Project 49

Urban Air Mobility Noise Reduction Modeling

Penn State

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Cost Share Partner: Continuum Dynamics, Inc/Penn State

Objective:

- Develop a first-principles noise modeling system for future UAM aircraft with varied configurations
- Produce noise database for notional UAM configurations for hover, transition, cruise
- Identify configuration changes and operational strategies that minimize acoustic impacts

Project Benefits:

- Initial capability to analyze UAM acoustics
- Understanding of UAM noise characteristics
- Identification of noise reduction opportunities
- Low noise design tool for the UAM industry
- Initial UAM noise data for input to Advanced Acoustic Model, which can provide input to AEDT

Research Approach:

- Build on success of helicopter noise prediction system developed under ASCENT Projects 6 & 38:
  - Couple flight simulation, aerodynamic modeling (CDI's CHARM), and PSU-WOPWOP
- Tailor approach to unique characteristics of UAM by modeling flight dynamics of distributed electric propulsion vehicles including multiple propellers and rotors with PSU-DEPSim
- Develop low noise UAM trim strategies

Major Accomplishments (since last meeting):

- Analysis of departure maneuver for lift-plus-cruise eVTOL
  - Aircraft transitioning from hover to cruise while gaining altitude
- Time-varying broadband noise implementation in system made more robust
  - Validating prior to external release
- Conducted literature review of turbulence ingestion noise models to implement in system

Future Work / Schedule:

- Implement models of broadband ingestion noise generated by aerodynamic interactions

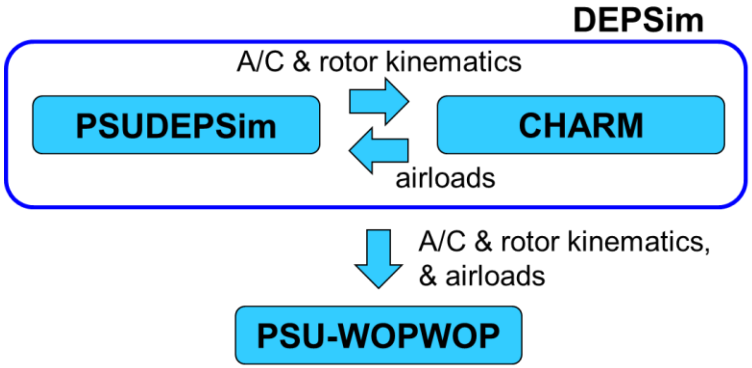
This research was funded by the U.S. Federal Aviation Administration Office of Environment and Energy through ASCENT, the FAA Center of Excellence for Alternative Jet Fuels and the Environment, project 49 through FAA Award Number 13-C-AJFE-PSU-099 under the supervision of Rick Riley. Any opinions, findings, conclusions or recommendations expressed in this this material are those of the authors and do not necessarily reflect the views of the FAA.

Presentation Outline

- Motivation
- Noise during transition maneuver
  - Dealing with over-actuated controls
  - Demonstration of impact of trajectory on acoustic impact
- Time-varying broadband noise
- Summary:
  - Accomplishments
  - Future work

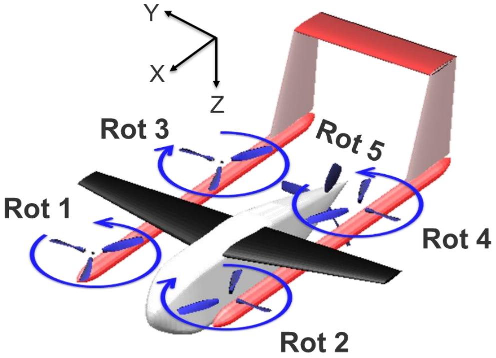
Motivation

- Noise is widely recognized as one of the foremost barriers to development and public acceptance of UAM operations
- Information about acoustic characteristics of UAM is needed:
  - To design quiet configurations
  - To understand how to operate UAM quietly
  - To inform the approach to noise certification
  - To understand the impact on communities
- Development of robust noise prediction system:
  - PSUDEPSim: flight simulation code for DEP aircraft
  - CHARM: aeromechanics modeling code by CDI
  - PSU-WOPWOP: acoustic propagation solver
- DEPSim/PSU-WOPWOP system enables systematic investigation of UAM configurations, flight physics, and noise emission
- System allows investigating:
  - Fundamental noise mechanisms of novel variable rotational speed rotors
  - Nature of multi-rotor noise
  - Trim strategies of compound aircraft

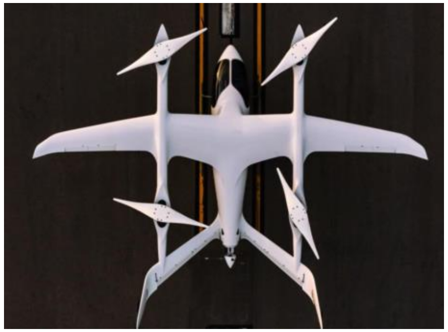


Aircraft models analyzed

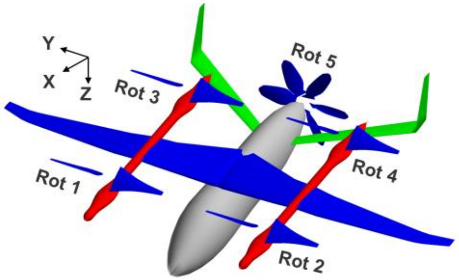
- PSU Reference Aircraft 1
  - Weight = 1000 lbf
  - Notional geometry
- PSU Reference Aircraft 2
  - Weight = 7000 lbf
  - Based on public information available on Beta Alia aircraft
- Both aircraft have
  - 4 lift rotors
  - 1 cruise pusher propeller
  - 1 wing for active lift (and propulsion)



PSU Reference Aircraft 1



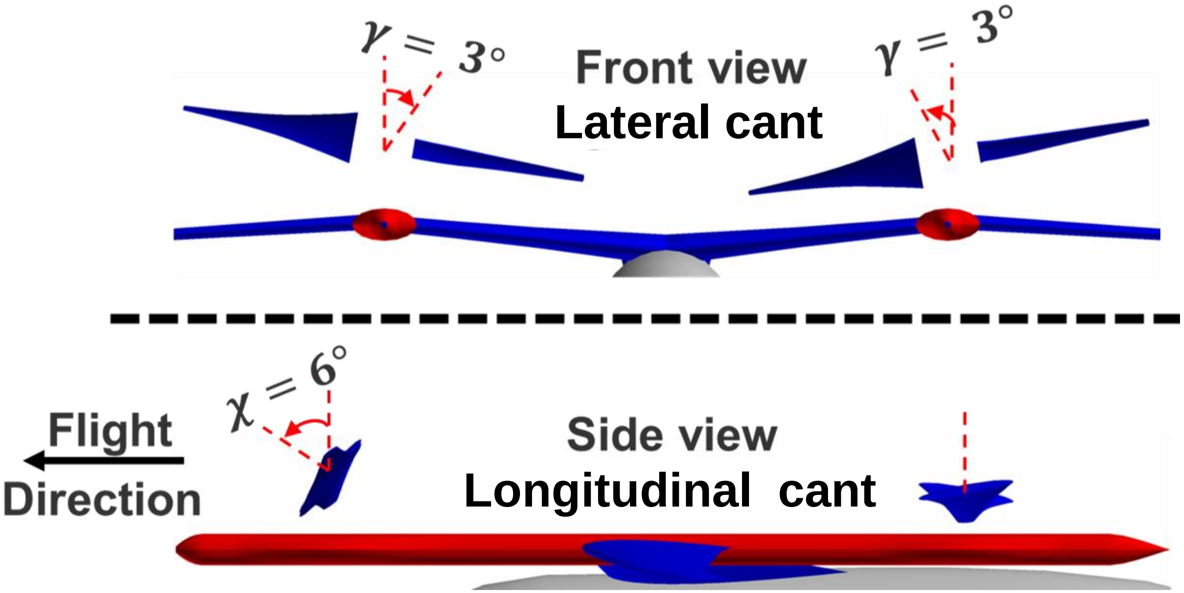
Beta Alia (source: evtol.com)



PSU Reference Aircraft 2

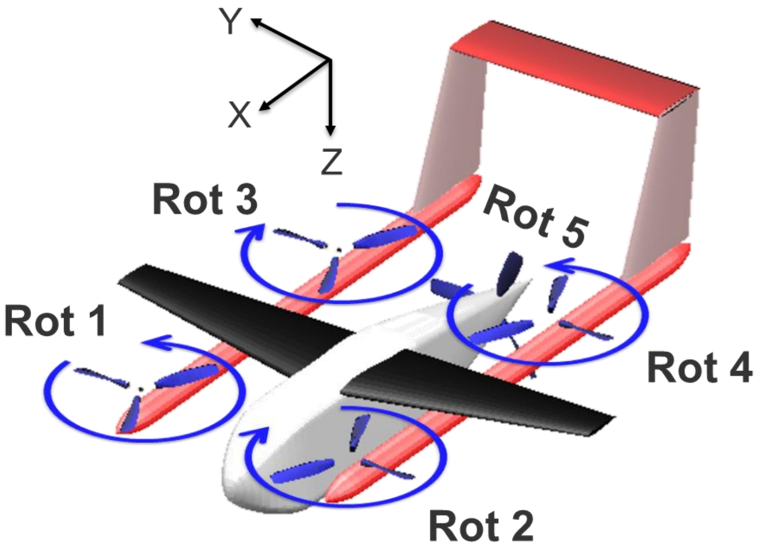
PSU Reference Aircraft 2: unique design

- Lift rotors are canted:
  - Rotor lateral cant 3°
  - Front rotors longitudinal cant 6°
- Rotor cant is known to improve controllability in transition
  - Lateral cant improves yaw control authority and stability
  - Longitudinal cant provides a component of lift rotor thrust in the flight direction during transition
- Impact of rotor cant on noise has not been studied yet



Low-noise lessons learned

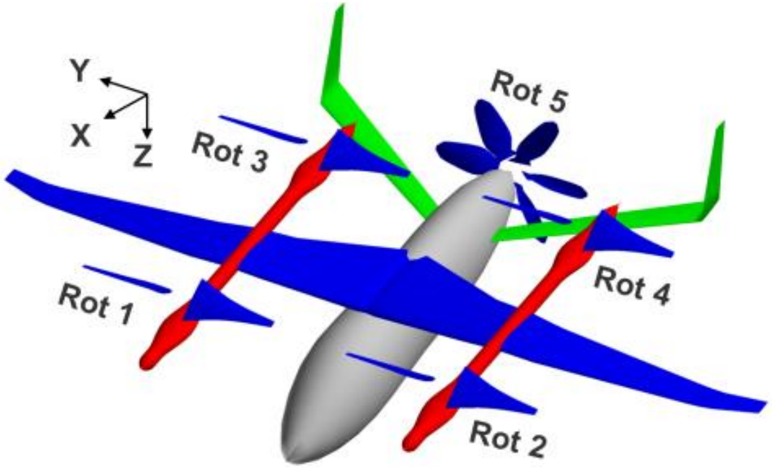
- Thrust on lift rotors (Rot 1 – 4) should be kept as low as possible
  - Helps reduce the required thrust to balance aircraft weight during transition
  - Results in lower operational tip-Mach number (important for noise)
- Rotor blades operating in **stall** at low tip-Mach number have significant contribution to self-noise
  - Turbulent boundary layer scattering via the trailing edge
  - Bad for performance/aerodynamics too



PSU Reference Aircraft 1

Low-noise strategy: Lift + Cruise Design

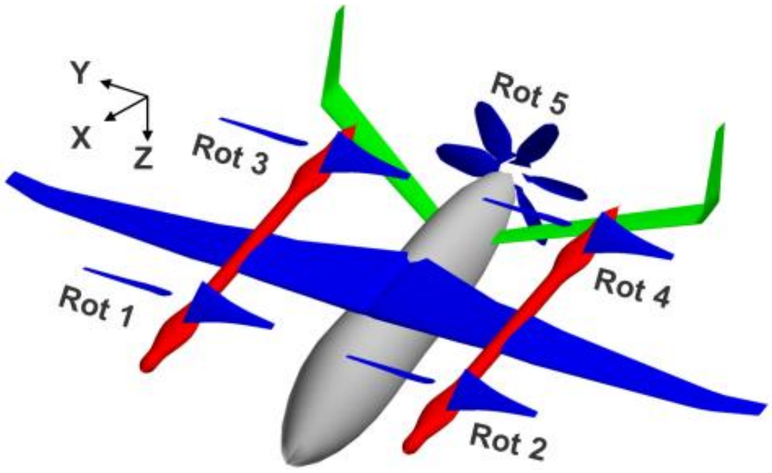
- Highest wing lift as soon as possible
- Wing lift proportional to:
  - Flight speed ($\sim V_\infty^2$)
  - Angle of attack (directly dependent on aircraft pitch)
- No rotor stall
  - Lift rotor thrust control strategies need to be adapted for no stall
  - Variable pitch, constant RPM
  - Variable RPM, constant pitch
- Rotors larger than 6ft diameter not well controlled using variable RPM scheme
  - Current aircraft rotor diameter is 12 ft



