Stacked Rotor Performance and Acoustic Tradeoffs in Hover and Forward Flight

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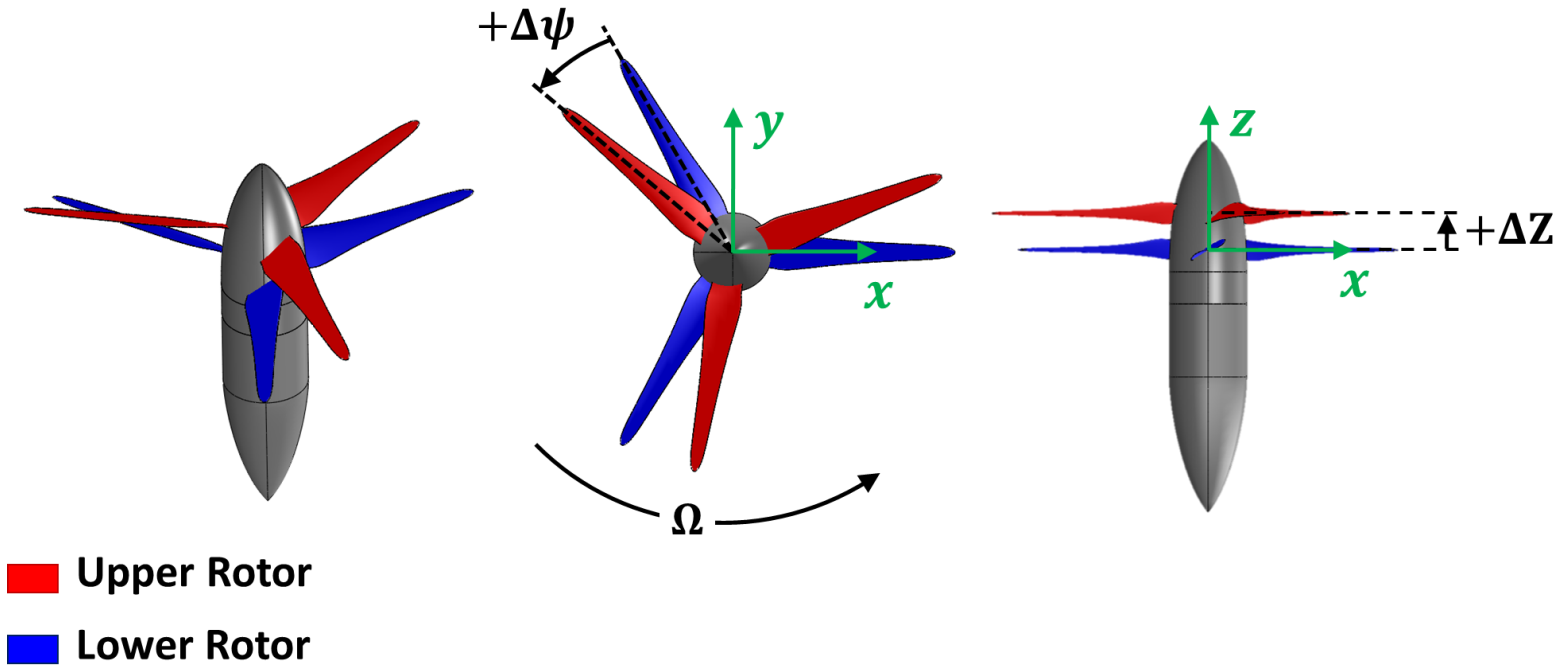
Outline

- Stacked Rotors Introduction
- Hover Experiments
  - Setup : SHAC [Small Hover Anechoic Chamber]
  - Performance and Acoustics Results
- Forward Flight Experiments
  - Setup : LSAWT [Low Speed Aeroacoustic Wind Tunnel]
  - Performance and Acoustics Results
- Conclusions

Introduction to Stacked Rotors

Stacked rotors definition: Multiple, corotating, rotors consisting of two or more blades, stacked axially out of plane of each other.

