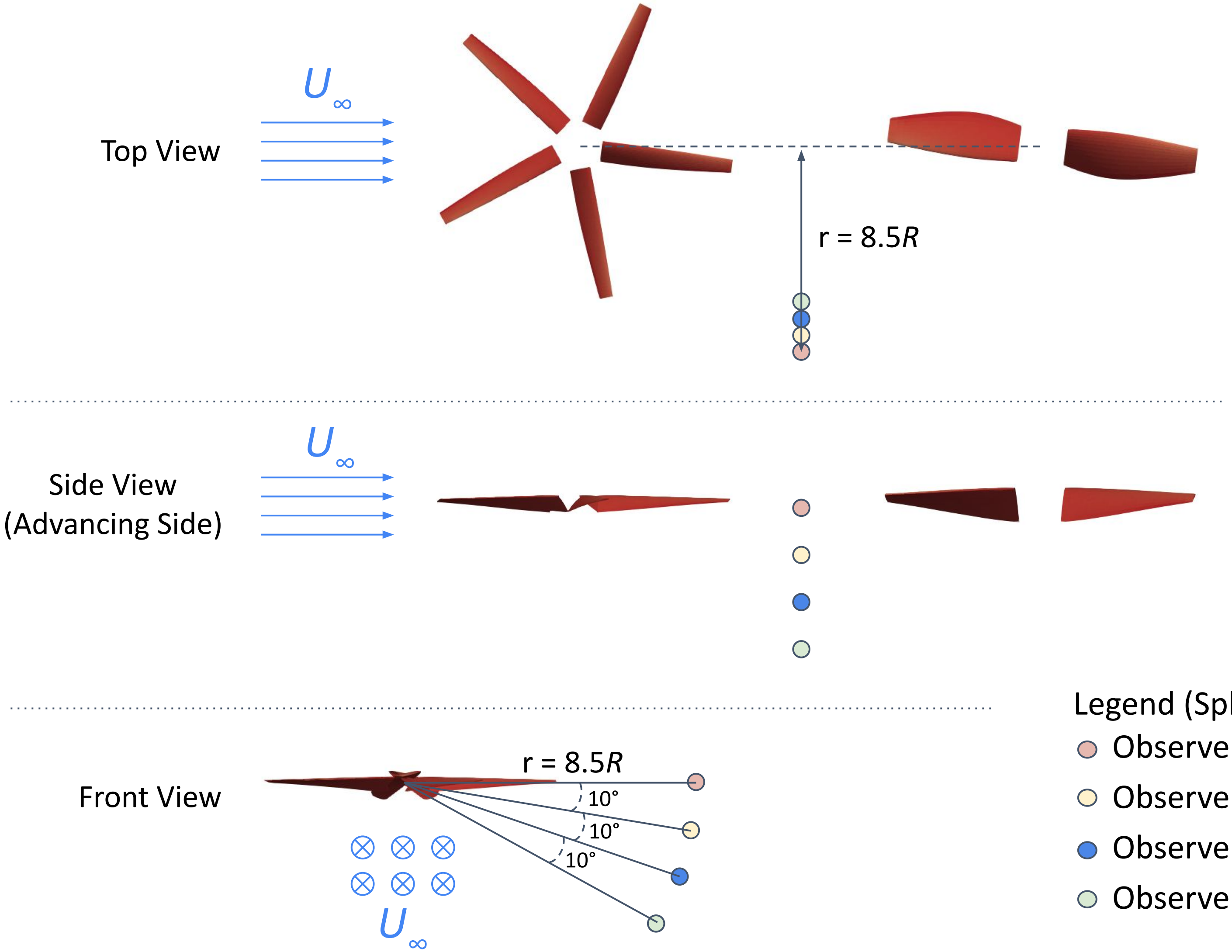

Controlled Variables:

- Tilt angle (60°, 70°, 80°, 90°)
- Rotor offset (2.5*R*, 3*R*, 3.5*R*, 4*R*, 4.5*R*)
- Free-stream velocity (0, 5, 10 m/s)

Studying Effects on:

- Individual Rotor Thrust
- Tonal Acoustic Radiation
    - SPL (@ 2-blade BPF)
    - OASPL

# Acoustic Observer Locations




Legend (Spherical Coordinates):