PSU Reference Aircraft 2

Low-noise strategy: Lift + Cruise

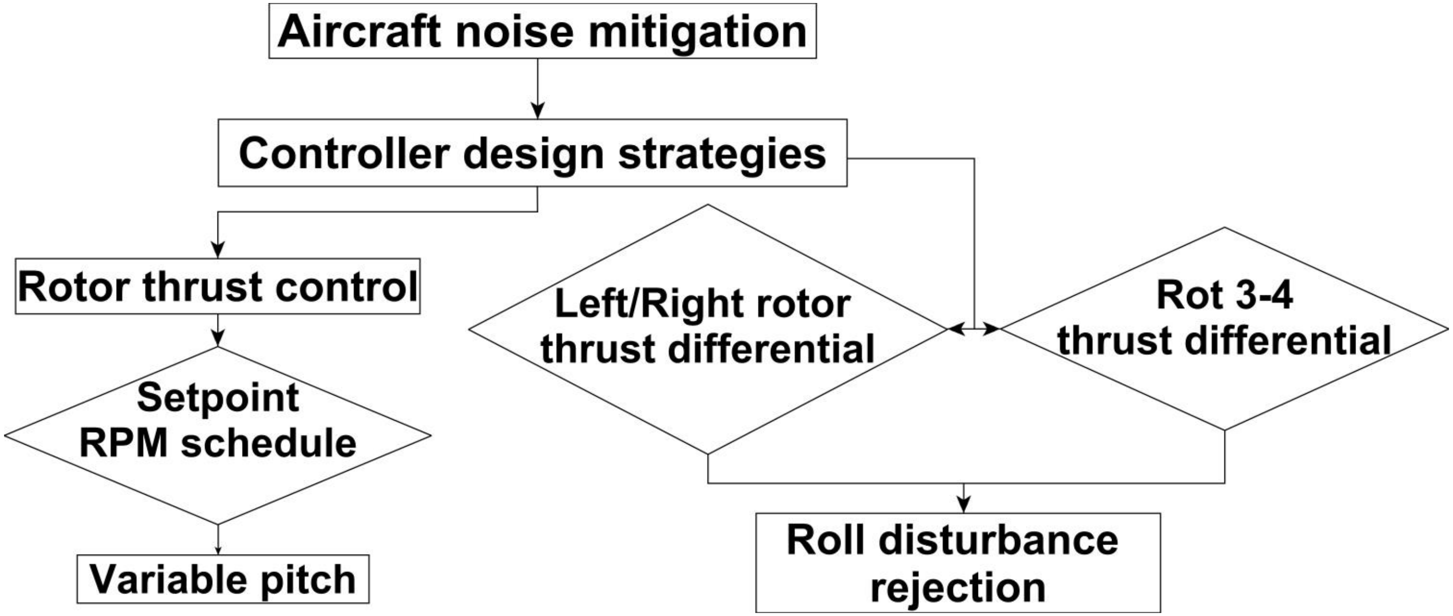
- Transition maneuver:
  - Maneuver that goes from vertical flight to cruise
  - Control of vehicle
    - Variable pitch
    - Constant RPM
  - "Constant RPM" – RPM set at different ***setpoints*** throughout maneuver
    - Dependent on flight condition
    - Advantage of electric motors
  - Rotor designs are usually optimal for a small range of flight conditions



PSU Reference Aircraft 2

Noise mitigation strategies

Multi-rotor aircraft design and availability of multiple lift rotor thrust control schemes allows a diverse approach in noise mitigation



Parametric sweep strategy

- Goal: Minimize computational cost associated with finding setpoint schedule suitable for controllability, acoustics and performance

Increasing computational cost →

Parameter sweep

Initial guess of setpoint schedule using parameter sweep

→

Steady flight DEPSim simulations

Verification of setpoint schedule

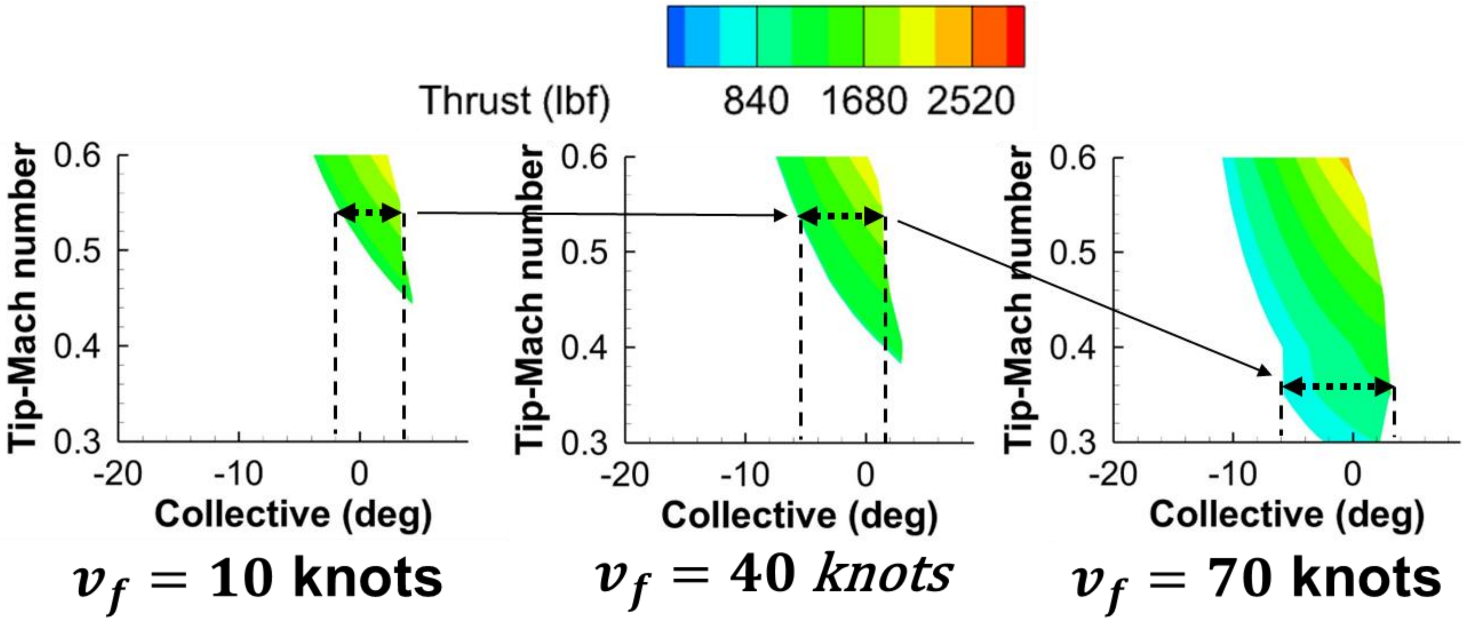
→

Transition simulation

Finalize trim for transition + additional control margin

Setpoint schedule: Initial guess

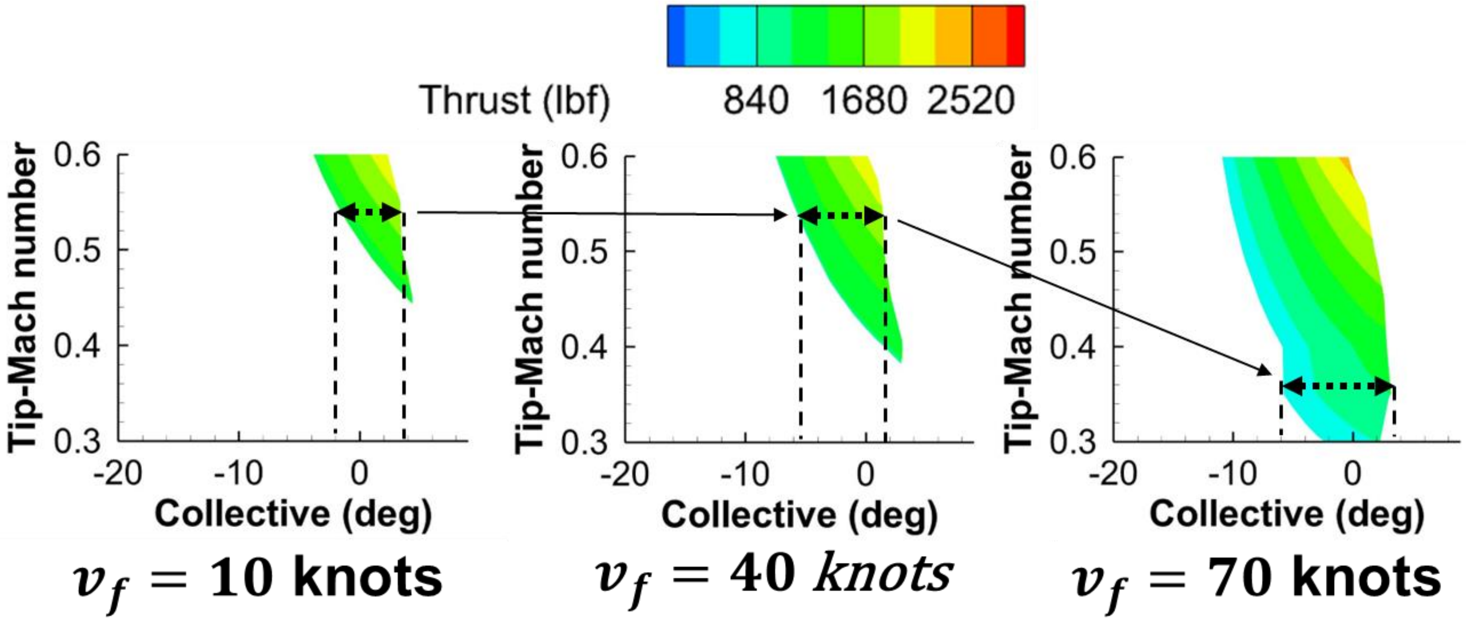
- Isolated lift rotor parametric sweep exploration space:
  - Tip-Mach: 0.3 to 0.6
  - Rotor collective pitch: $-20°$ to $9°$
  - Velocity: 10, 20, 30, 40, 50, 60, 70 knots at $\theta = 8°$
- Metrics evaluated: rotor thrust, power, stall
  - Conditions with rotor stall rejected on account of noise



Setpoint schedule: Initial guess

- Metrics evaluated: rotor thrust, power, stall
  - Conditions with rotor stall rejected on account of noise
  - Rotor thrust must be enough to balance aircraft weight

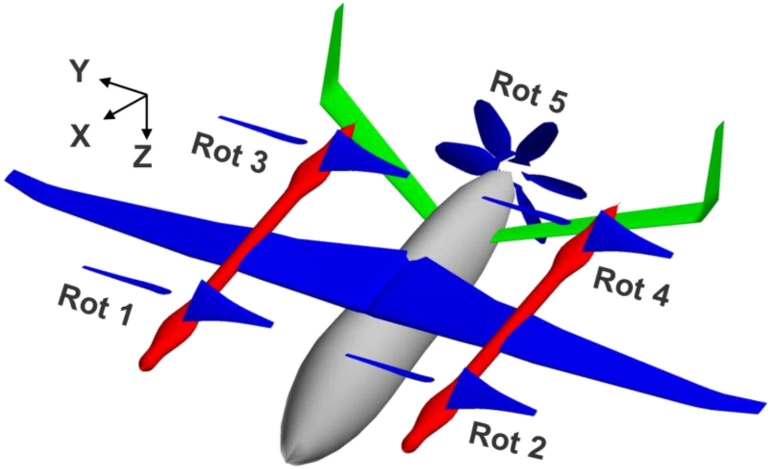
- $\text{Rotor thrust estimate} = \dfrac{\text{Aircraft weight} - \text{Wing lift}}{\text{number of lift rotors}}$
  - Works well in predicting the range of rot 1 – 4 collective pitch angles for steady flight conditions



Setpoint schedule: Initial guess

- Comparison of initial guess with DEPSim steady simulations

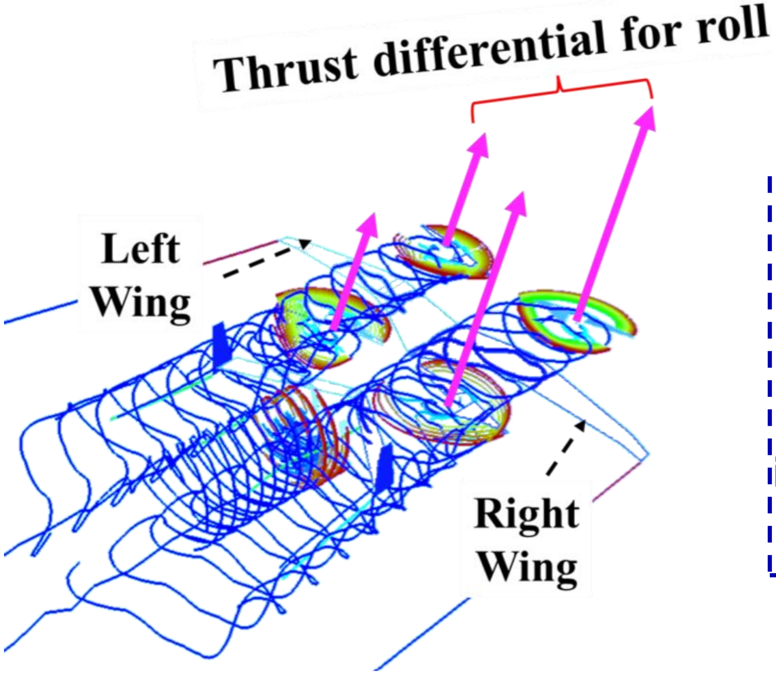
v_f (knots), tip-Mach	10, 0.55	40, 0.55	70, 0.35
Collective range from sweep (deg)	-2 to 4	-6 to 2	-6 to 4
DEPSim collective Rot 1,2,3,4 (deg)	1.8, 1.5, 2.6, 2.3	-4.8, -3.9, 1, 0.2	0.6, -11, 2.5, -2.8

