Aeroacoustic and Aerodynamic Interaction Effects Between eVTOL Rotors

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I thank my parents and brother for their loving encouragement, sacrifices, and support that have led me here today.

Outline

- Introduction & Motivation
- Thesis' Objectives
- Numerical Method
- Experimental Validation
- Overview of Study
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    - Thrust
    - Acoustics
- Conclusions
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    - Future Work

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 necessary flight characteristics


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


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

Fig 4. S4 by Joby Aviation (via. JobyAviation.com).


Fig 5. Vahana by A^3 by Airbus (via. Acubed.Airbus.com).

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Literature Review

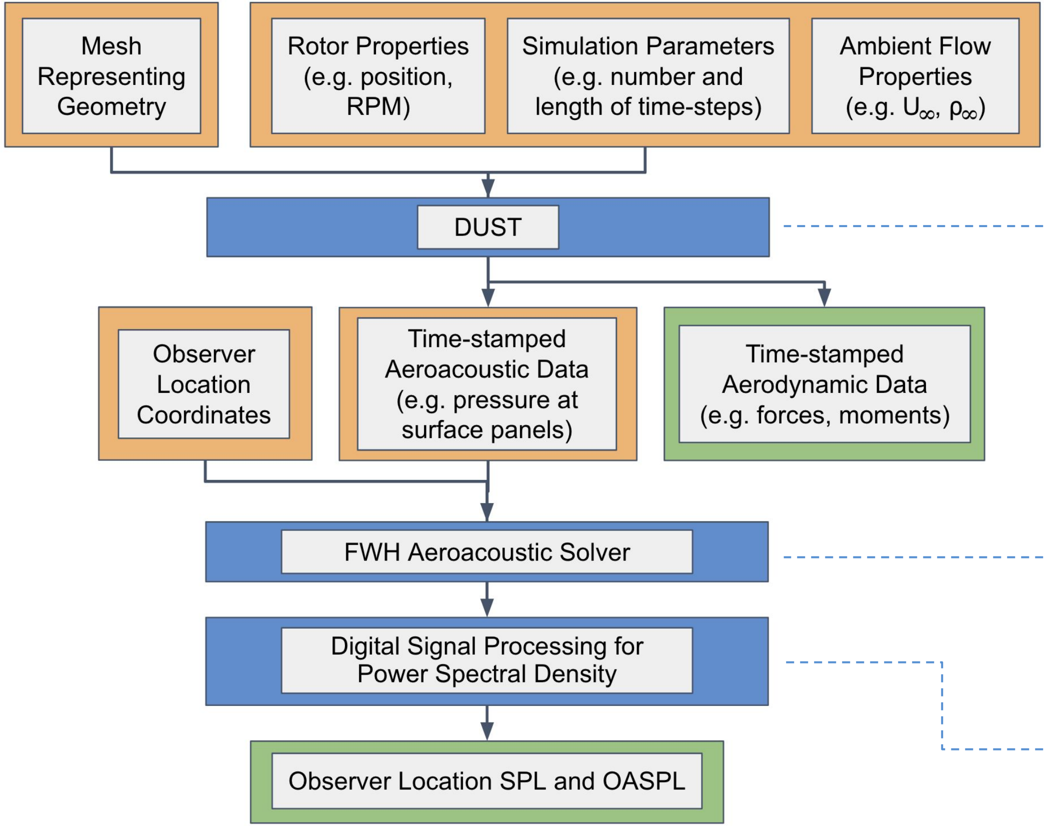
Despite having been around for decades, rotorcraft research lacks:

- Capturing rotor-rotor interactions
  - Extensive research of isolated propellers (e.g. helicopter rotors)
- Focusing on edgewise flight
  - Critical to understanding noise emissions in eVTOL configurations
- Investigating rotor-rotor interaction across a range of eVTOL flight conditions
  - E.g. varying rotor angles, flight speeds, and RPMs
- Investigating complex eVTOL configurations
  - E.g. Different rotor offsets, rotor distributions, and rotor/wing interactions

Thesis' Objectives

- Validate and highlight the significance of using mid-fidelity tools, like DUST, in systematic studies and preliminary design
- Provide a comprehensive investigation of rotor-rotor interactions across a range of flight conditions
- Address limitations of certain rotor configurations, and provide insights into how the aircraft's performance can be improved
- Help accelerate the development of eVTOL aircraft and enable the design of more efficient and safe vehicles

Prediction Method



- Open-source flexible medium-fidelity aerodynamic solver (by Politecnico di Milano and A^3 by Airbus)
- Model aerodynamic flow-field

- Ffowcs-Williams and Hawkings Farassat 1A formulation 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

DUST

- Promotes a fast and reliable method to obtain flow-field around complex bodies
  - Models 3D bodies by combined integrating thick surface panels, zero-thickness lifting surfaces, thin vortex lattices, and lifting lines
  - Models wakes using wake panels and vortex particles
  - Simulates interactive behaviour using Fast Multipole Method (FMM)
- Algorithm is based on the Helmholtz decomposition of the velocity field: $\vec{u} = \overrightarrow{u_\phi} + \overrightarrow{u_\psi}$
  - Solution progresses through time steps by alternating between a three-dimensional boundary element method for $\overrightarrow{u_\phi}$ and the Lagrangian evolution in time for $\overrightarrow{u_\psi}$

FWH Acoustic Solver

- Used to propagate the pressure from the surface panels (noise sources) to the far-field
  - Uses the Farassat 1A formulation, an extension to the Ffowcs-Williams Hawkings equation
- A retarded time algorithm is used to march in time at the observer location
  - This time is calculated by tracing the sound signal back to the surfaces
  - Quantities are interpolated to match DUST's sample time data
- Total acoustic pressure fluctuation is acquired by summing all of the panels' contributions
  - This results in the loading pressure, thickness pressure, and total pressure at observer locations as function of time
- Digital Signal Processing for Power Spectral Density (PSD) is performed

Surface Mesh Generation

- Quadrilateral surface panels are used to represent the rotors' bodies
- Mesh size study is performed to find an optimum number of chordwise and spanwise panels
  - Find an appropriate balance between required computational power and results accuracy