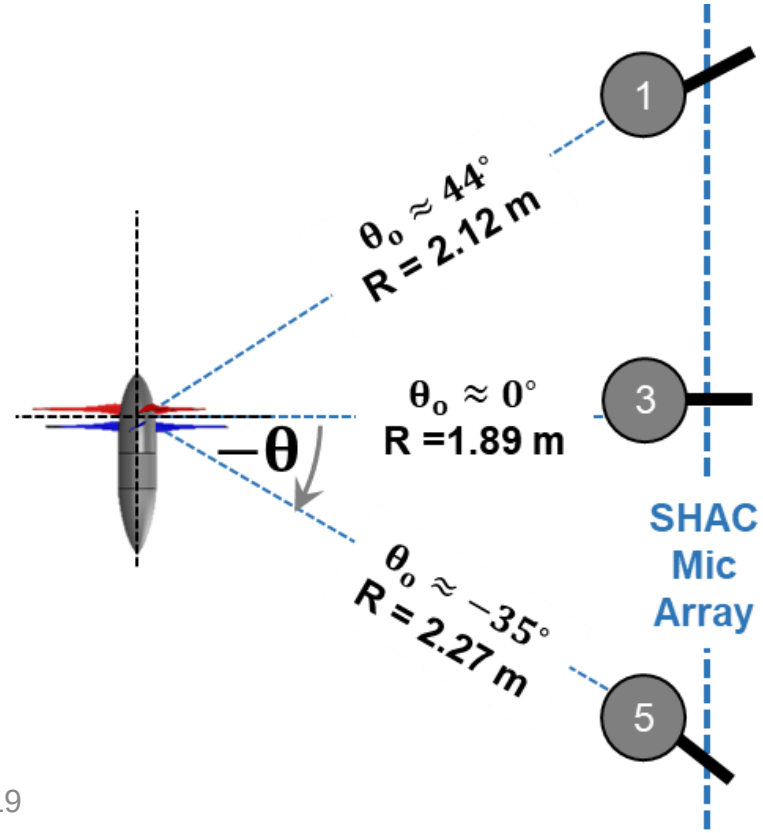
- Rotors
  - KDE Direct
  - R = 6.25 in.
  - 6 blades at various configurations
- Baseline Case
  - Coplanar, symmetric configuration
  - 6 blades
  - $\Delta\Psi = -60°$
  - $\Delta Z = 0.0R$