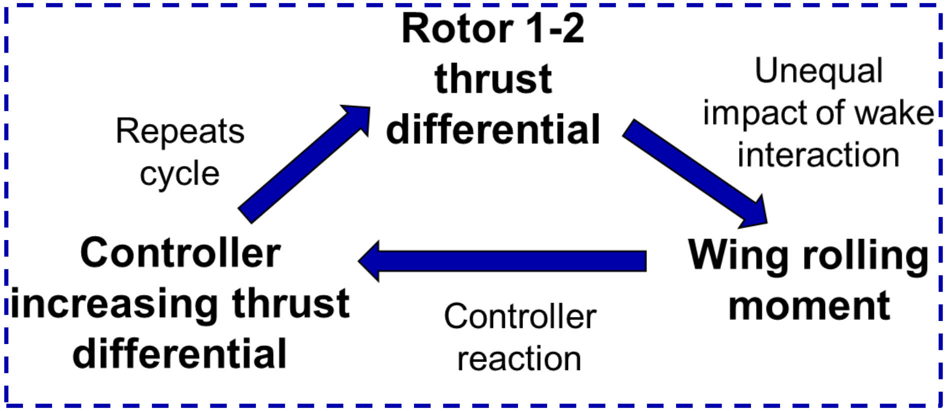


This discrepancy has a reason.

Role of interaction in dynamics

- DEPSim controls aircraft roll disturbance using the difference in thrust between rotors on each side
  - Rot 1 – Rot 2 thrust & Rot 3 – Rot 4 thrust





Rotor 1-2 thrust differential

Unequal impact of wake interaction

Wing rolling moment

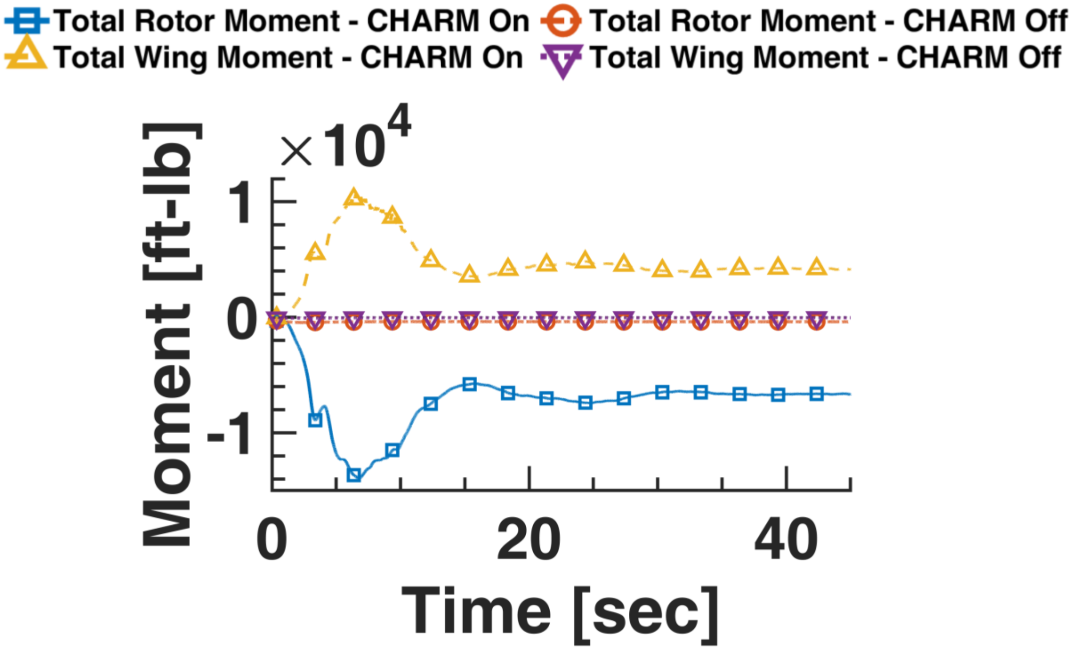
Controller reaction

Controller increasing thrust differential

Repeats cycle

Rolling Moment: 70 knots

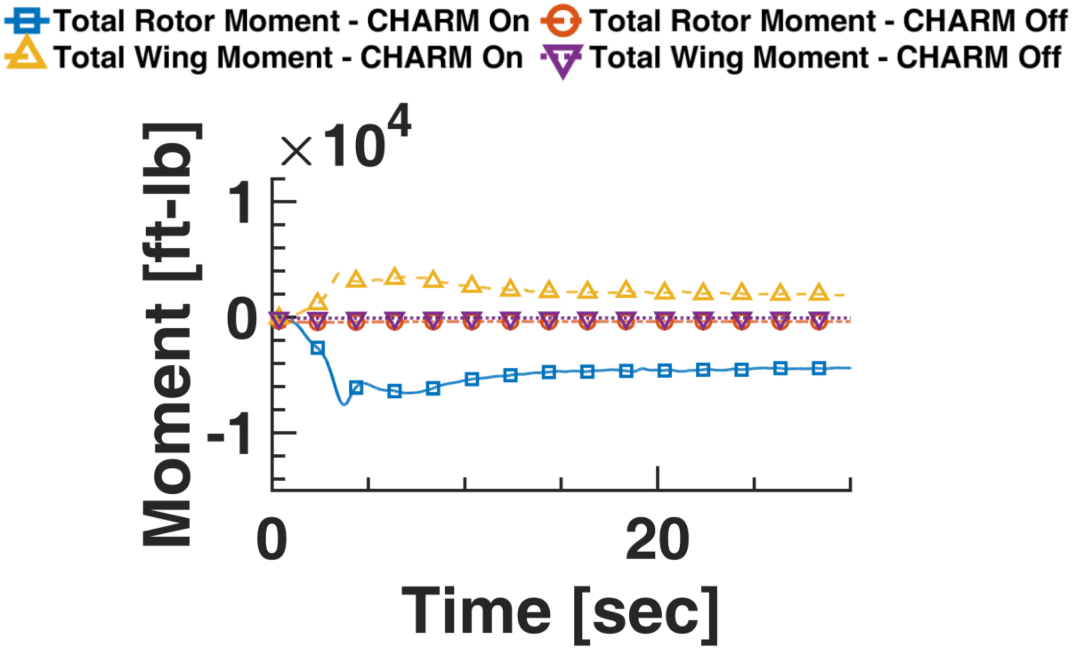
- Break moment cycle by changing how the controller compensates for rolling moment
  - Do not use rotors 1-2 thrust differential for roll rejection!
- Steady flight simulation 70 knots
  - Controller starts without knowledge of interactions
  - Interaction feedback starts around 5 seconds
- “CHARM Off” aero model has no aerodynamic interactions
  - Magnitude of rolling moment is much lower



Roll moment vs Time

Rolling Moment: 70 knots

- Same steady flight simulation
- **Change in controller design**
  - Rotor 1,2 no longer involved in roll rejection
- Notice large reduction in wing and rotors moments
  - Improvement in controllability and performance
  - No significant change in noise



Roll moment vs Time

Setpoint schedule: Initial guess

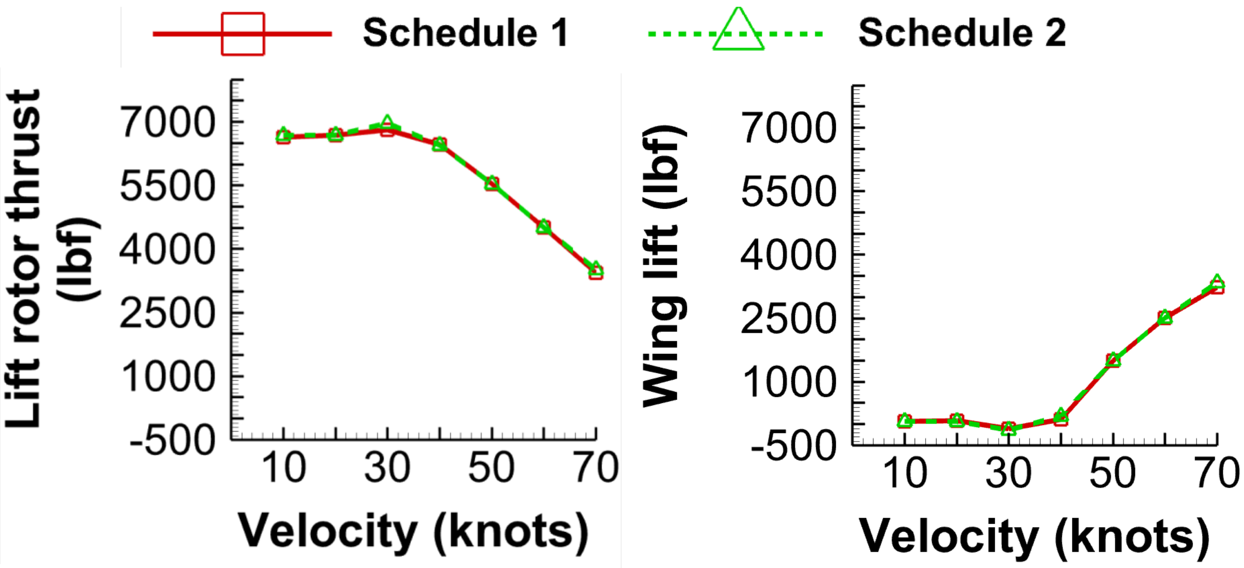
- Initial guess:
  - Schedule 1 expected to work
  - Schedule 2 used to verify whether schedule 1 is the lowest tip-Mach number that maintains reasonable controllability
  - 14 steady flight simulations

Velocity (knots)	Schedule 1	Schedule 2
10	0.55	0.50
20	0.55	0.50
30	0.55	0.50
40	0.55	0.50
50	0.50	0.50
60	0.45	0.45
70	0.35	0.35

Verifying setpoint schedule: Steady flight DEPSim

- Wing lift starts to increase significantly after 40 knots
- Note the dip in wing lift around 30 knots
  - Due to wakes from the front two rotors
  - Wakes creates downwash on wing
  - Downwash results in negative lift!

Velocity (knots)	10	20	30	40	50	60	70
Schedule 1	0.55	0.55	0.55	0.55	0.50	0.45	0.35
Schedule 2	0.50	0.50	0.50	0.50	0.50	0.45	0.35