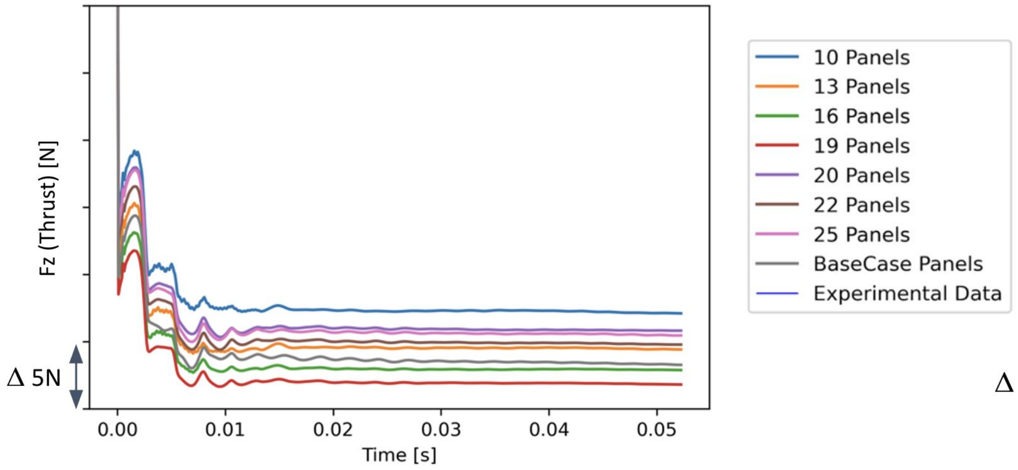


Fig 6. Spanwise mesh size study for thrust.

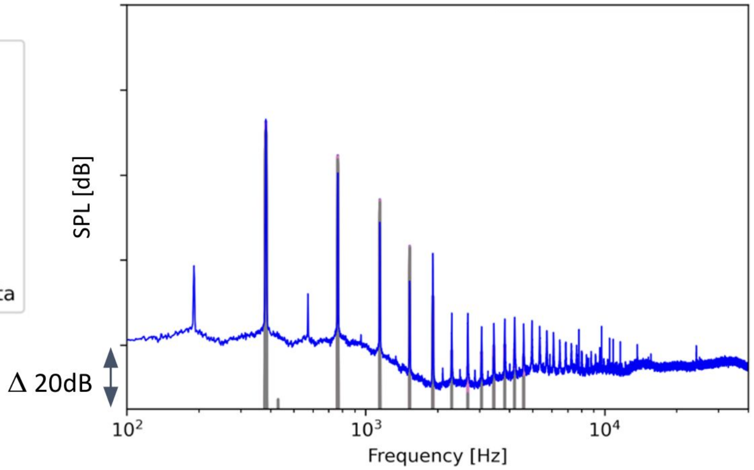


Fig 7. Spanwise mesh size study for SPL.

Surface Mesh Generation

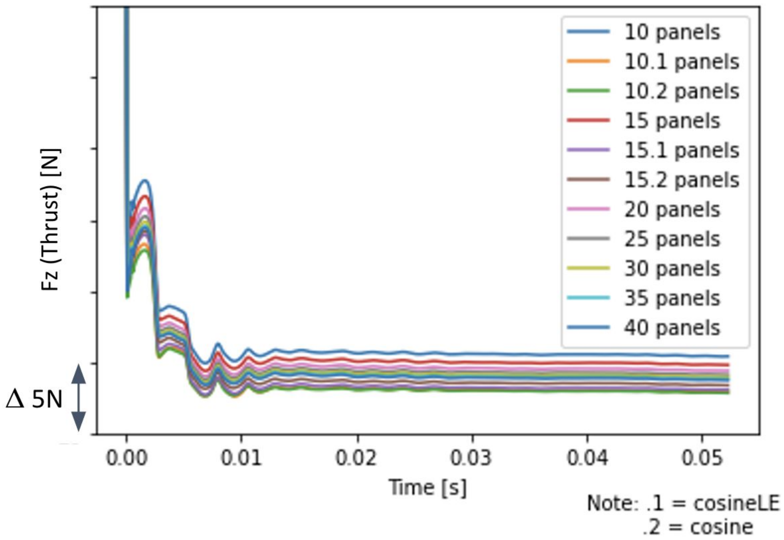


Fig 8. Chordwise mesh size study for thrust.

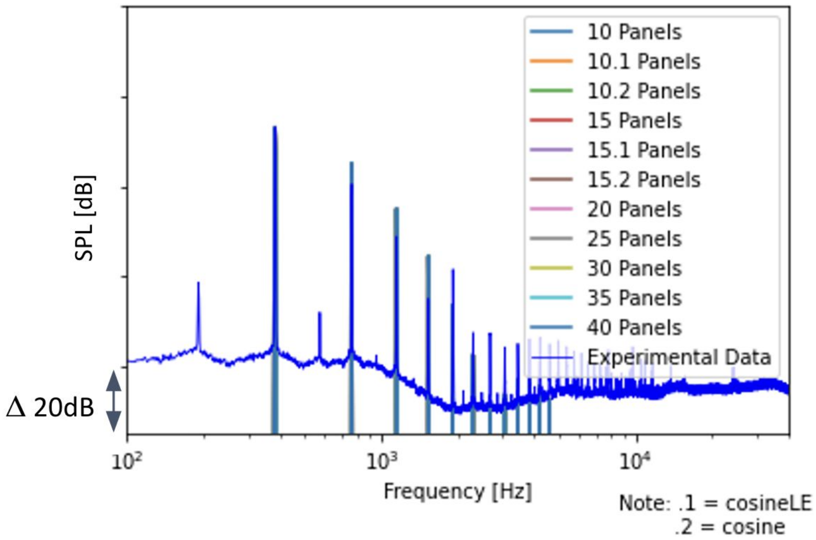


Fig 9. Chordwise mesh size study for SPL.