- Observer #1 (Φ = 270°, θ = 0°)
- Observer #2 (Φ = 270°, θ = -10°)
- Observer #3 (Φ = 270°, θ = -20°)
- Observer #4 (Φ = 270°, θ = -30°)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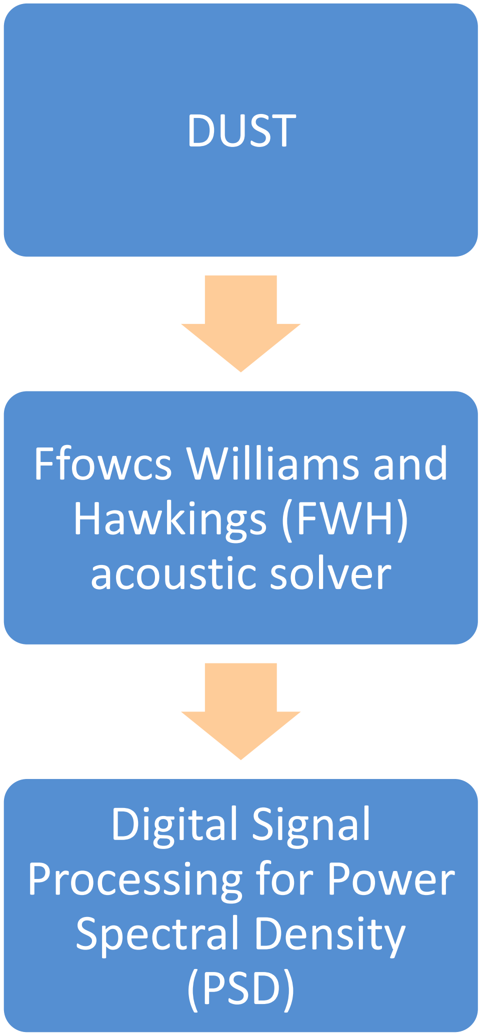
# Prediction Method

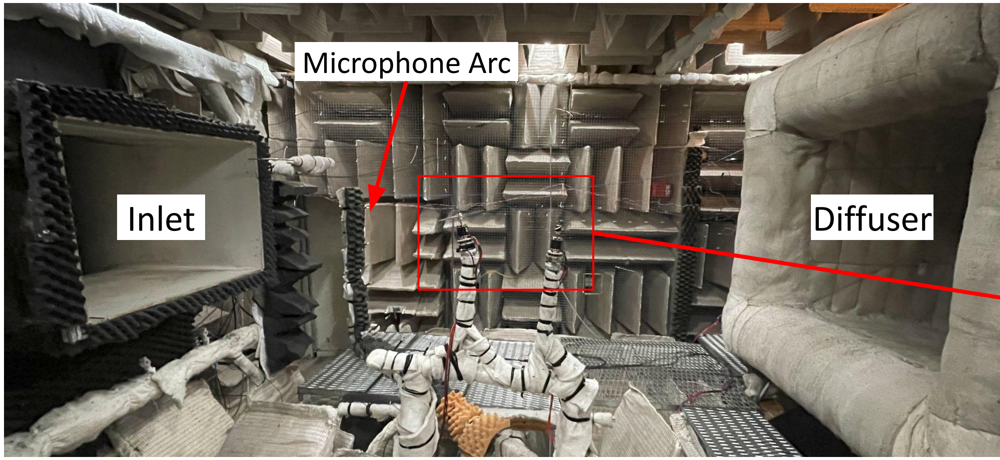



- Open-source flexible medium-fidelity aerodynamic solver, using a mixed boundary elements-vortex particles method (by Politecnico di Milano and $A^3$ by Airbus)
- Setup geometry and flight conditions
- Model aerodynamic flow-field

- Ffowcs-Williams and Hawkings Farassat 1A for acoustic prediction
- Predicts loading pressure, thickness pressure, and total pressure at observer locations as function of time

- Process time-domain data into spectra for direct comparison with measurement
- Validation and prediction of results

# Experimental Validation



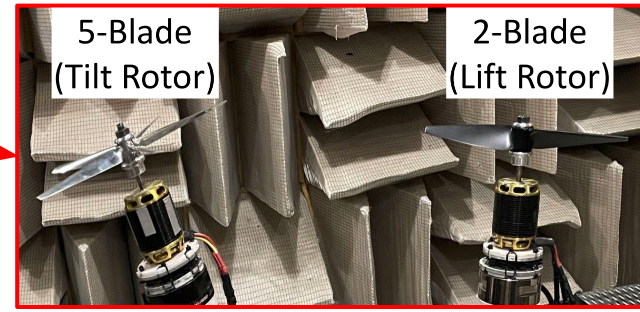




Fig 4. University of Florida's anechoic wind tunnel with dual rotor in tandem configuration set up.