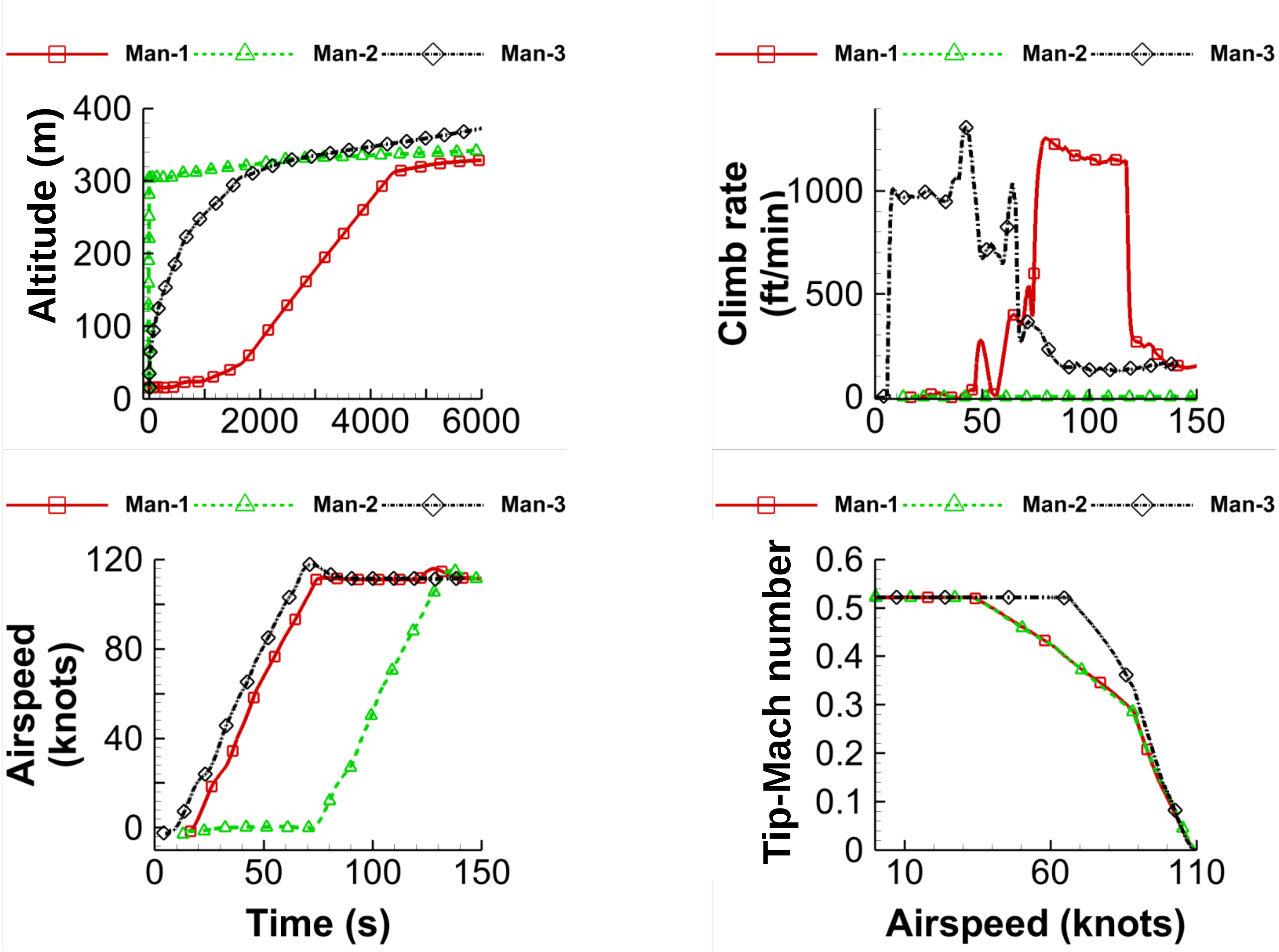


Departure maneuver

- Departure maneuver was simulated using Penn State eVTOL Noise prediction system
  - This maneuver makes the aircraft transition from rotorcraft mode (hover) to fixed-wing airplane mode (cruise)
- Three departure maneuvers: all start at hover, 50 ft altitude, and end at 110 knots, 1000 ft altitude, 20,000 ft downrange
  - **Level acceleration:** Hover -> 0.1g low altitude level acceleration to 110 knots (rotors off by 110 knots), then climb to 1000 ft at 1000ft/min
  - **Axial climb:** Hover -> 1000ft/min climb to 1000 ft -> 0.1g level acceleration to 110 knots
  - **Continuous climb:** Hover-> 0.1g level acceleration + 1000ft/min climb -> Rotors off at 110 knots -> Climb to 1000 ft in aircraft mode
    - Higher bias schedule due to higher demands of thrust for continuous climb rate + level acceleration

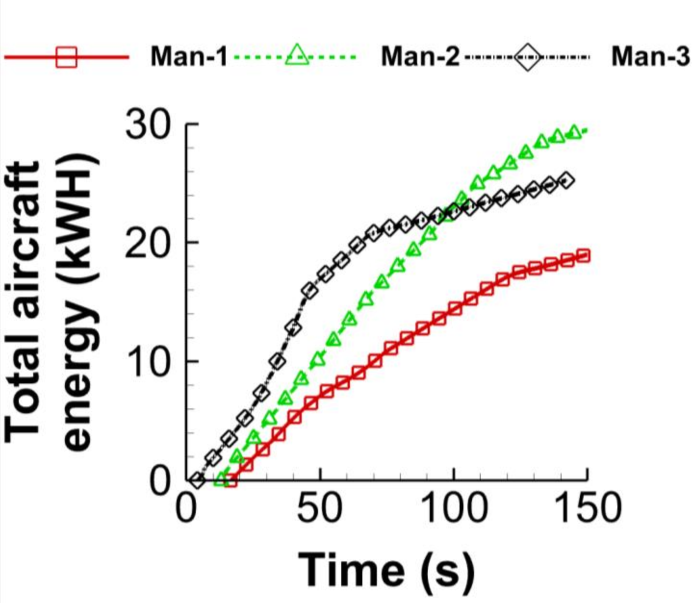
Departure maneuver: Trajectory

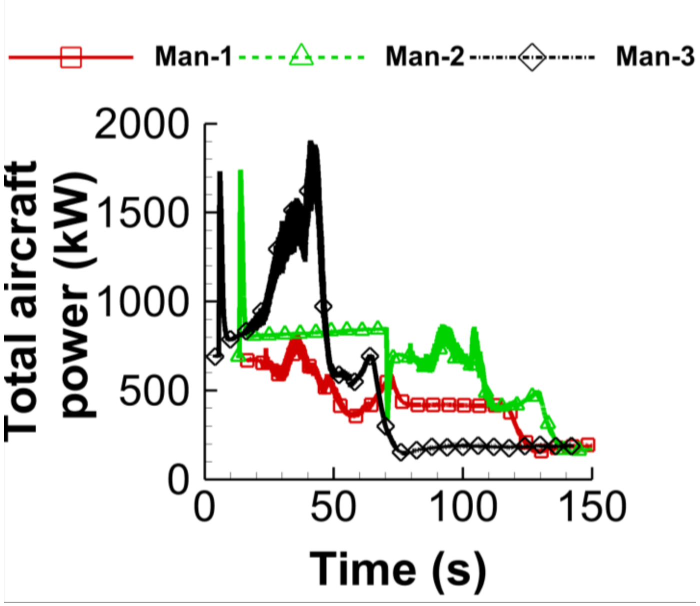
- **Level acceleration:** Man-1; **Axial climb:** Man-2; **Continuous climb:** Man-3



Departure maneuver: Energy, Power

- **Level acceleration:** Man-1: Lowest energy, lowest peak power
- **Axial climb:** Man-2: Highest energy, second highest peak power
- **Continuous climb:** Man-3: Second highest energy, highest peak power

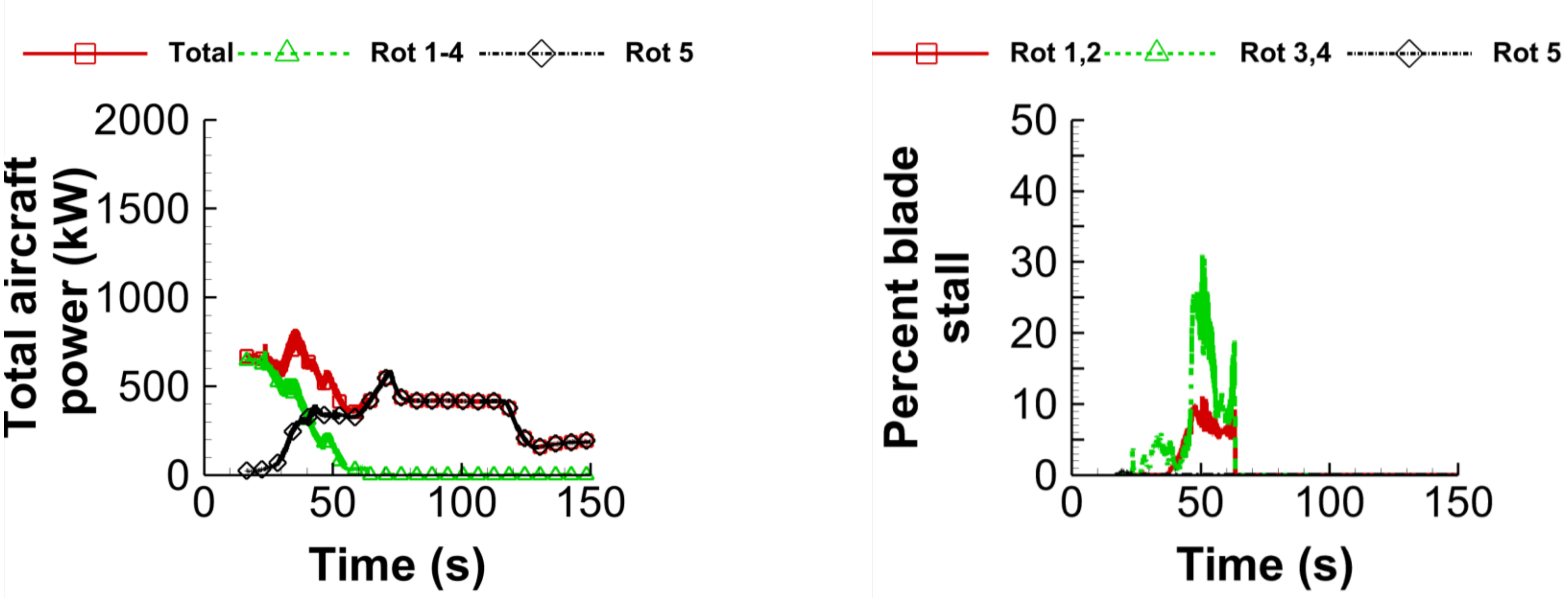




Departure maneuver: Power, Stall

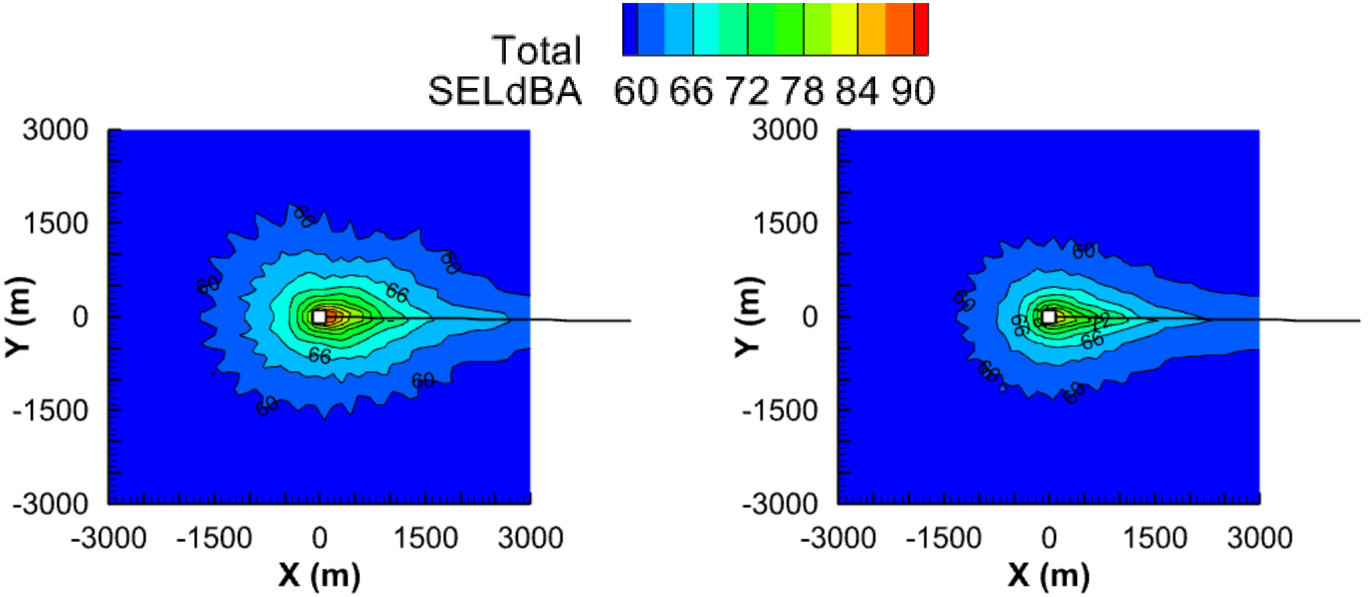
- **Level acceleration:** Lowest energy, lowest peak power
  - Lift rotor power higher than pusher prop in level acceleration (it balances weight)
  - Pusher prop increases during climb in aircraft mode

- Lift rotor blade stall: 10 – 30 %



Departure maneuver: Noise

- **Level acceleration:** Lowest energy, lowest peak power
  - Lift rotor stall: 10 – 30 %
- Stall is not playing a major role in noise
  - Setpoint schedule works
- Noise levels high along trajectory (marked in black)