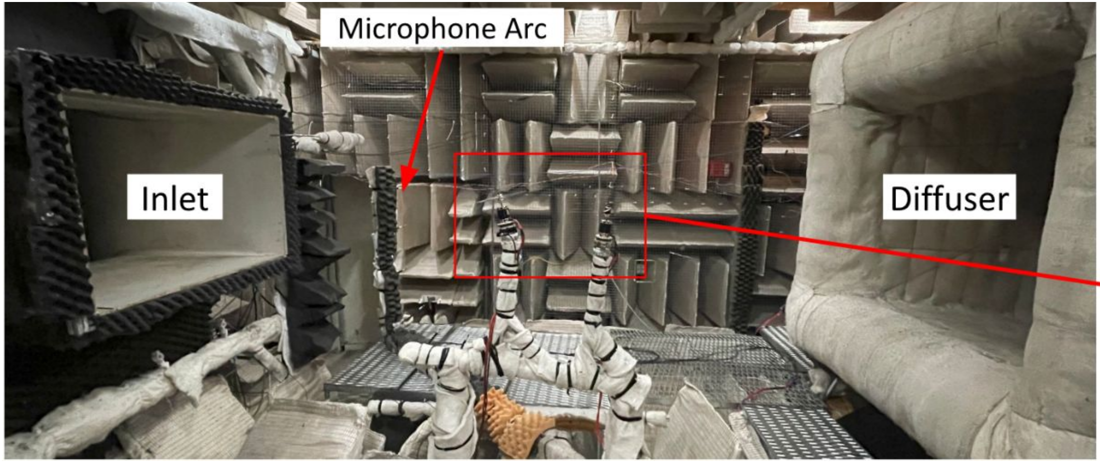
Surface Mesh Generation

- Surface mesh size study results:
  - Spanwise: change of up to 6.5% in thrust and 7% in SPL at the BPF
  - Chordwise: change of up to 7% in thrust, but negligible change in SPL at the BPF
- A mesh size of 13 chordwise (cosine LE distribution) and 25 spanwise panels was chosen
  - Dual rotor simulation took approximately 45 minutes
    - Single-processor 11th generation Intel Core i7-11700K at 3.60 GHz with 32GB of RAM

Fig 10. Top view of mesh used to represent 2-blade rotor

Experimental Validation

- Validation performed by comparison with experimental data
  - Both isolated rotors and the dual rotor configuration were validated
  - Hover and forward flight conditions were validated
  - Coefficient of thrust (c_T), SPL at the BPF, and OASPL were measured and compared



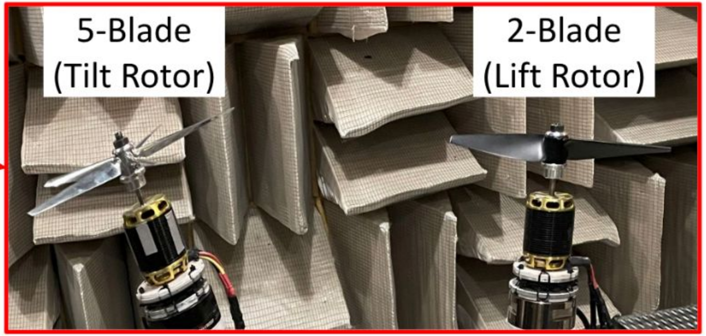


Fig 11. University of Florida's anechoic wind tunnel with dual rotor in tandem configuration set up.

Experimental Validation

- c_T is calculated using steady state range
- ±1% in c_T is observed in low free-stream velocity (< 15 m/s) flows
- Larger errors are observed with flows involving speeds larger than 20 m/s (consistent with literature)

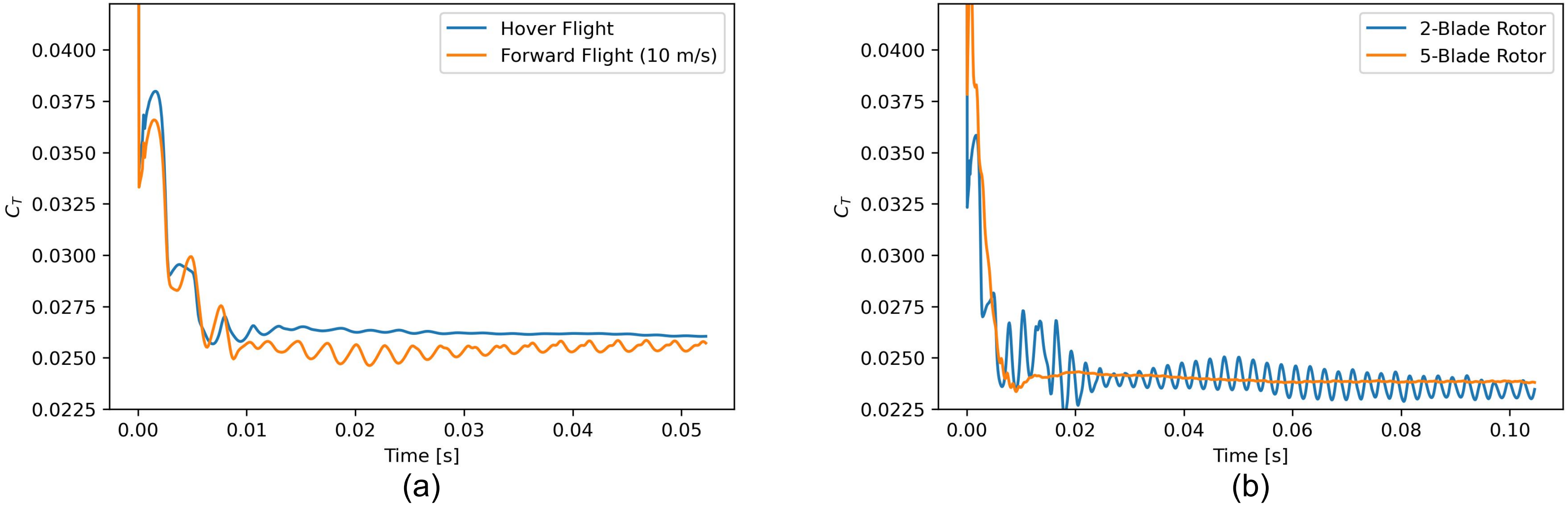


Fig 12. Time histories of the c_T for the (a) 2-blade rotor in hover and forward flight conditions and for the (b) dual rotor system in forward flight conditions.

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Experimental Validation

- SPL is measured at the BPF; OASPL is acquired by integrating the SPL data
- SPL at the BPF and OASPL are in good agreement in low free-stream velocity cases
  - SPL at the BPF ΔdB is within 1.5 dB and OASPL ΔdB is within 2.0 dB