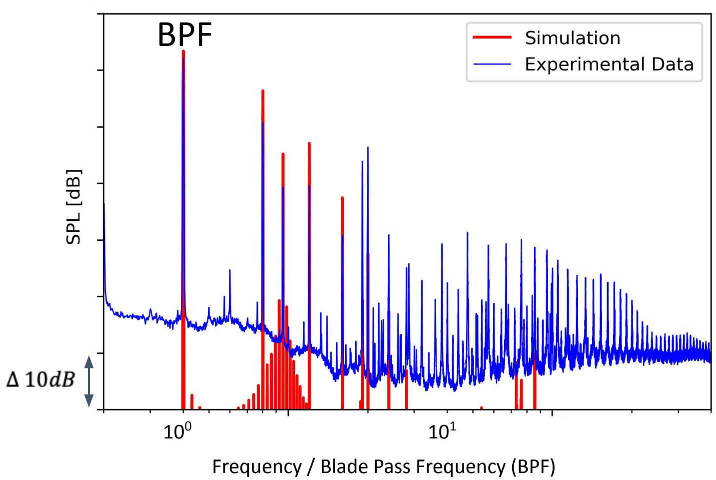



Fig 5. Dual rotor in tandem configuration, hover case ($U_\infty$= 0 m/s, Tilt = 90°).

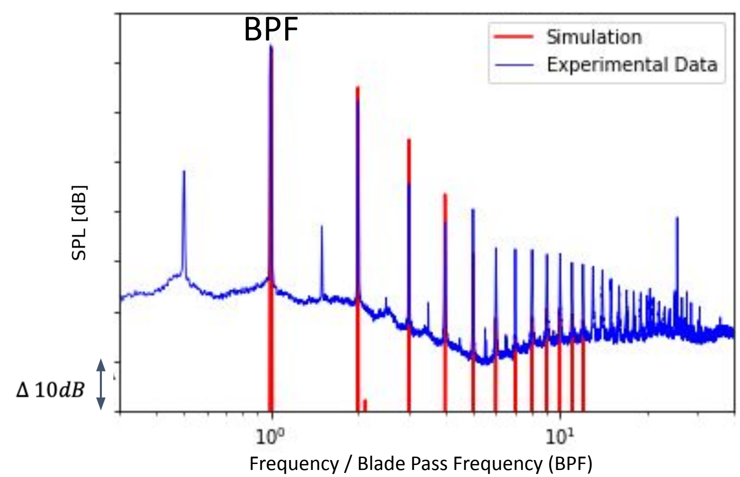
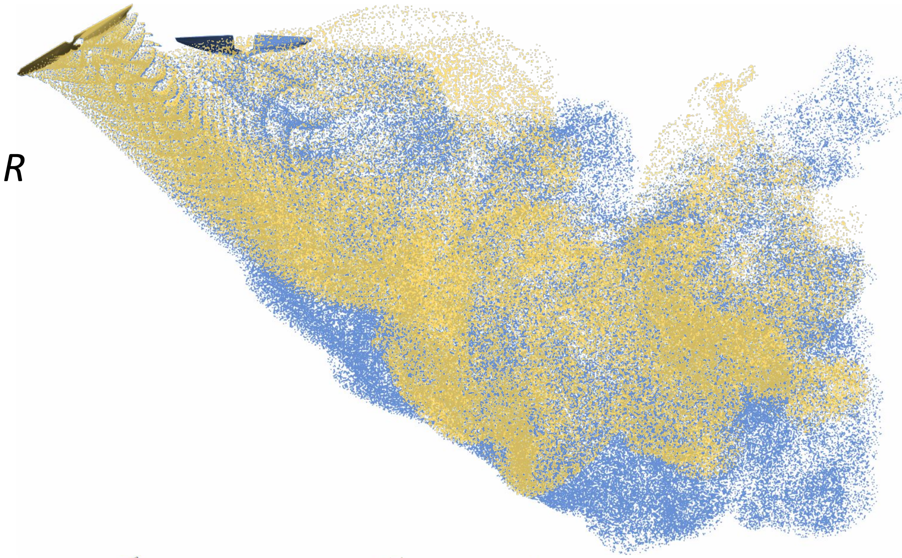



Fig 6. Isolated 2-blade rotor, hover case ($U_\infty$= 0 m/s).

# Predictions: 5-Blade Wake



Rotor Offset = 2.5$R$

Test Case:

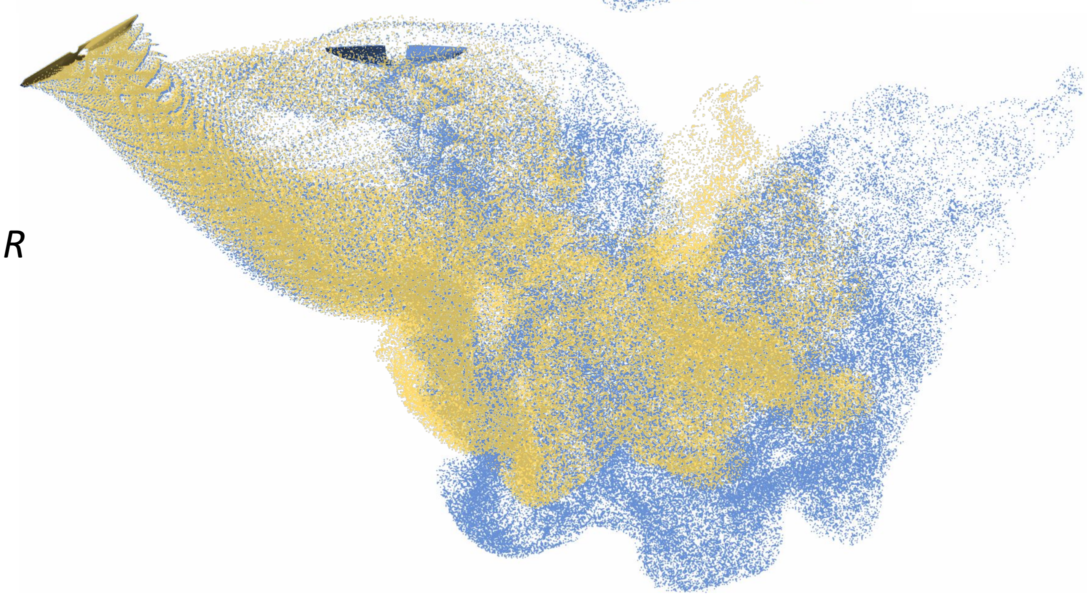
Tilt Angle = 60°

$U_\infty$ = 10 m/s

Legend:

Isolated 5-Blade Rotor

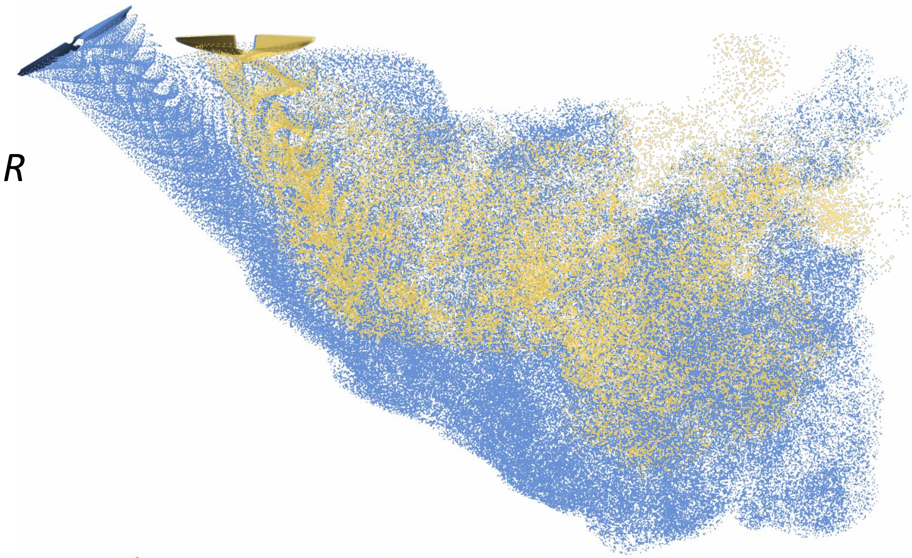
Tandem Dual Rotor



Rotor Offset = 4.5$R$

# Predictions: 2-Blade Wake

Rotor Offset = 2.5*R*



Test Case:

Tilt Angle = 60°

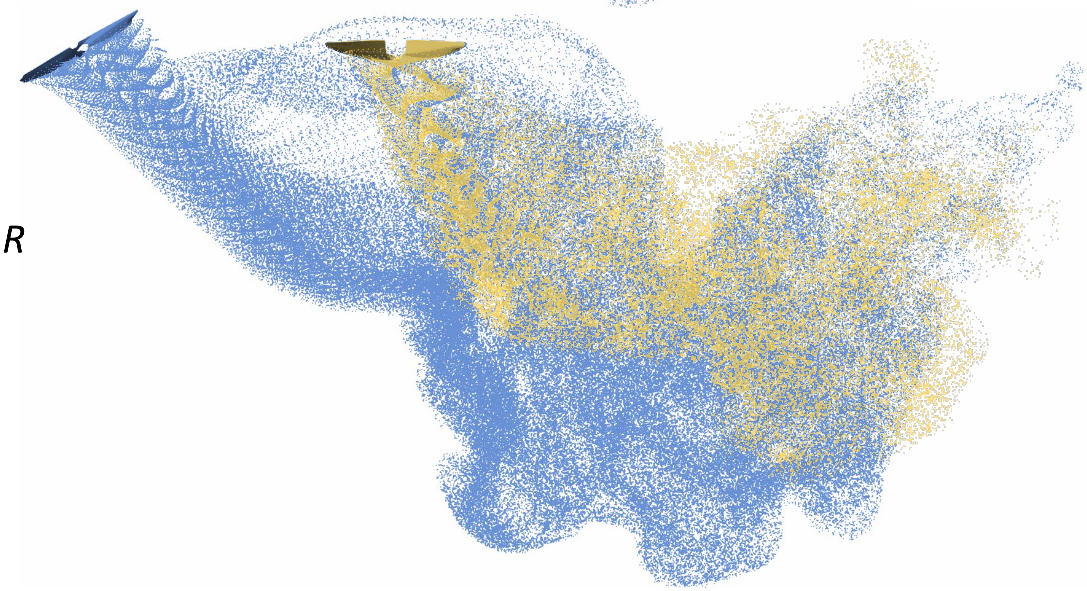
$U_{\infty}$ = 10 m/s

Legend:

Isolated 2-Blade Rotor

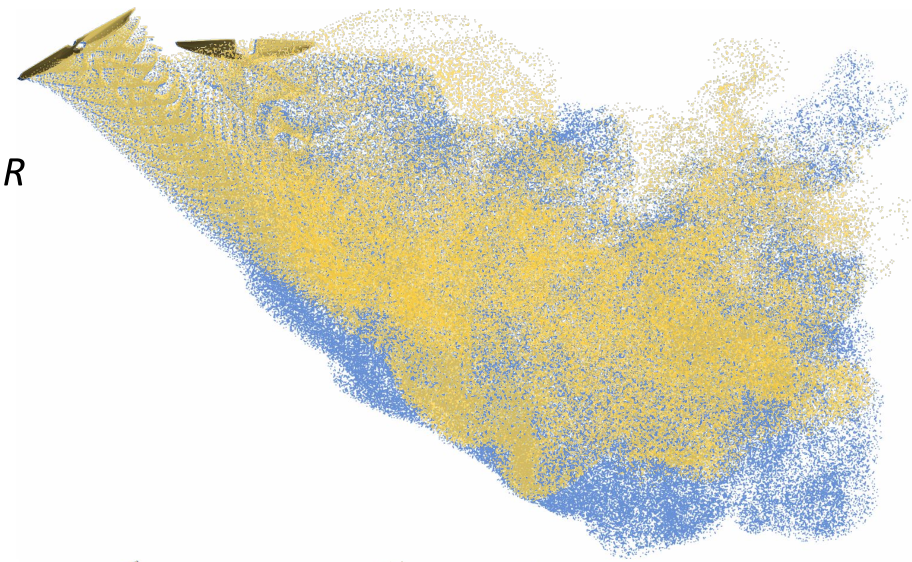
Tandem Dual Rotor

Rotor Offset = 4.5*R*



# Predictions: Combined Wake

Rotor Offset = 2.5*R*



Test Case:

Tilt Angle = 60°

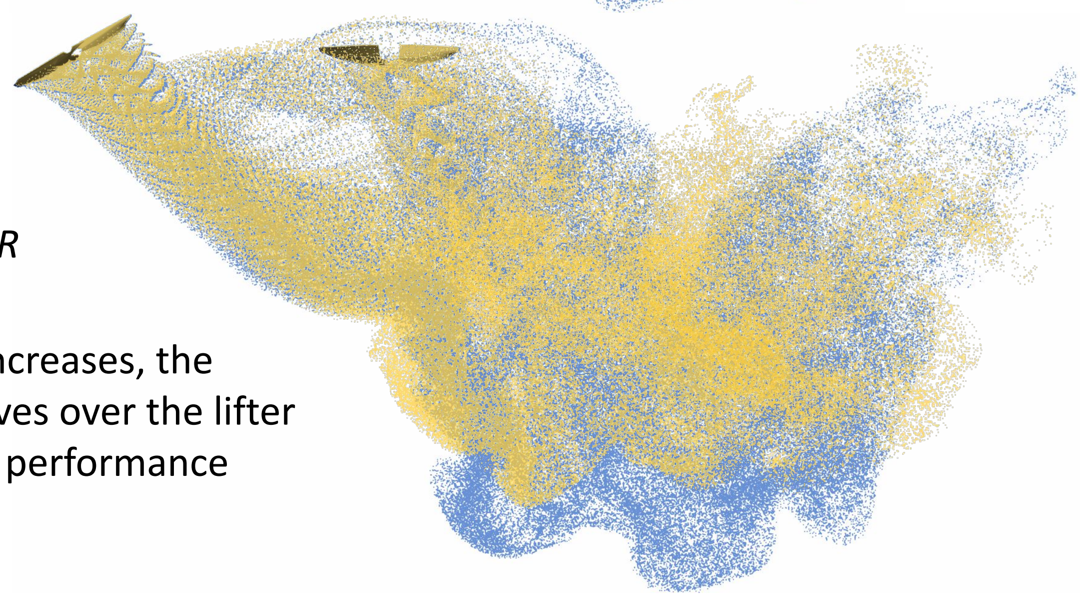
$U_\infty$ = 10 m/s

Legend:

Combined Isolated Rotors

Tandem Dual Rotor

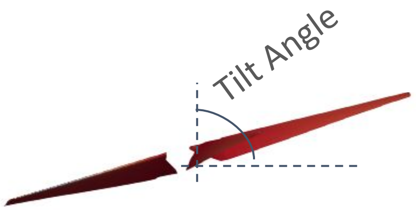
Rotor Offset = 4.5*R*



As rotor horizontal offset increases, the wake of the tilter rotor moves over the lifter rotor, impacting the lifter's performance and radiated noise

# Predictions: Thrust

- 2-blade rotor $C_T$ is mainly altered by tilt angle, unless it is at largest $U_\infty$
- At $U_\infty$ = 10 m/s, 2-blade % change in $C_T$ varies up to 5% depending on rotor offset
- Different tilt angles require a different rotor offset to maximize thrust



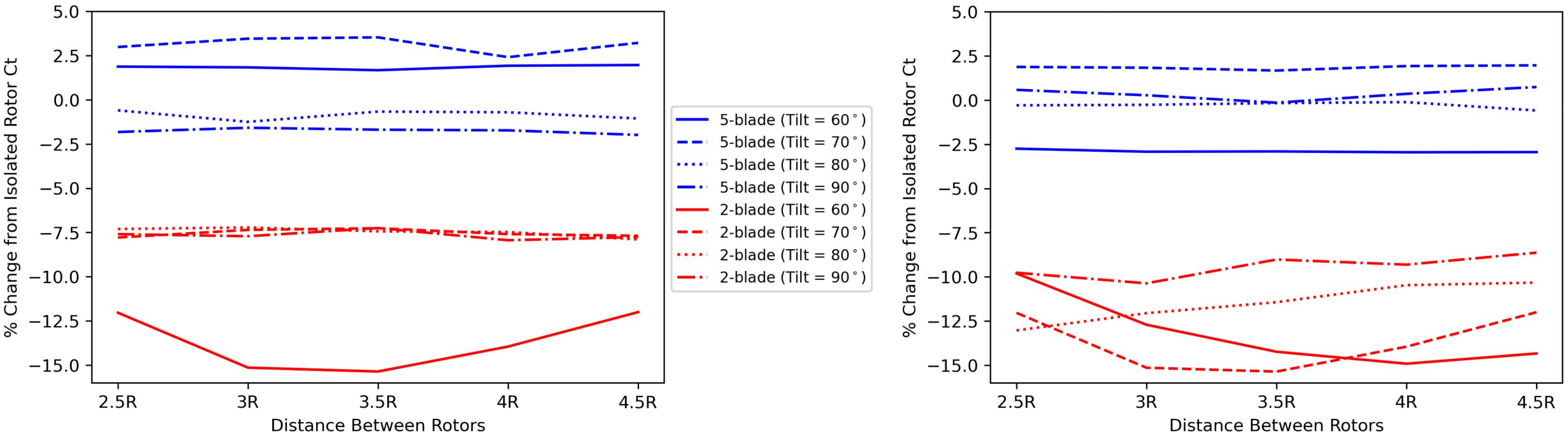
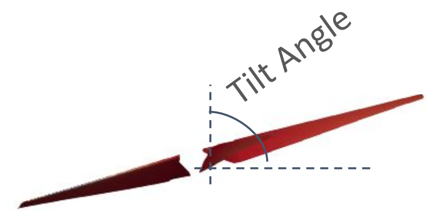




Fig 7. Percentage change in $C_T$ as a function of rotor offset at $U_\infty$= 0 m/s (left) and $U_\infty$= 10 m/s (right).

# Predictions: Thrust

- Rotor offset does not impact 5-blade rotor $C_T$ significantly
- For the 2-blade rotor, $C_T$ does not depend strongly on tilt angle, unless it is at the highest ambient velocity
- At tilt angle of 60° and an offset of 4.5$R$, 2-blade rotor thrust decreased by about 1.1% at 5 m/s and 7.2% at 10 m/s