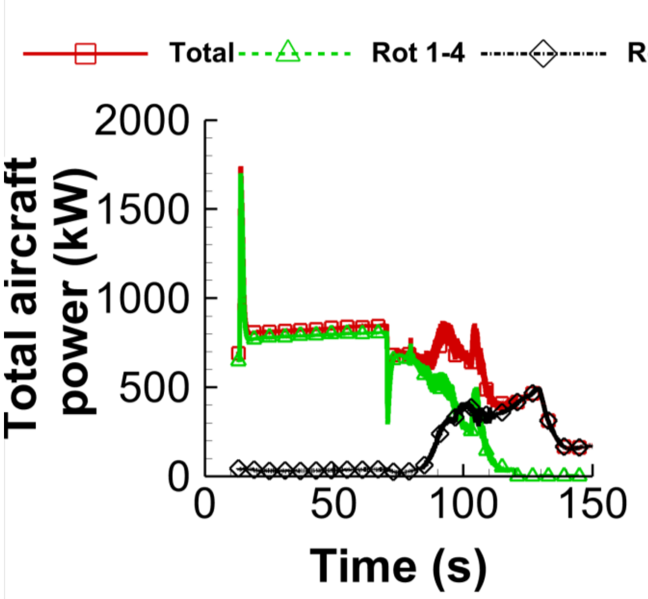
Total noise

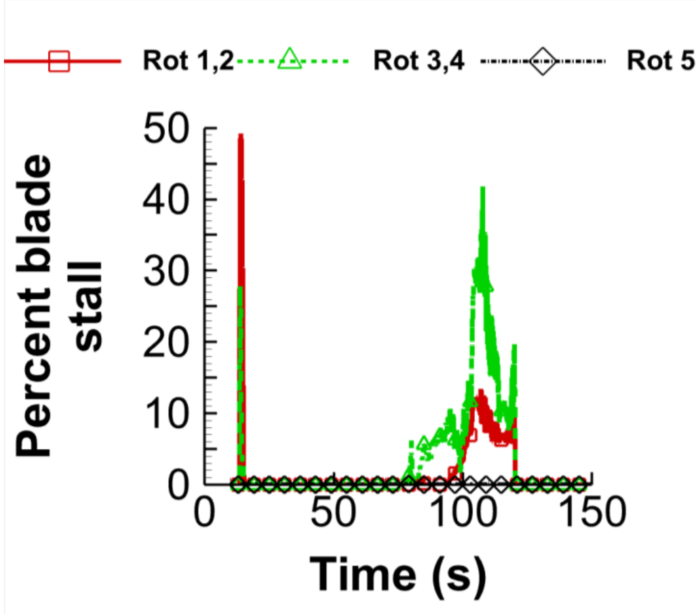
Total noise excluding stall from BPM

Departure maneuver: Power, Stall

- **Axial climb:** Highest energy, second highest peak power
  - High lift rotor power for majority of flight: Because its responsible for climb
  - Spike in power is when the controller ramps rotor collective to have a short period of vertical acceleration to gain 1000 ft/min climb rate

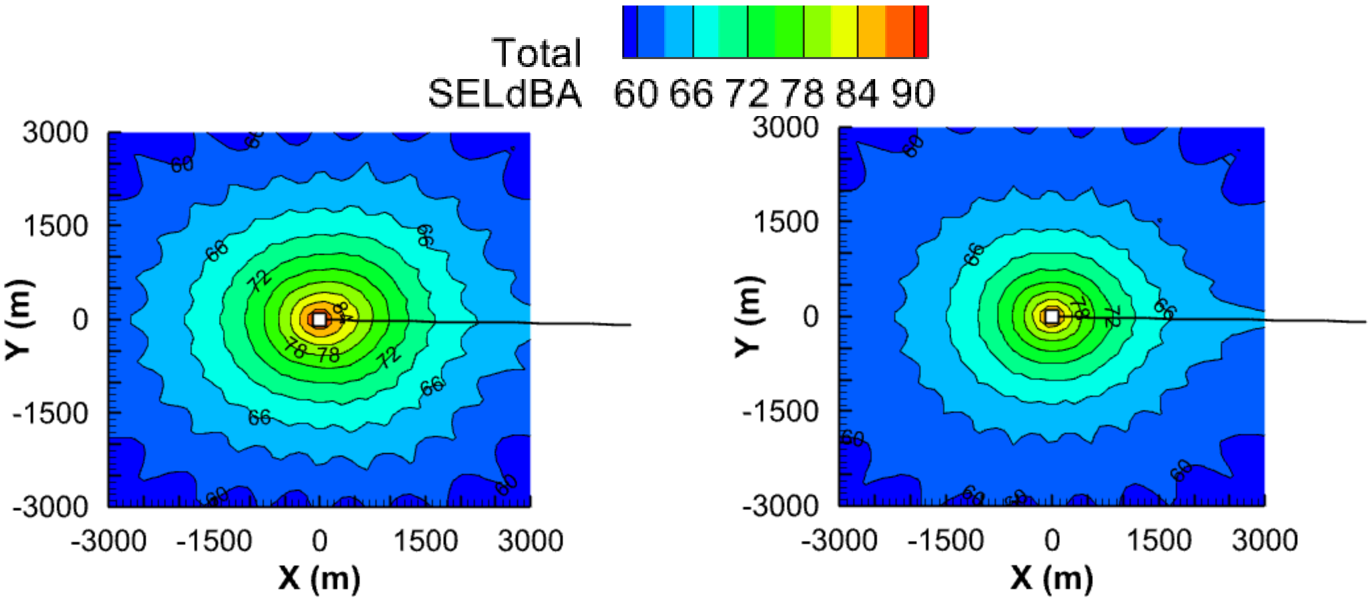
- Lift rotor stall: 10 – 40 %





Departure maneuver: Noise

- **Axial climb:** Highest energy, second highest peak power
  - Lift rotor stall: 10 – 40 %
- Stall is not playing a major role in noise
  - Setpoint schedule works
- Noise levels high throughout plane: aircraft is in rotorcraft mode for longest time

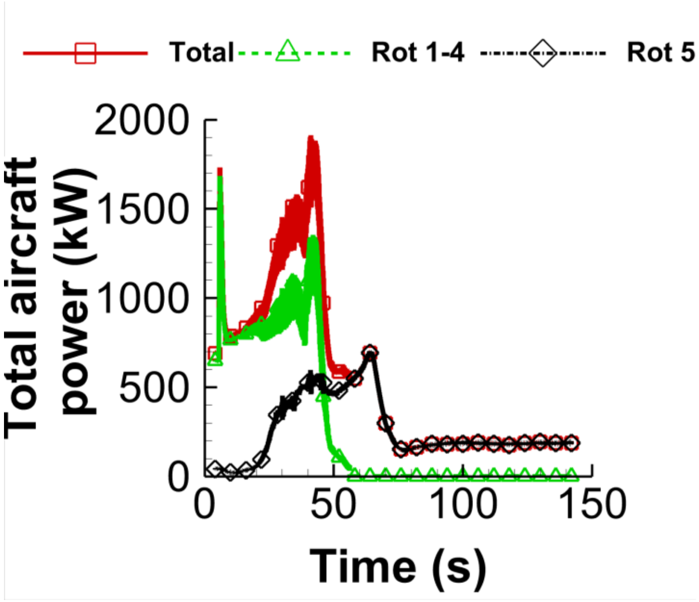


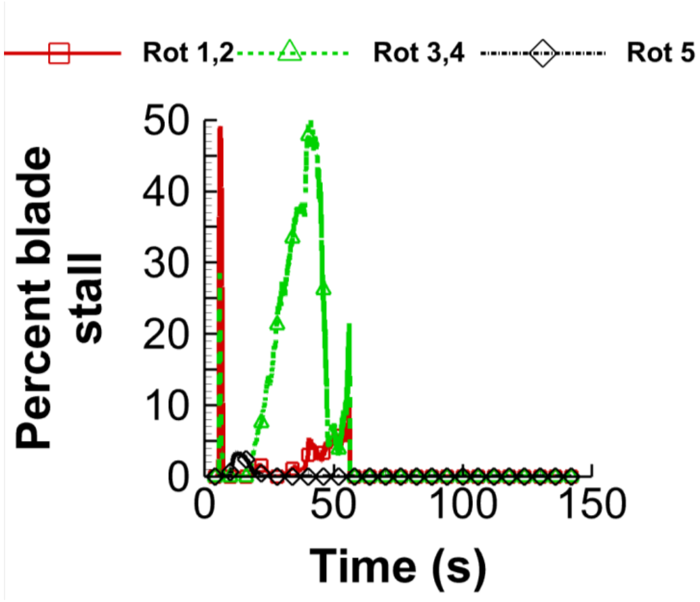
Total noise

Total noise excluding stall from BPM

Departure maneuver: Power, Stall

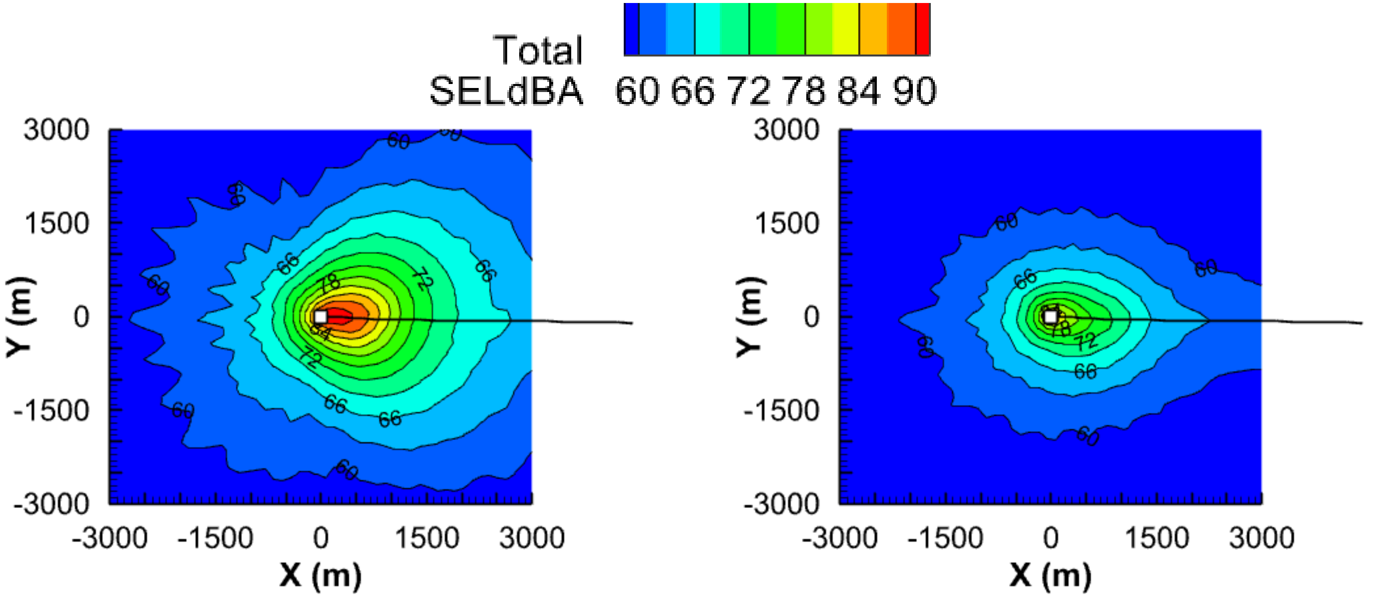
- **Continuous climb:** Second highest energy, highest peak power
  - Climb + level acceleration leads to really high lift rotor power
  - Note higher sustained cruise prop power as it is contributing to climb
- Lift rotor stall: 10 – 50 %
  - Stalled for longer period of time





Departure maneuver: Noise

- **Continuous climb :** Second highest energy, highest peak power
  - Lift rotor stall: 10 – 50 %
- Stall is playing a major role in noise
  - Recall: Setpoint schedule was not developed for climb
- Noise levels similar to level acceleration when stall is excluded: Low noise strategy is phasing off rotors as quickly as possible



Total noise

Total noise excluding stall from BPM

Time Variation of Broadband Noise

Background and Motivation

- Literature typically only analyzes broadband noise spectrum time-averaged over rotor revolution
- But spectrum varies within a rotor revolution, due to:
  - Edgewise flight
  - Aerodynamic interactions
- Time variation of broadband noise spectrum:
  - Not only affects noise levels, but likely perception [1]
  - Important for helicopters, but not well-understood
  - Must investigate for UAM – especially interactions

[1] A. Christian, J. Caston, and E. Greenwood, VFS 75th Annual Forum, 2019

Coding Status

- Past conference paper results [2, 3]:
  - Time-varying predictions **not** for external release (prototype code)
  - Did not post-process spectrum time history
- **Completed**: Fully implemented robust time-varying broadband noise prediction in PSU-WOPWOP
- **In progress**: Validation prior to external release

[2] Z. F. T. Gan, K. S. Brentner, and E. Greenwood, VFS 9th Biennial Autonomous VTOL Technical Meeting, 2021.
[3] Z. F. T. Gan, K. S. Brentner, and E. Greenwood, 28th AIAA/CEAS Aeroacoustics Conference, 2022.