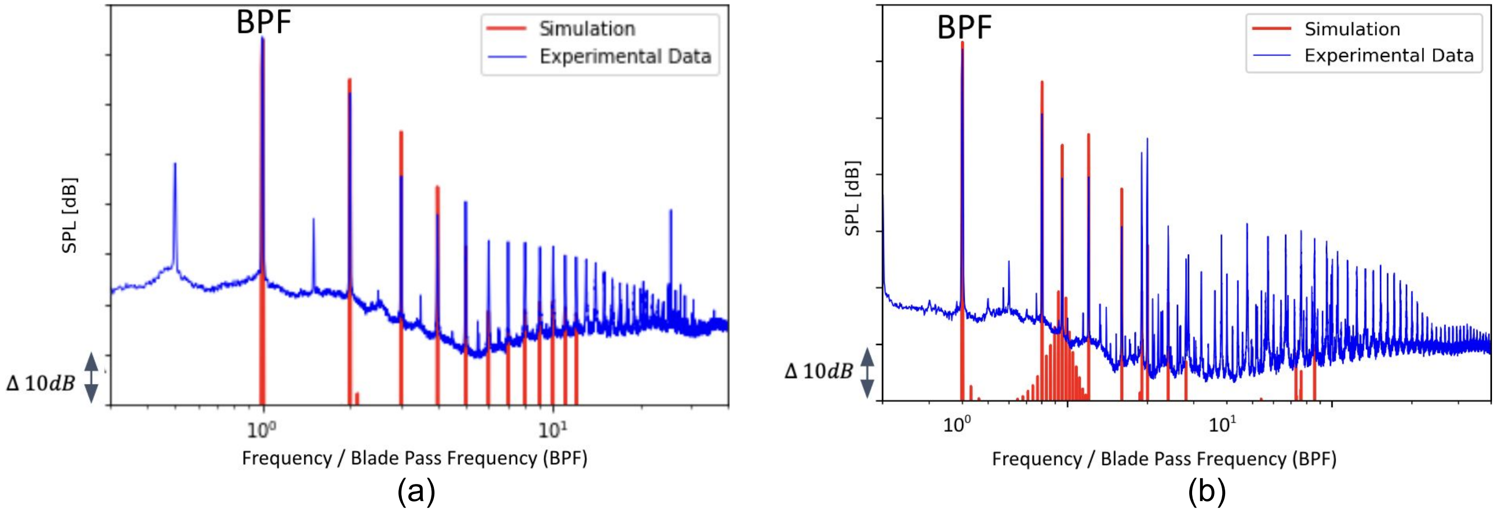

Fig 13. Comparison of SPL at BPF in the frequency spectra between the simulation and experimental data. (a) 2-blade rotor in hover and (b) the dual rotor system in hover. BPF refers to the 2-blade BPF.

Overview of Study

- Study aerodynamic and aeroacoustic interactive effects between sub-scale eVTOL rotors
- Configuration used is based on Archer's Maker, a prototype aircraft

Fig 14. Archer's Maker aircraft in forward flight configuration during a test flight.

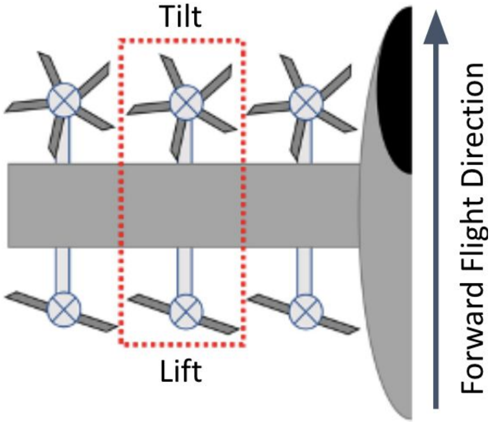

Fig 15. Simplified rotor configuration outlined by red box

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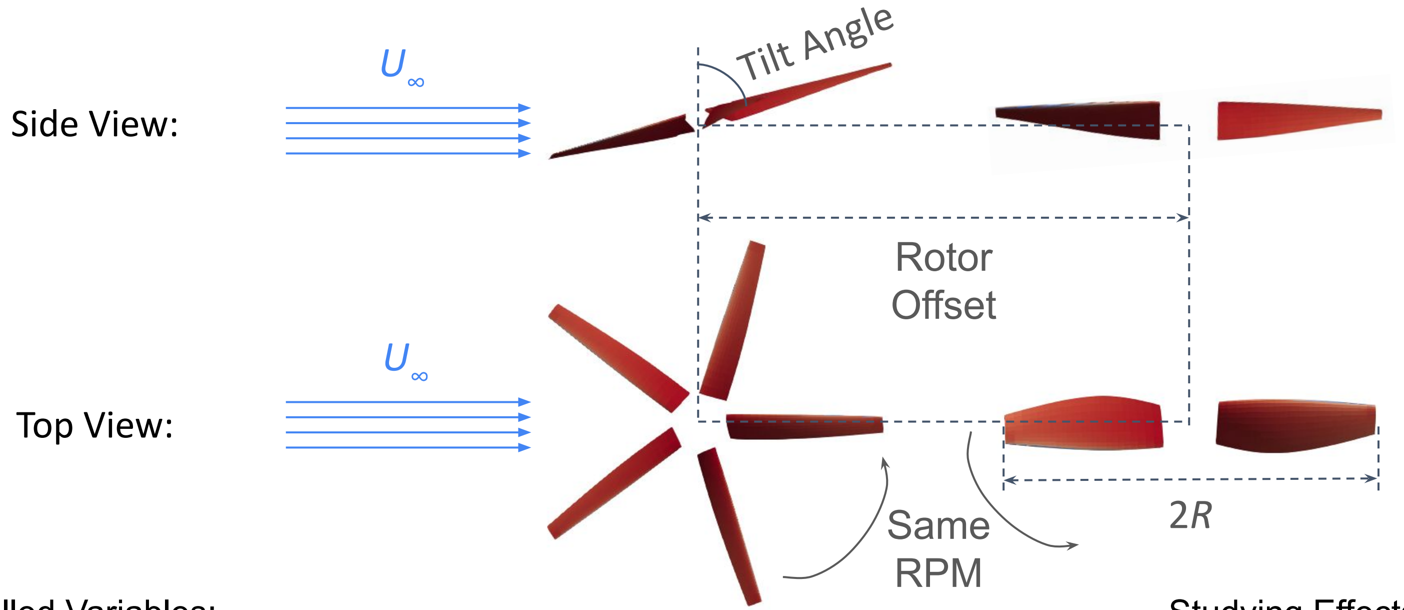
Overview of Study



Controlled Variables:

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

Studying Effects on:

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

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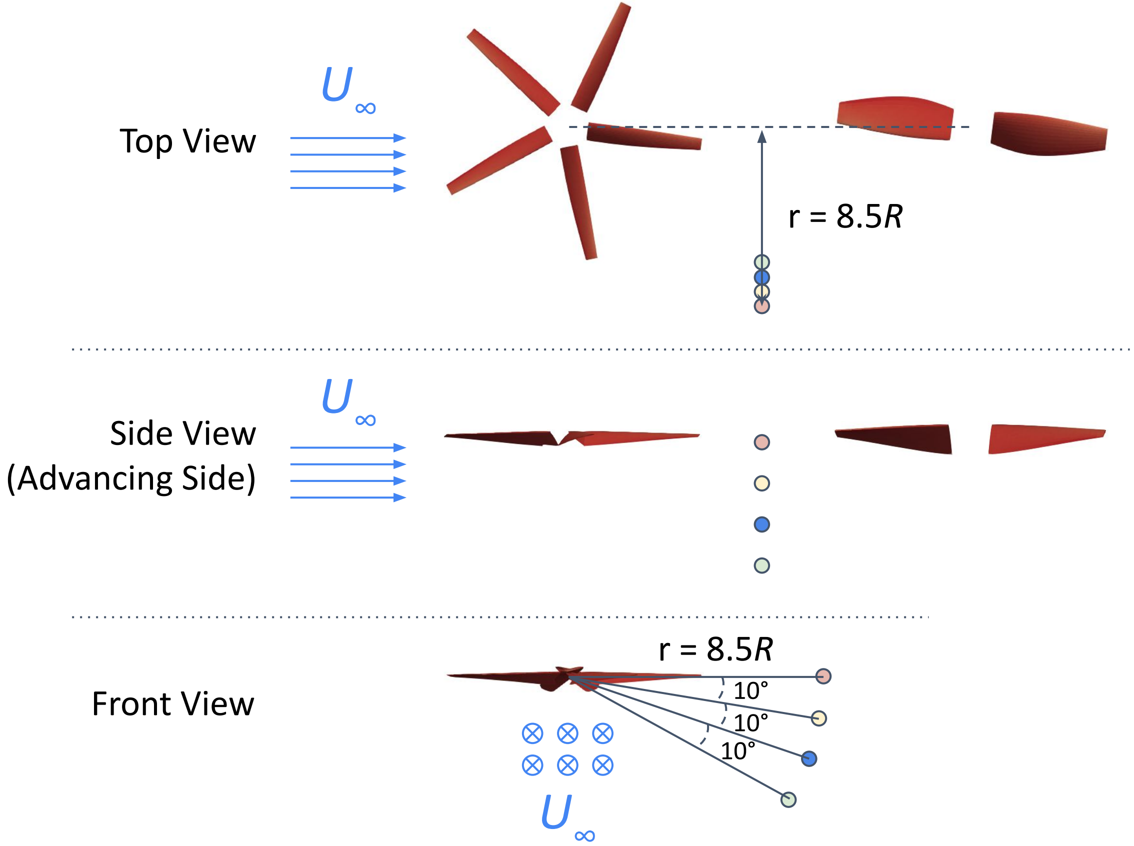
Acoustic Observer Locations

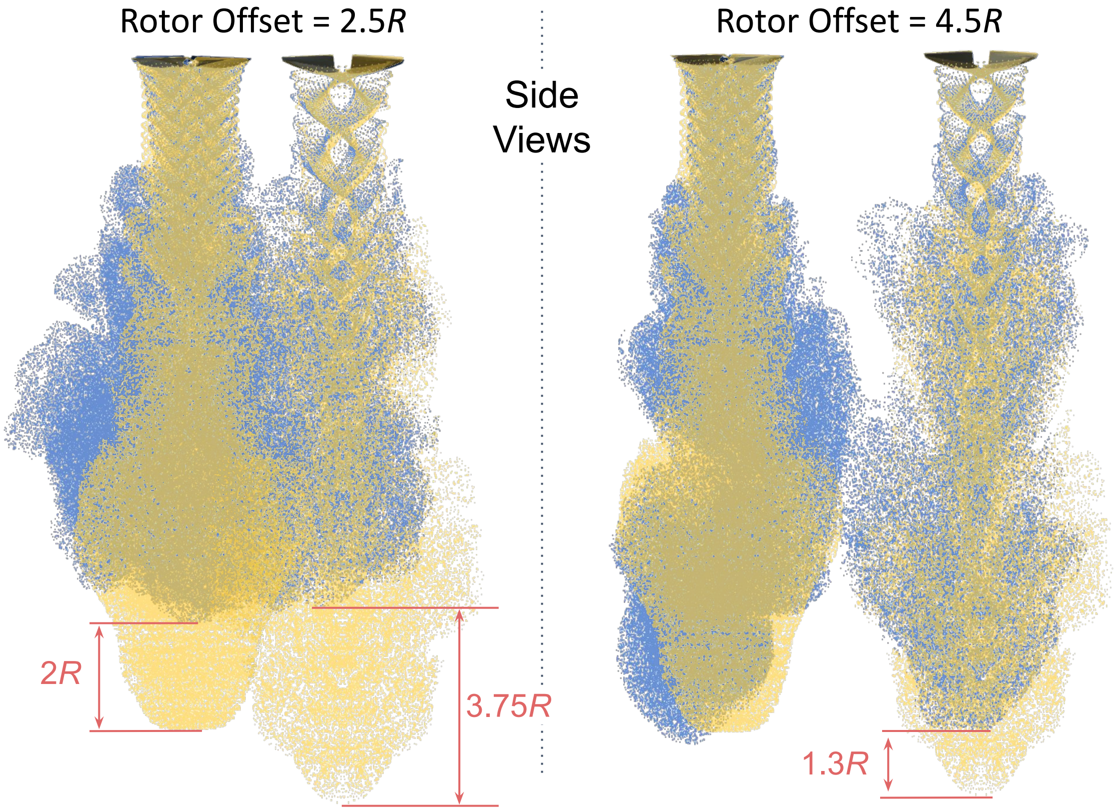


Legend (Spherical Coordinates):

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

Prediction: Wakes

Test Case: Hover (θ_{tilt} = 90°, U_∞ = 0 m/s)



Legend:

Combined Isolated Rotors (Non-Interactive)

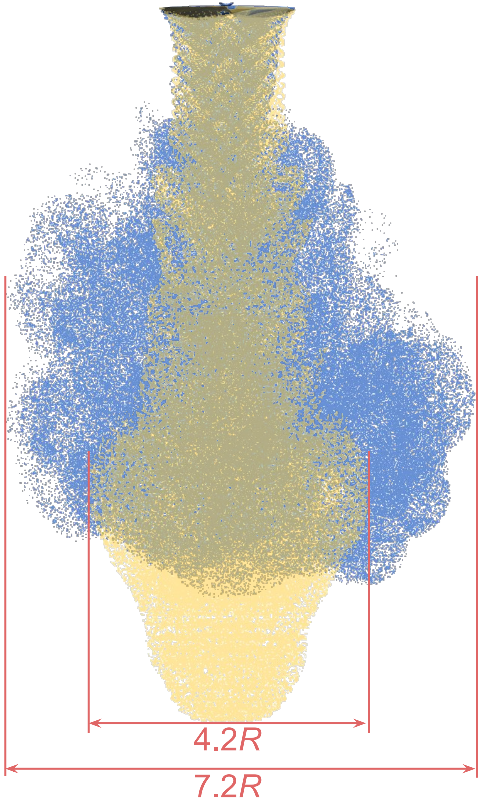
Tandem Dual Rotor (Interactive)