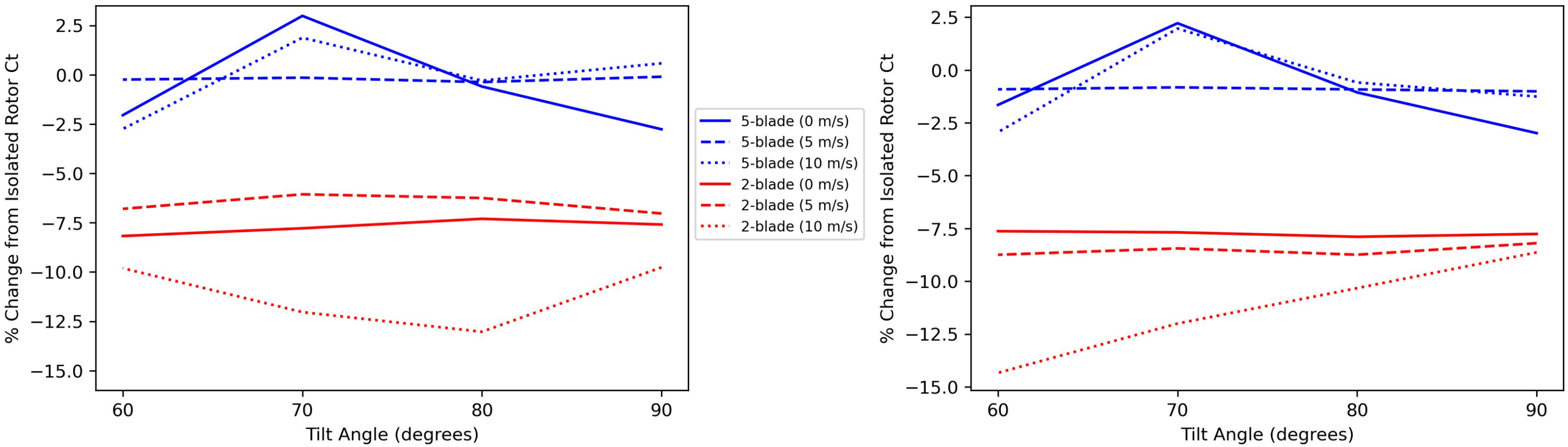




Fig 8. Percentage change in $C_T$ as a function of tilt angle with a rotor offset of 2.5$R$ (left) and 4.5$R$ (right).

# Predictions: Acoustics (SPL @ BPF)

- Thickness noise (dominated by the blade geometry) is responsible for SPL and OASPL changes in the rotor plane
- Little change when cruise speed is at 0 m/s
- At lower tilt angle, there is less effect of forward flight speed
- At high tilt angle and $U_\infty$ = 10 m/s, SPL increases 3.5 dB as rotor offset decreases from 4.5*R* to 2.5*R*
- A 7.8 dB decrease is observed when increasing $U_\infty$ from 0 to 10 m/s, at observer #4

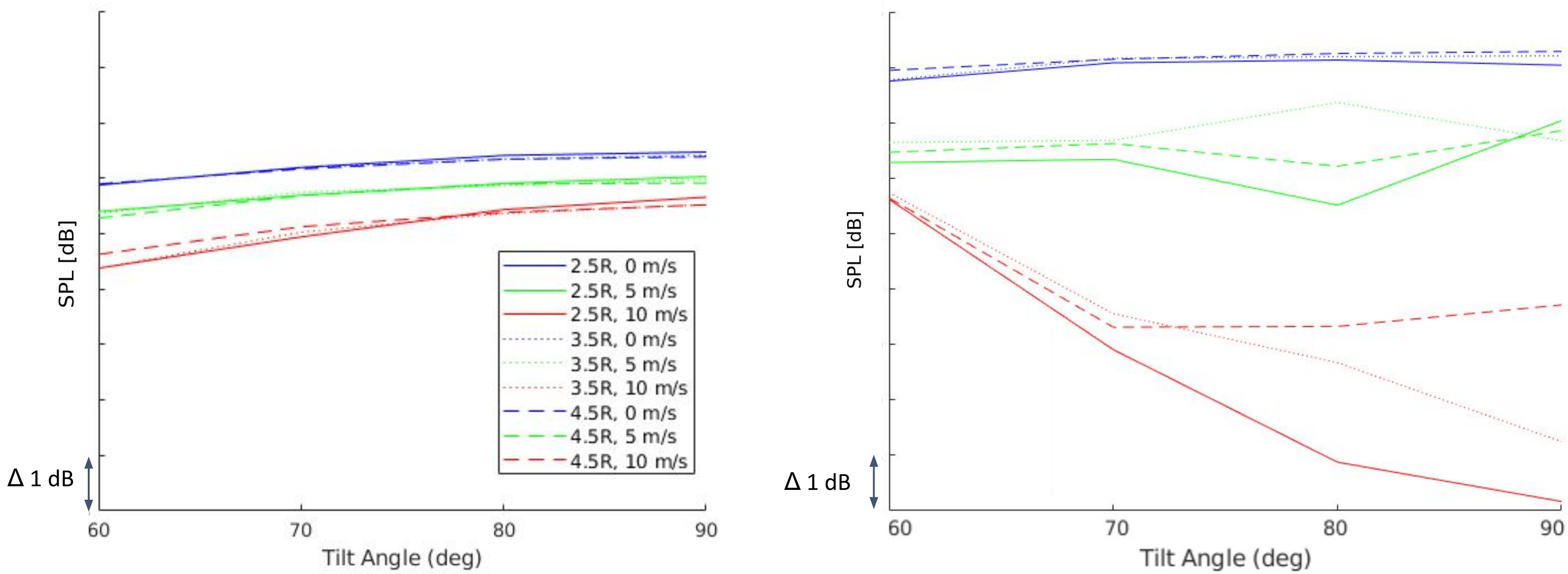



Fig 9. Sound pressure level at blade pass frequency (2-blade) for observer #1 (left) and observer #4 (right).