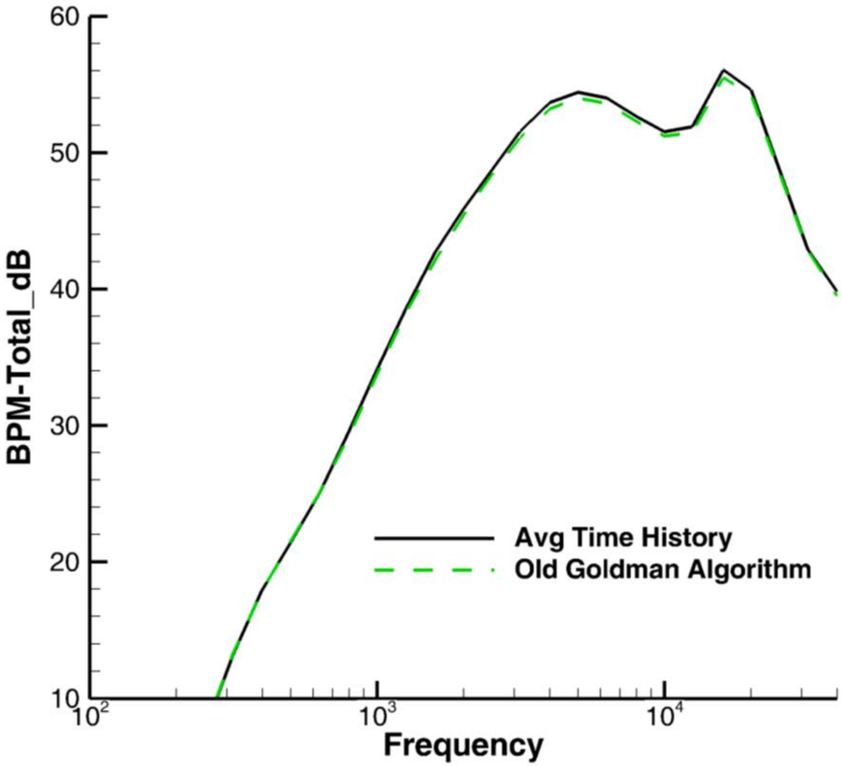
Validation Approach

- Validation approach: Check if
  1. Time-**averaged** BPM model implemented correctly: i.e., match BPM model predictions of other code(s)
  2. Time-**varying** BPM predictions match experimental data
- Previous validation with flight test data [3]: modulation captured, but levels under-predicted
- Improved validation case: NASA ideally-twisted rotor
  - NASA provided time-averaged noise predictions
    - Used to check implementation (Step #1)
  - NASA provided noise measurements
    - Processing measured data to compare with time-varying PSU-WOPWOP predictions (Step #2)
  - Wind tunnel environment more controlled than outdoor flight test

[3] Z. F. T. Gan, K. S. Brentner, and E. Greenwood, 28th AIAA/CEAS Aeroacoustics Conference, 2022.

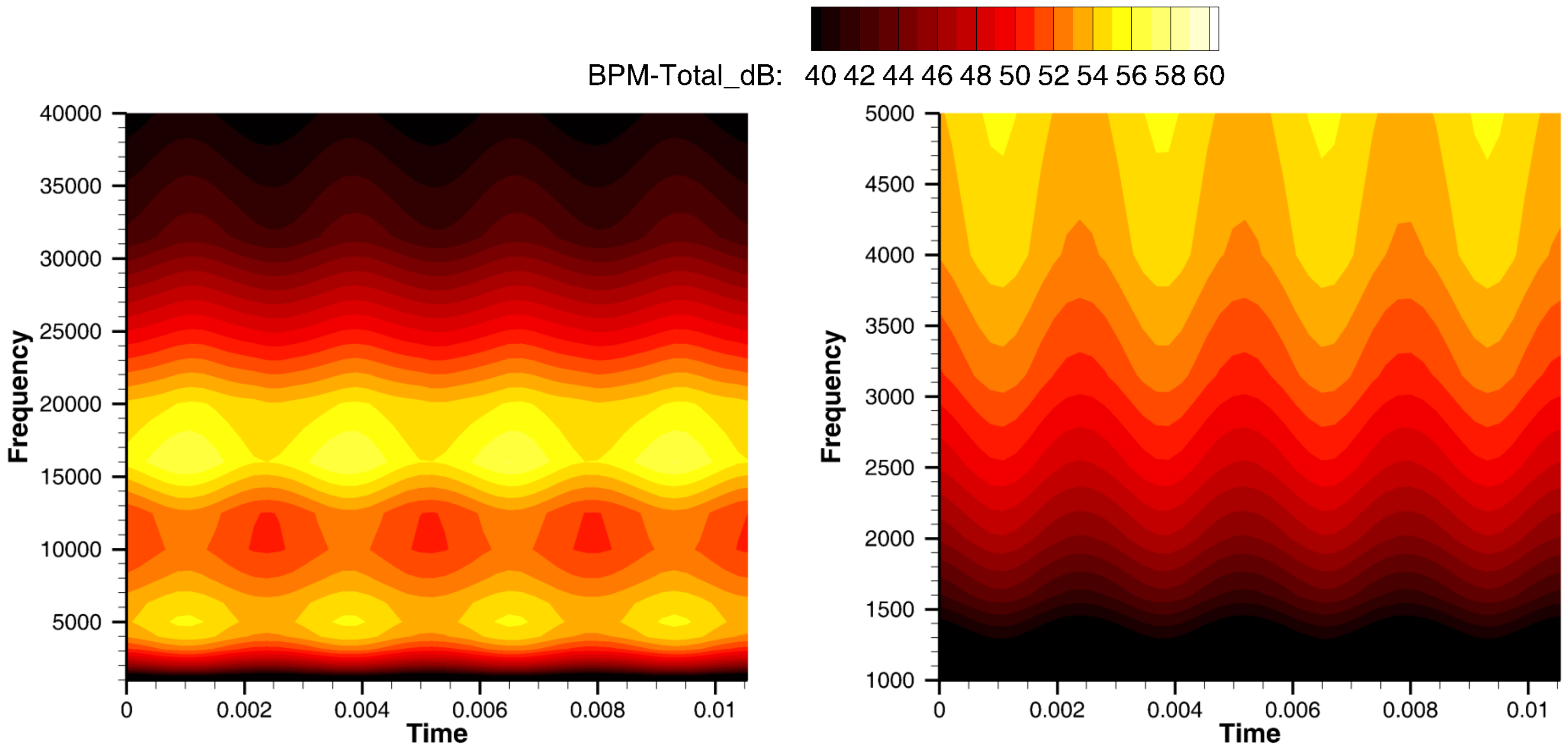
Validation – Time-averaged spectrum

- Previously validated prior to implementing time-varying broadband noise prediction framework
- After implementing time-varying broadband noise:
  - Time-averaging of spectrum time history does NOT significantly change results generated using previous PSU-WOPWOP versions



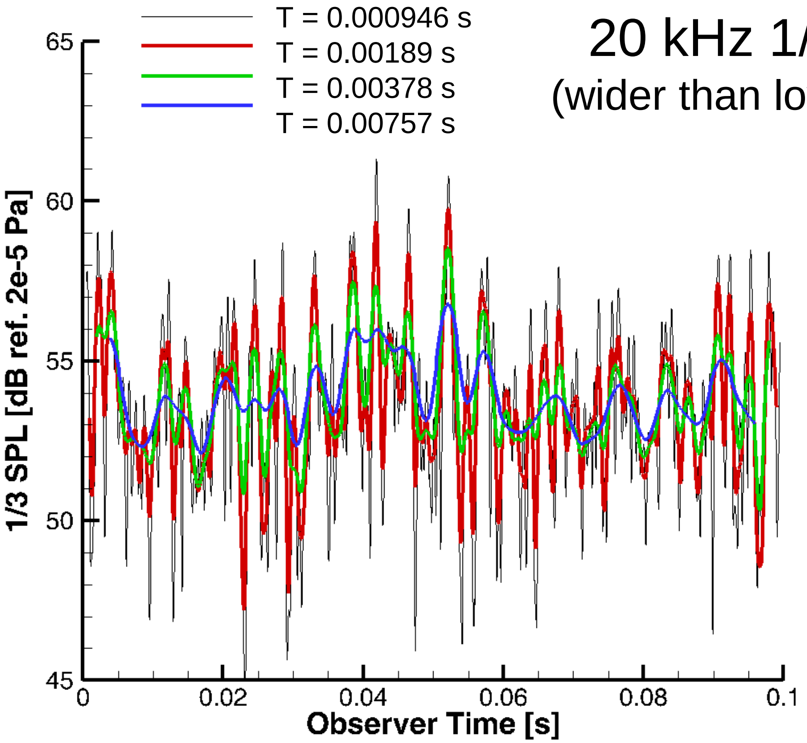
Validation – Time-varying spectrum

- Predicted time-varying broadband noise
- Will compare with experimental data, currently being processed



Validation – Spectrogram

- Processed experimental data into spectrogram
  - Modulation sensitive to chosen time window length **T**
  - Time-frequency trade-off for spectrograms:
    - Criteria: **T << BPP** (blade passage period)
    - Result: Δf >> BPF (blade passage frequency)
    - If Δf > bandwidth, cannot resolve frequencies below this band



20 kHz 1/3rd octave band

(wider than lower frequency bands)

Wind turbine noise studies:

- Window length < 5% of BPP

Our study (BPP = 0.0027 s):

- T = 0.000946 s → 0.35 BPP
- T = 0.00189 s → 0.7 BPP
- T = 0.00378 s → 1.4 BPP
- T = 0.00757 s → 2.8 BPP

Validation – Cyclostationary analysis

- Alternative solution to processing experimental data: Apply cyclostationary analysis:
  - Class of statistical methods developed to study modulating signals
  - Used to study time-varying wind turbine noise: by creating time-frequency representations (TFR)
- TFR created by cyclostationary analysis: Offers advantages over spectrograms:
  - More mathematically correct than stationarity:
    - Spectrogram assumes spectrum constant over chosen window
  - Better time-frequency resolution:
    - Cyclostationary analysis: $\Delta f \leq BPF$
    - Spectrogram: $\Delta f >> BPF$
- In progress: creating TFR using cyclostationary analysis

Turbulence Interaction Noise

- Motivation:
  - Geometric configurations of UAM aircraft create many opportunities for aerodynamic interactions
  - Only self-noise is modeled by BPM model
  - Broadband noise underpredicted when only self-noise included: by past Project 49 work and literature

- Upstream turbulence ingested into rotor generates broadband noise
  - Atmospheric
  - Rotor and/or airframe wake ingestion

Turbulence Interaction Noise

- Chosen model: Amiet’s leading edge noise model: time and frequency domain approaches:
  - Frequency domain approach:
    - Input: turbulence velocity spectrum
- Next steps: implement in noise prediction system
  - Integrate into existing time-varying broadband noise prediction framework used for BPM model for self-noise

Summary

- Major Accomplishments:
  - Analysis of departure maneuver for lift-plus-cruise eVTOL
    - Aircraft transitioning from hover to cruise while gaining altitude
  - Time-varying broadband noise implementation in system made more robust
  - Conducted literature review of turbulence ingestion noise models to implement in system
- Future Work:
  - Validate time-varying broadband noise predictions by processing experimental data using cyclostationary analysis
  - Implement models of broadband ingestion noise generated by aerodynamic interactions
  - Include impact of aerodynamic interactions such as BVI, BWI etc.

References

A. Christian, J. Caston, and E. Greenwood and F. H. Schmitz, “Regarding the Perceptual Significance and Characterization of Broadband Components of Helicopter Source Noise,” Vertical Flight Society 75th Annual Forum & Technology Display, Philadelphia, Pennsylvania, May 13–16, 2019.

Z. F. T. Gan, K. S. Brentner, and E. Greenwood and F. H. Schmitz, “Time Variation of Rotor Broadband Noise,” Vertical Flight Society 9th Biennial Autonomous VTOL Technical Meeting, Virtual, January 26–28, 2021.

Z. F. T. Gan, K. S. Brentner, and E. Greenwood and F. H. Schmitz, “Time Variation of Helicopter Rotor Broadband Noise,” 28th AIAA/CEAS Aeroacoustics Conference, Southampton, UK, June 14-17, 2022.

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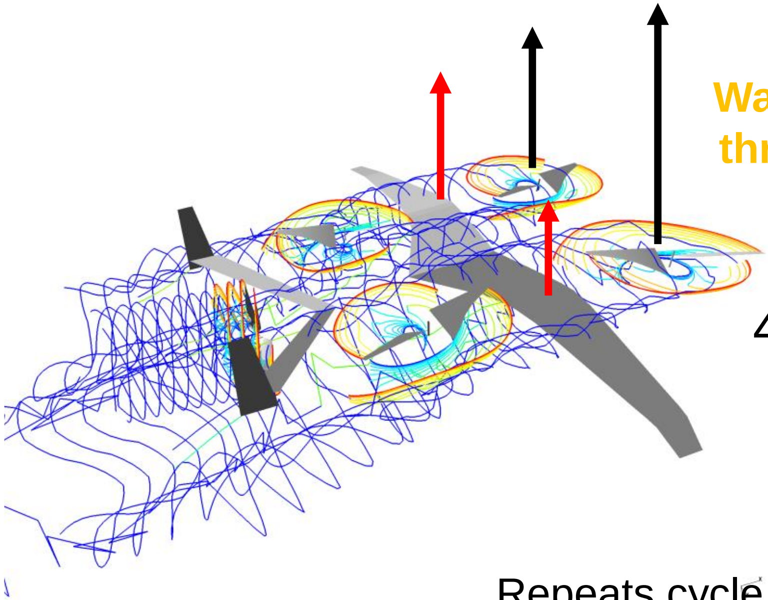
- Graduate Research Assistants: Ze Feng Gan and Bhaskar Mukherjee (PSU)
- Industrial Partners: Continuum Dynamics, Inc. (CDI)

Questions?