- In both cases, the wakes develop unaffected for a distance of about 2*R*
- Low pressure region forces wakes together, impacting their vertical and horizontal spreads
- Larger offset results in less interactions for the hover case

Prediction: Wakes

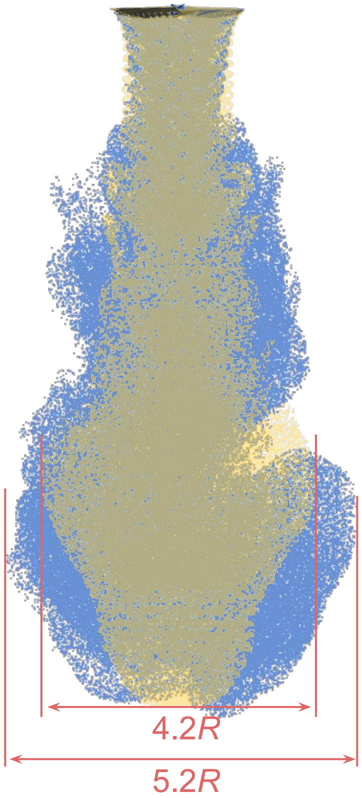
Test Case: Hover (θ_{tilt}= 90°, U_∞ = 0 m/s)

Rotor Offset = 2.5*R*



Front Views

Rotor Offset = 4.5*R*



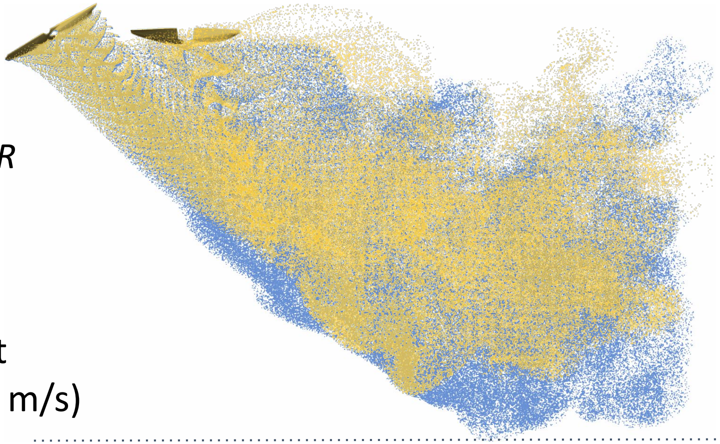
Legend:

- Combined Isolated Rotors (Non-Interactive)
- Tandem Dual Rotor (Interactive)

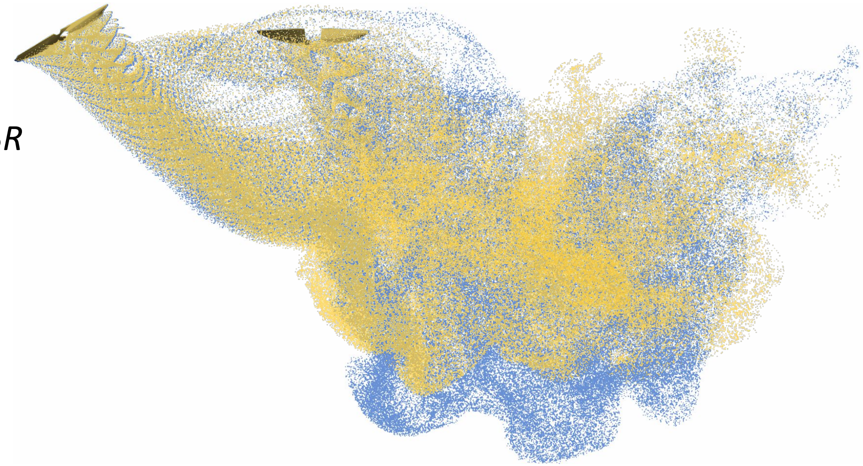
- Larger offset results in less interactions for the hover case
- The system's wake becomes wider as the rotors come closer together
- At 4.5*R*, wake interactions still exist, but are minimal

Prediction: Wakes

Rotor Offset = 2.5R



Test Case:
Forward Flight
(θ_{tilt} = 60°, U_∞ = 10 m/s)



Rotor Offset = 4.5R

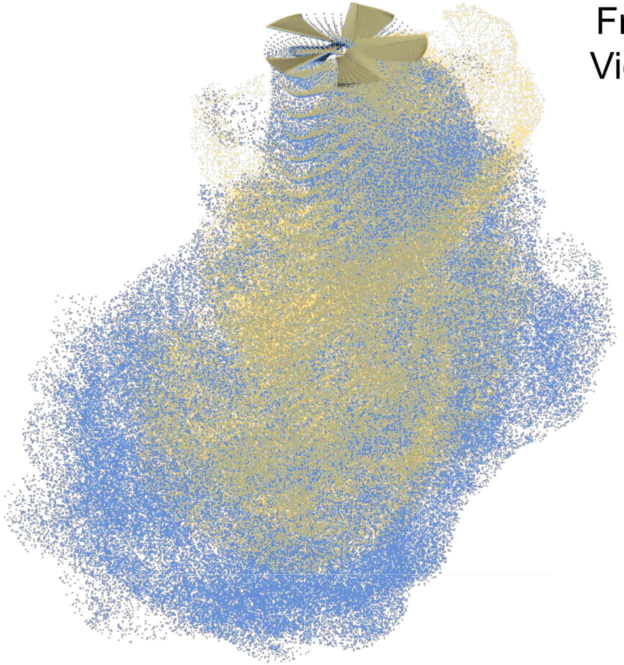
Legend:
Combined Isolated Rotors (Non-Interactive)
Tandem Dual Rotor (Interactive)

- Interaction is hard to avoid due to flight conditions
- Interaction effects seem to worsen as offset increases
  - Lower wake boundary becomes less smooth
- Tilter's wake is fed into lifter's inlet more as rotor offset increases