# Predictions: Acoustics (OASPL)

- OASPL is invariant with rotor offset
- OASPL decreases from 0.2 dB to 1 dB as tilt angle changes from 60° to 90°
- OASPL is lowest at 10 m/s as it produces 2-2.5 dB lower than at hover at different observer locations

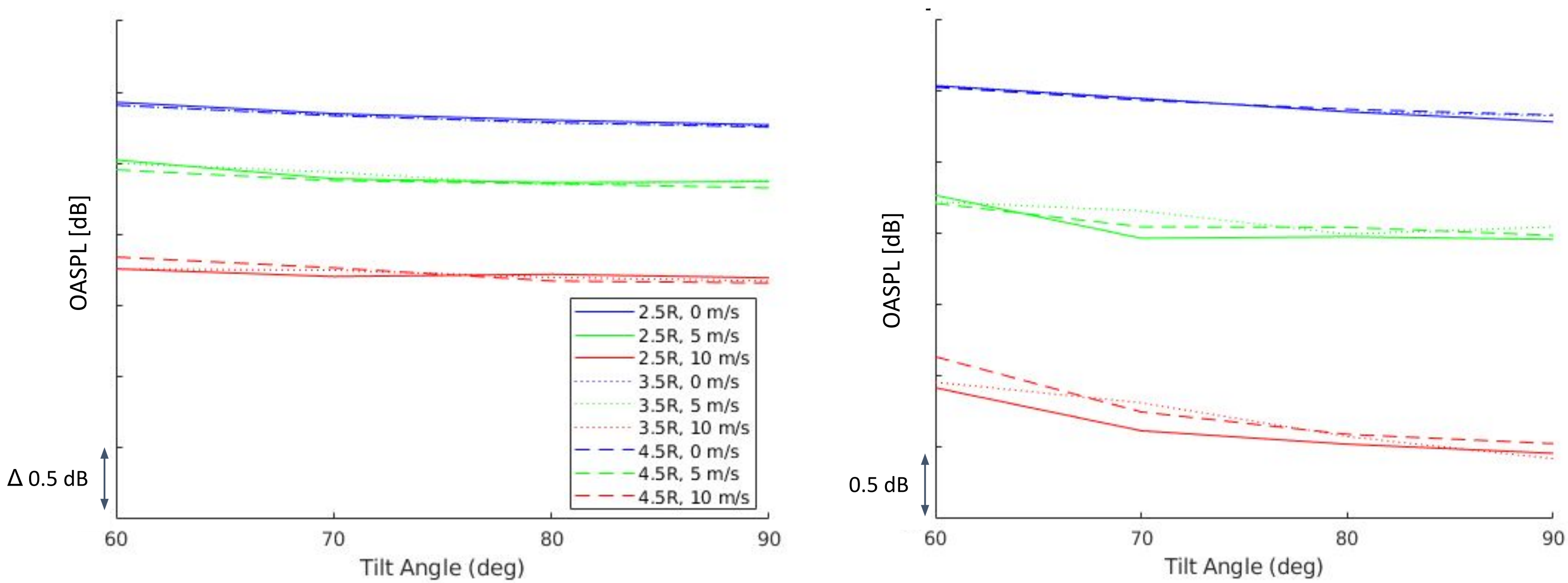



Fig 10. Overall sound pressure level for observer #1 (left) and observer #4 (right).

# Conclusions

**Thrust:**

- 5-Blade rotor $C_T$ is primarily impacted by the tilt angle; a ±3.5% change in thrust is observed, depending on the tilt angle.
- Under low cruise speeds, 2-blade rotor $C_T$ only varies under low tilt angles
- Under cruise speeds of 10 m/s, 2-blade rotor $C_T$ decreases up to 5% depending on the combination of tilt angle and rotor offset

**Acoustics:**

- The SPL at the BPF is primarily affected by cruise speed and tilt angle
    - Little change is observed across all predictions when $U_\infty$ = 0 m/s
    - Always decreases substantially as cruise speed increases (2 dB to 7.5 dB decrease as cruise speed is increased by 10 m/s, depending on tilt angle)
    - Rotor offset only impacts SPL under high cruise speeds and high tilt angles
- OASPL is mainly only affected by cruise speed
    - Does not vary with rotor offset
    - Always lower at higher cruise speeds
    - Higher tilt angles can lower OASPL up to 1 dB

# Future Work

- Expand variable pool to include:
    - Vertical rotor offsets
    - Different RPM for different rotors
    - Rotor rotation directions (CCW vs CW)
- Include different rotor configurations (e.g. side-by-side)
- Identifying acoustic trends in different flight conditions when keeping thrust constant

# Thank you – Questions?