Extra draft slides (delete them from final)

Role of interaction in dynamics

- DEPSim controls aircraft roll disturbance using the difference in thrust between rotors on each side
  - Rot 1 – Rot 2 thrust & Rot 3 – Rot 4 thrust



Wake passing through wing

40 knots

Rotor 1-2 thrust differential

Unequal wake strengths

Wing rolling moment

Controller reaction

Controller increasing thrust differential

Repeats cycle

Role of interaction in dynamics

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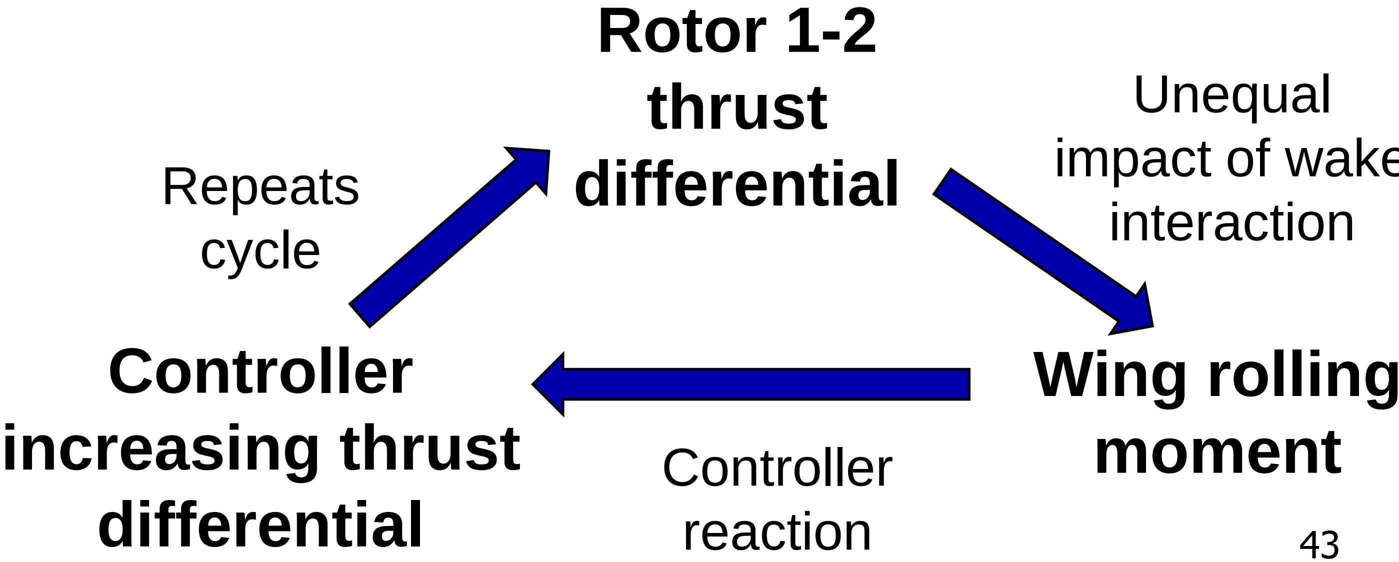


Rotor 1-2 thrust differential

Unequal impact of wake interaction

Wing rolling moment

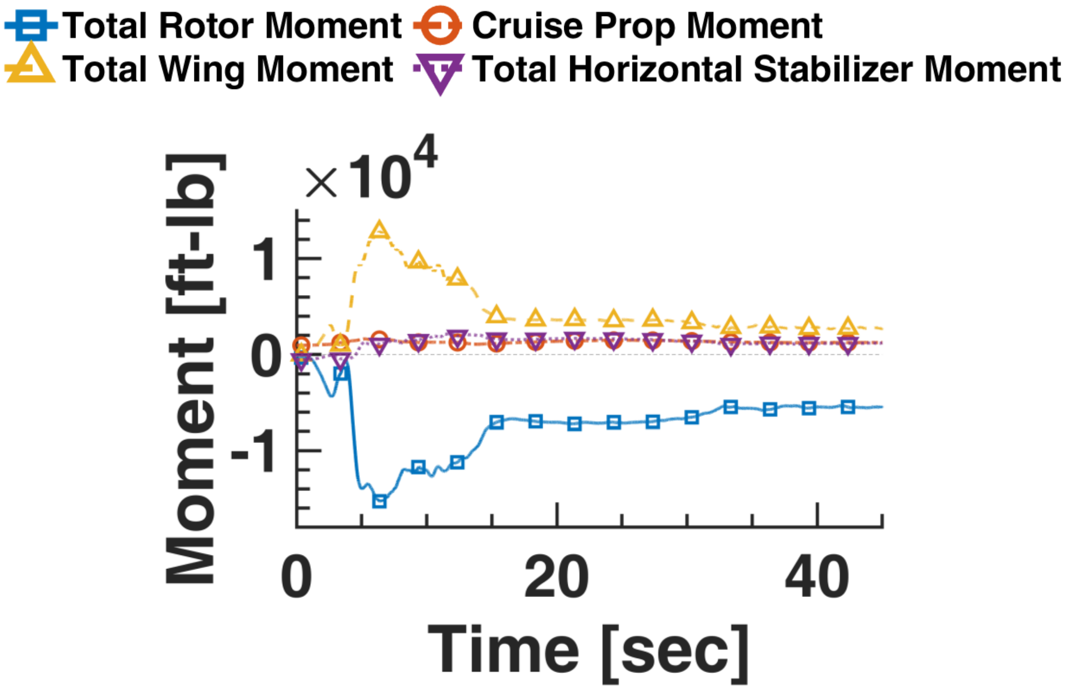
Controller reaction

Controller increasing thrust differential

Repeats cycle

Rolling Moment: 70 knots

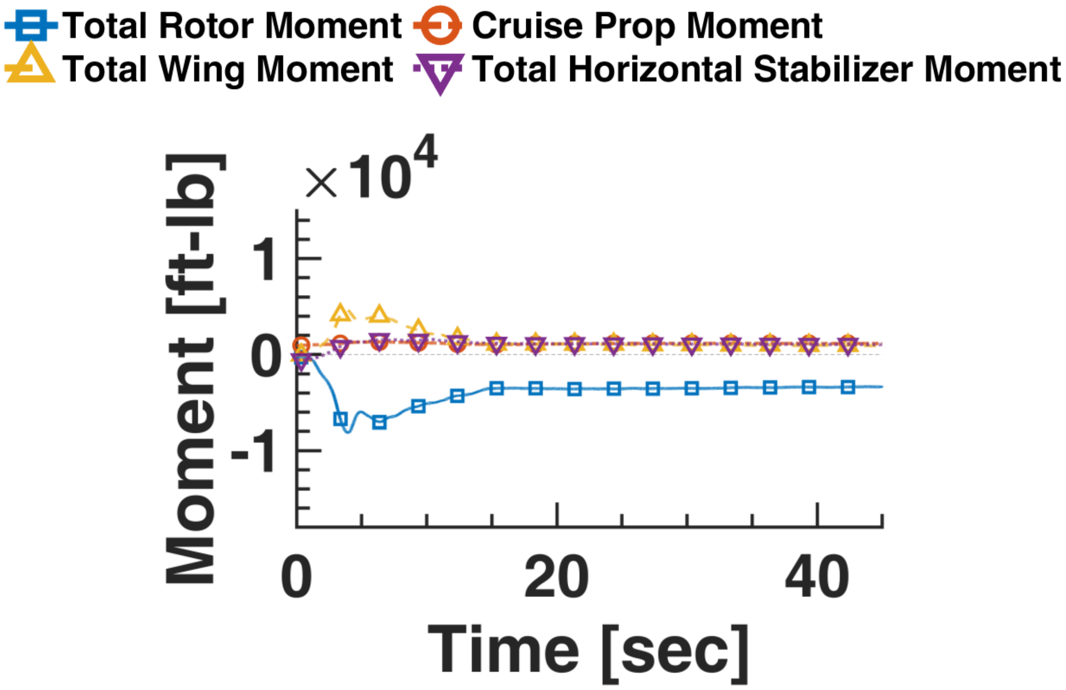
- Break moment cycle by changing how the controller compensates for rolling moment
  - Do not use rotors 1-2 thrust differential for roll rejection!
- Steady flight simulation 70 knots
  - Controller starts without knowledge of interactions
  - Interaction feedback starts around 5 seconds



Roll moment vs Time

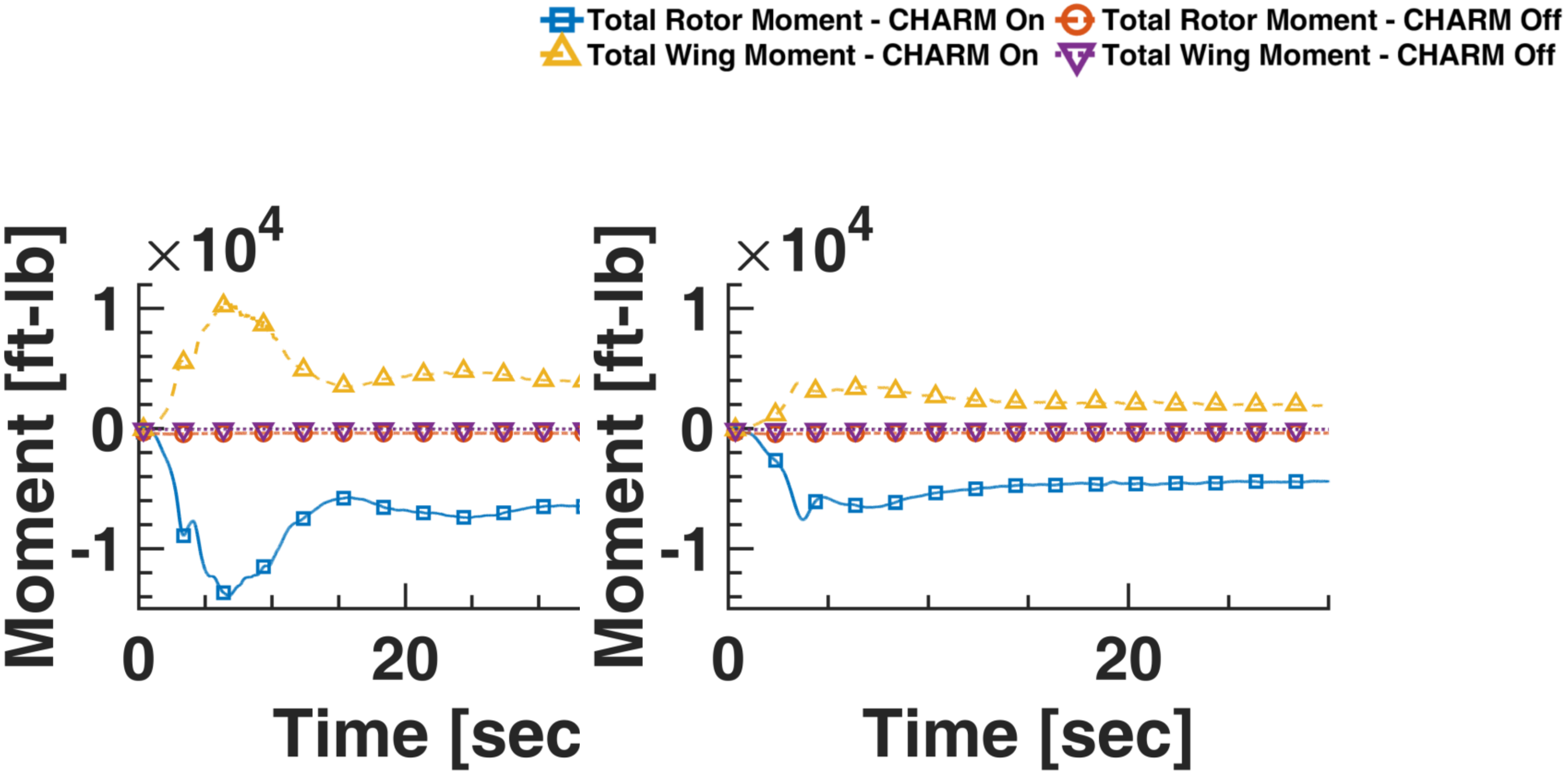
Rolling Moment: 70 knots

- Same steady flight simulation
- **Change in controller design**
  - Rotor 1,2 no longer involved in roll rejection
- Notice large reduction in wing and rotors moments
  - Improvement in controllability and performance
  - No significant change in noise



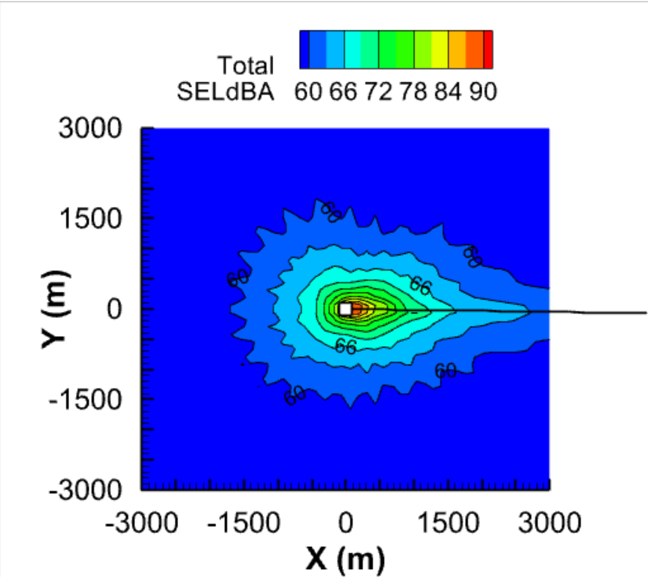
Roll moment vs Time

Rolling Moment: 70 knots

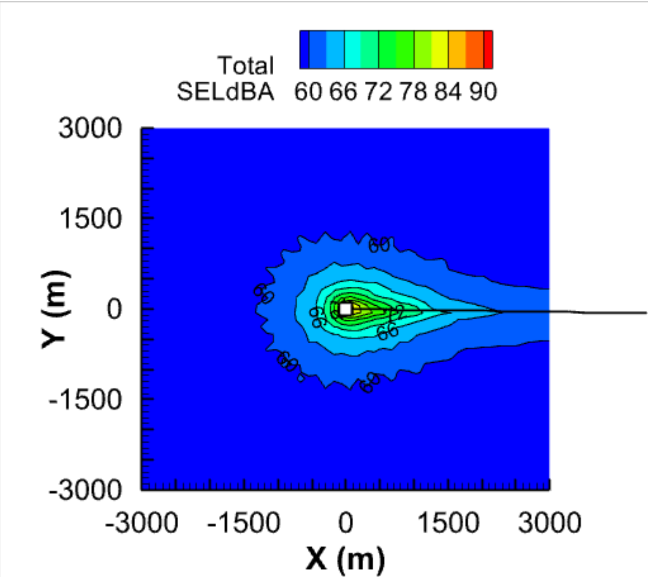


Departure maneuver: Noise

- **Level acceleration:** Lowest energy, lowest peak power
  - Lift rotor stall: 10 – 30 %
- Note difference in SEL levels when stall broadband noise is removed
  - BPM is semi-empirical and we can separate components out!