Prediction: Wakes

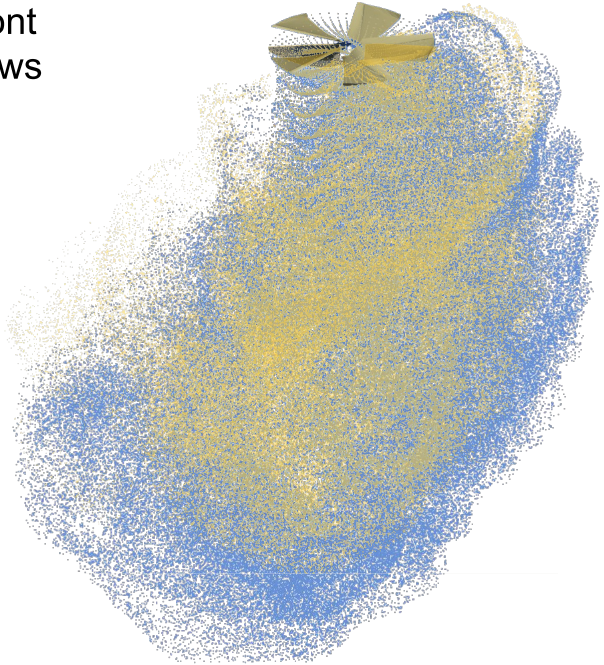
Test Case: Forward Flight (θ_{tilt} = 60°, U_{∞} = 10 m/s)

Rotor Offset = 2.5*R*



Front Views

Rotor Offset = 4.5*R*



Legend:

Combined Isolated Rotors (Non-Interactive)

Tandem Dual Rotor (Interactive)

- System's wake does not seem to become significantly wider as offset changes
- At 2.5*R*, wake seems to widen much lower than rotor plane

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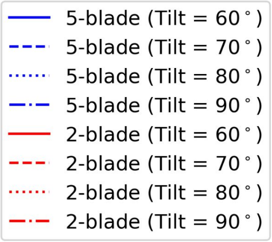
Prediction: Thrust

- 2-blade rotor c_T is mainly altered by tilt angle, unless it is at largest U_∞
- Lifter's c_T decreases by 6% and 15% in the best and worst case scenarios, respectively.
- At U_∞ = 10 m/s, lifter's c_T varies up to 5% depending on rotor offset and up to 6.5% depending on tilt angle
- Different tilt angles require a different rotor offset to maximize thrust



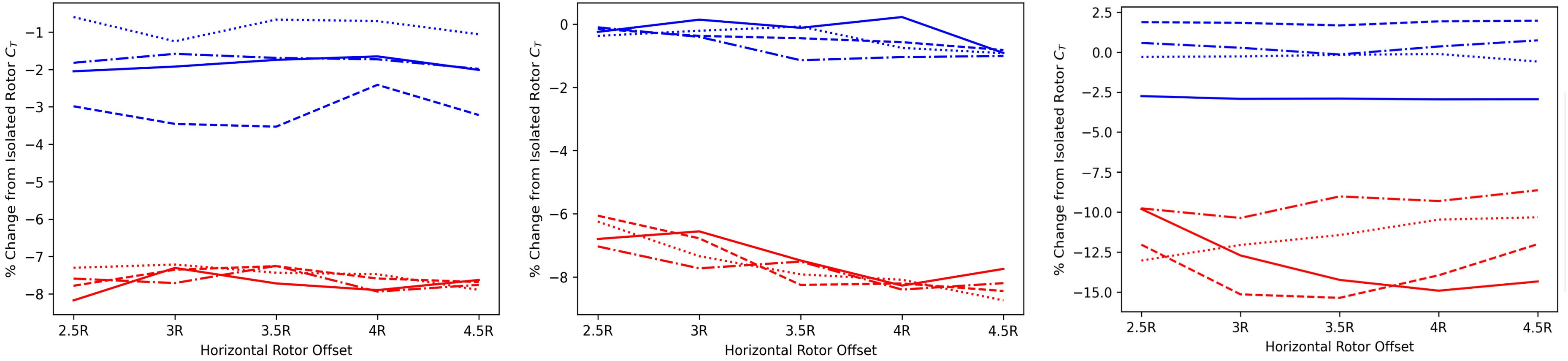
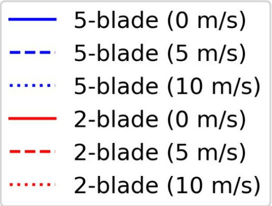


Fig 16. Percentage change in C_T as a function of rotor offset at U_∞= 0 m/s (left), U_∞= 5 m/s (center), and U_∞= 10 m/s (right).

Prediction: 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 relative to hover condition



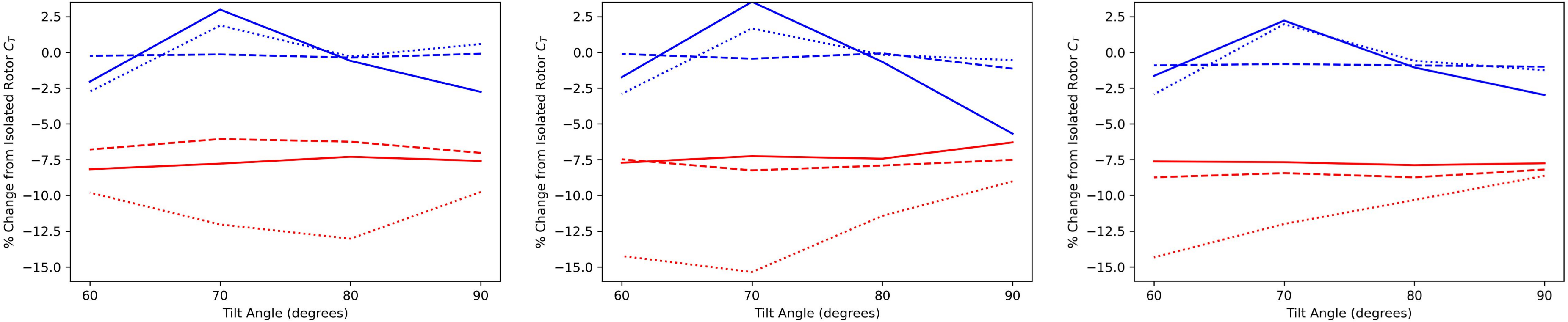


Fig 17. Percentage change in C_T as a function of tilt angle with a rotor offset of 2.5*R* (left), 3.5*R* (center), and 4.5*R* (right).