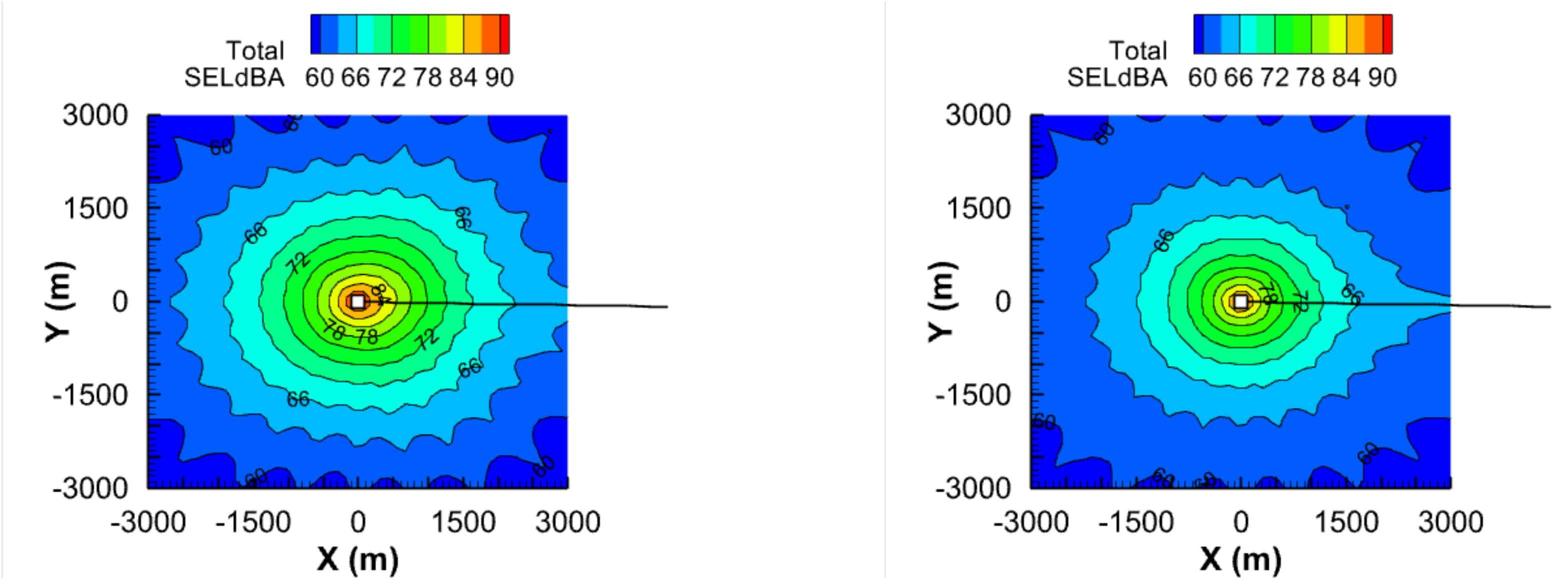
Total noise



Total noise excluding stall from BPM

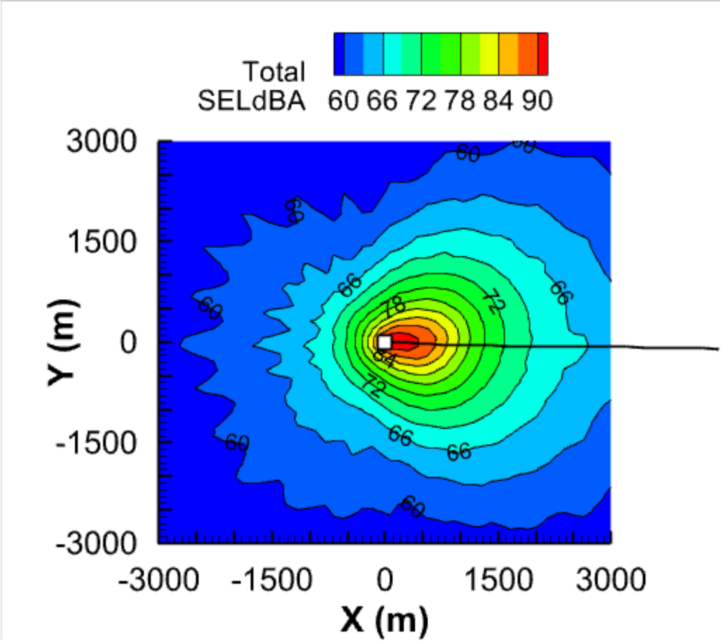
Departure maneuver: Noise

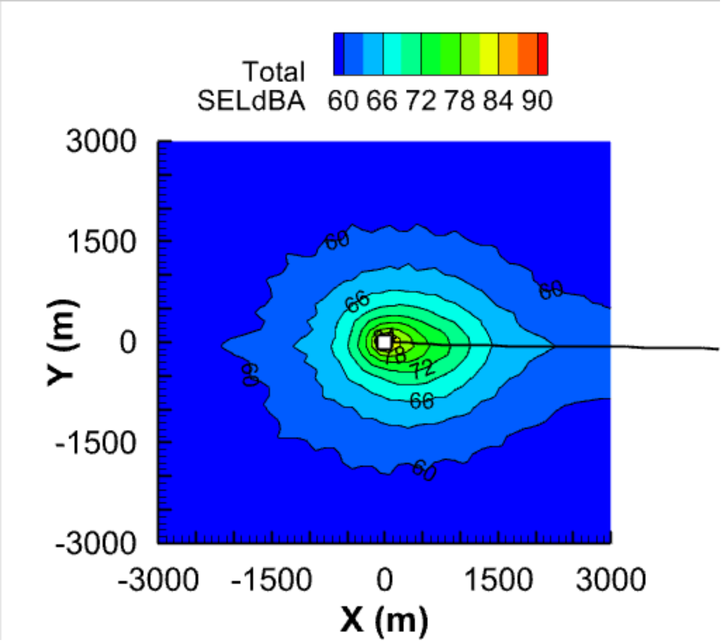
- **Axial climb:** Highest energy, second highest peak power
  - Lift rotor stall: 10 – 40 %
- Note difference in SEL levels when stall broadband noise is removed
  - **Design of blade matters!!!**



Departure maneuver: Noise

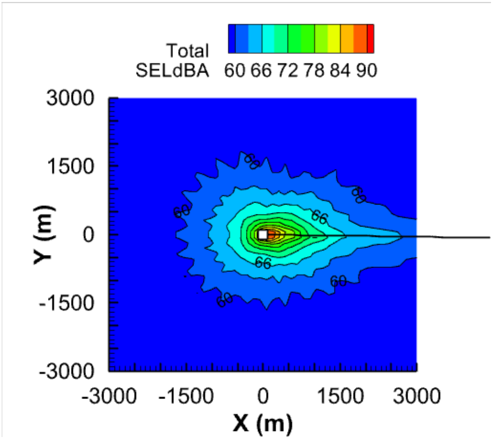
- **Continuous climb :** Second highest energy, Highest peak power
  - Lift rotor stall: 10 – 50 %
- Note difference in SEL levels when stall broadband noise is removed
  - Stall was contributing to significant noise!





Departure maneuver: Noise

- **Level acceleration:** Lowest energy, lowest peak power
  - Lift rotor stall: 10 – 30 %
- Stall is not playing a major role in noise
  - Setpoint schedule works



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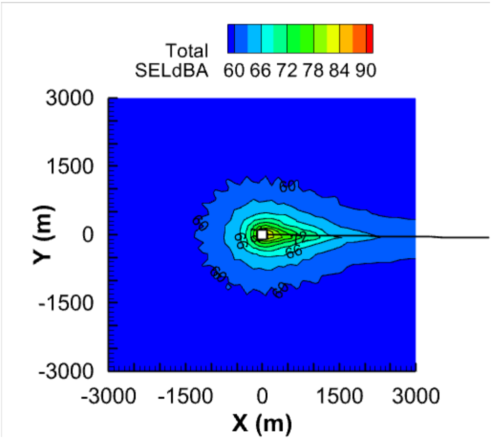

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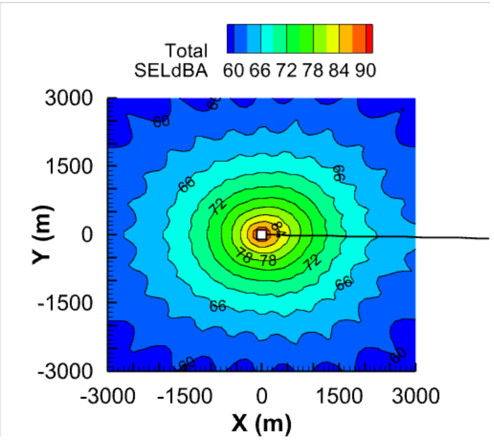

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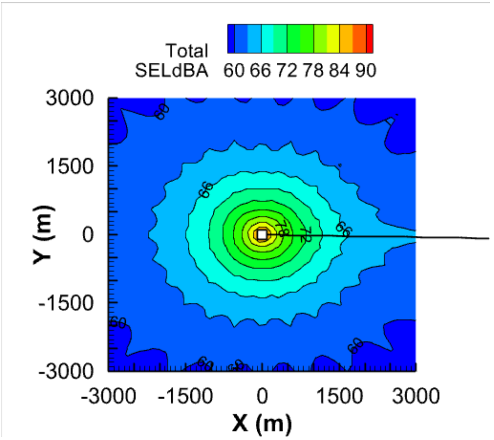

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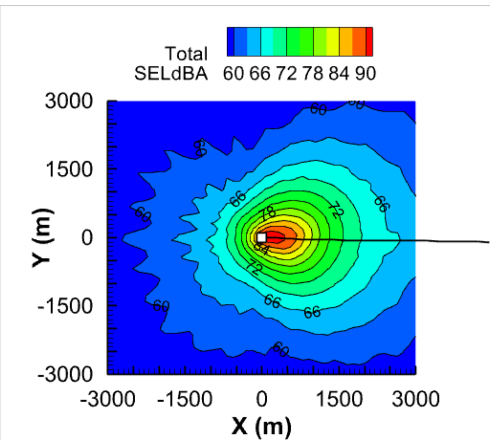

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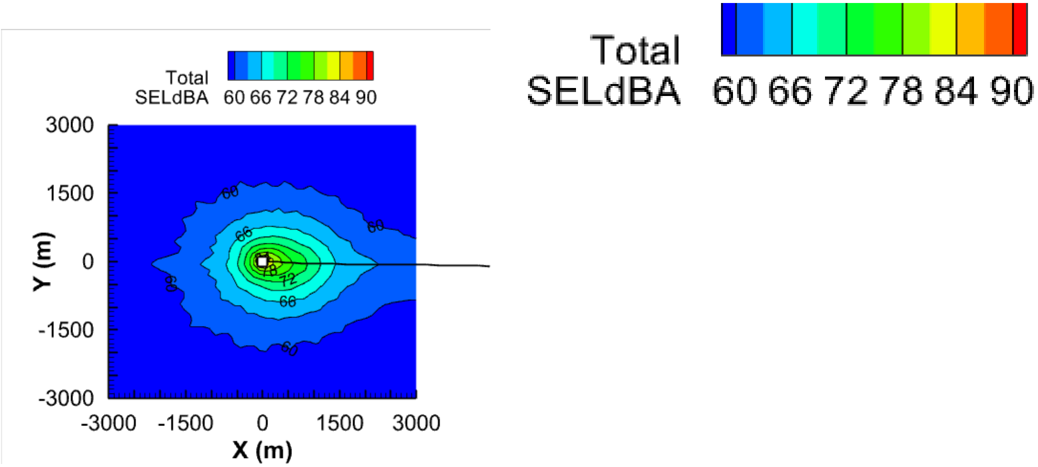

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