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Prediction: 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_∞ = 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_∞ from 0 to 10 m/s, at 30° below the rotor plane

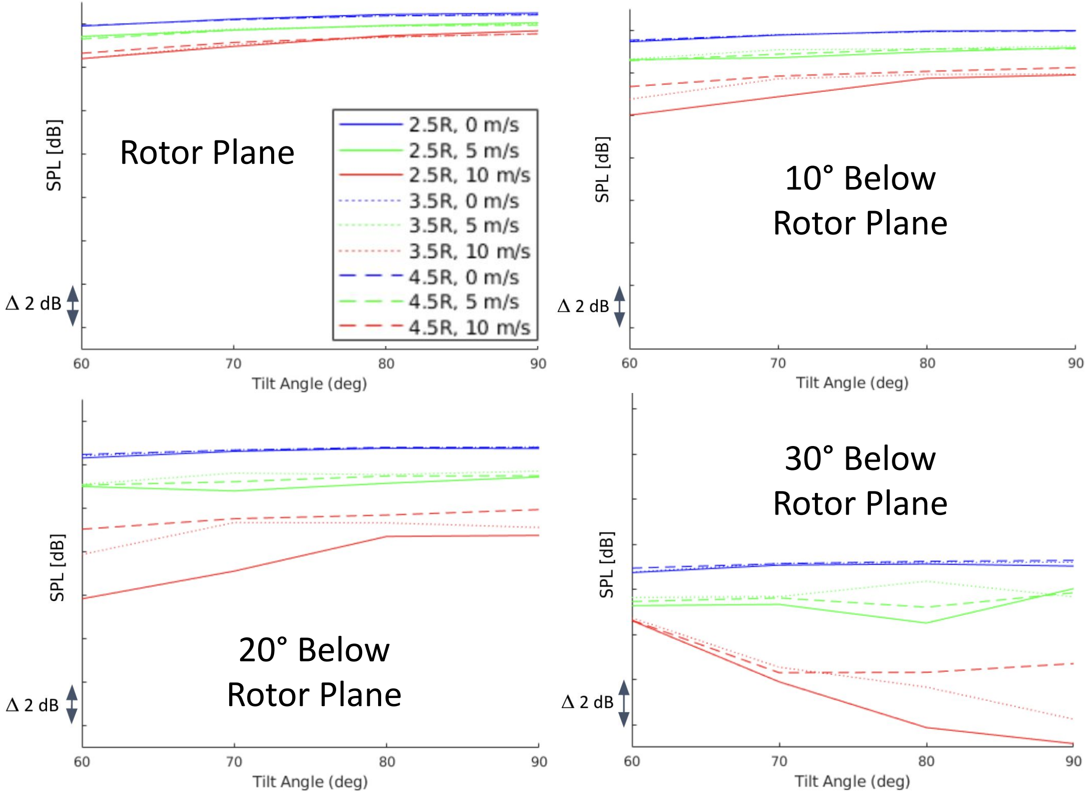

Fig 18. SPL at blade pass frequency (2-blade) for all four observer locations

Prediction: 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 1.3-2.5 dB lower than at hover at different observer locations

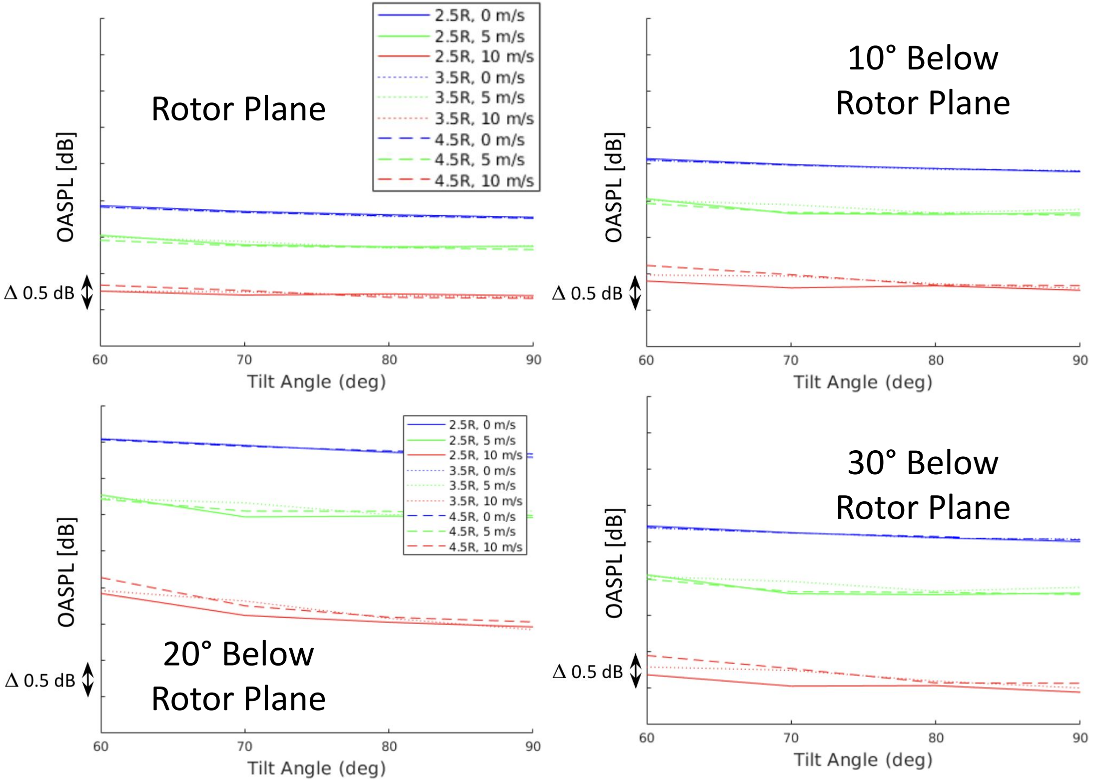

Fig 19. OASPL all four observer locations

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Conclusions

- DUST is a valuable tool for systematic studies and preliminary design. High free-stream velocity cases are one of its limitations
- Larger rotor offsets result in less interaction effects in the wake during hover, while the opposite is true for forward flight conditions
- Under low cruise speeds, the lifter's c_T only varies under low tilt angles, due to its interaction with the wake from the front rotor
- The system's BPF SPL is primarily affected by cruise speed and tilt angle, as rotor offset only plays a role in high U_∞ and high tilt angle conditions
- Little change is observed to SPL and OASPL at hover conditions when varying rotor offset and tilt angles
- OASPL varies little with different tilt angles, but it does not vary with rotor offset and U_∞
- To maximize performance and lower noise, different rotor offsets are required for different flight conditions

Future Work

- Study interactive effects while changing RPMs and rotor rotation directions
- Study aeroacoustic effects while keeping thrust the same (by varying RPM and blade collective angles)
- Investigate the interactive effects when considering the aircraft’s fuselage and wings, as well as side-by-side rotor configurations
- Explore different vertical offset configurations to minimize interaction between rotors

Thank You – Questions?

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