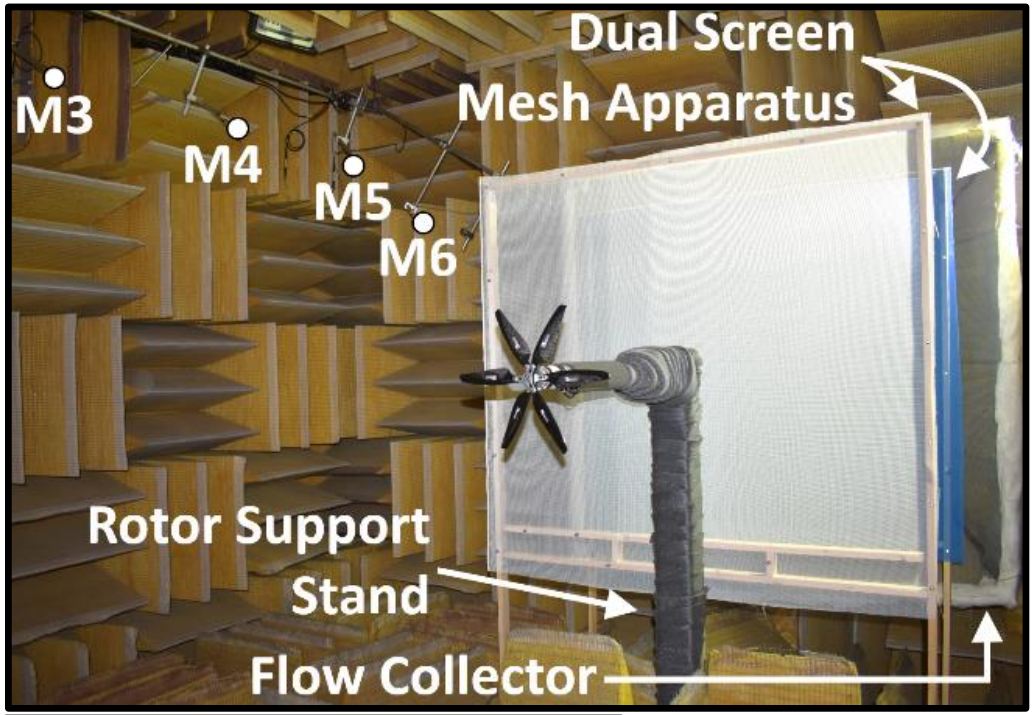


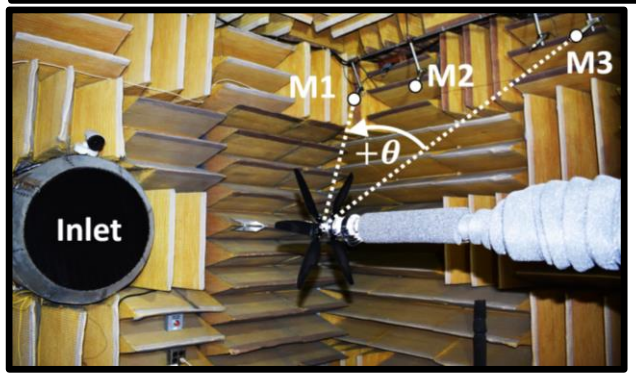
Azimuthal Offset $\Delta\Psi$,Stacking Offset ΔZ

Hover Tests – Experimental Setup

- Data taken in Small Hover Acoustic Chamber (SHAC, formerly SAJF)
- Results published in AIAA SciTech 2019*





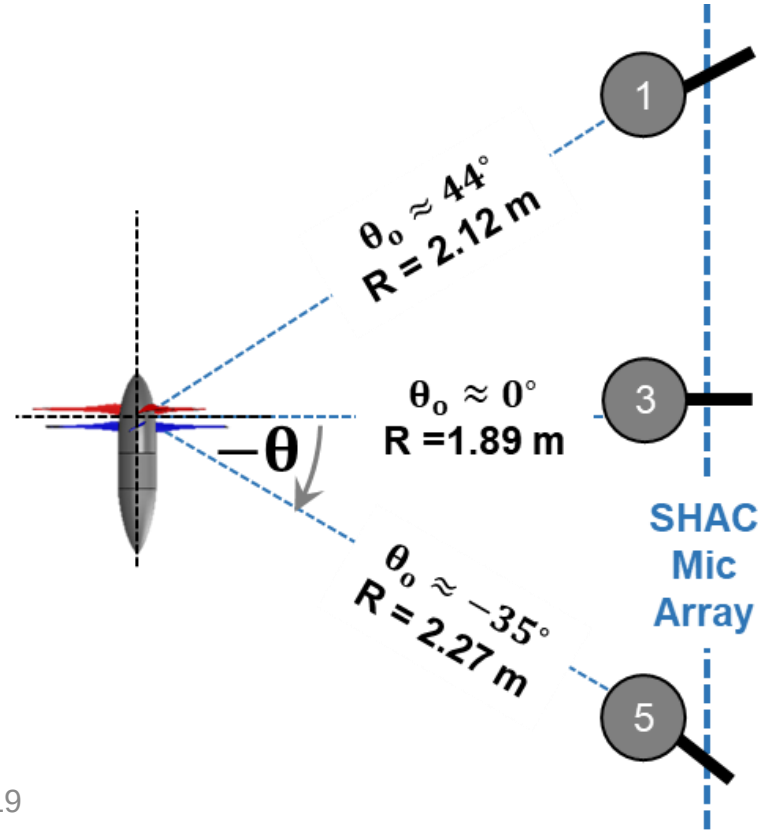


** Whiteside, S. K. S., Zawodny, N. S., Fei, X., Pettingill, N. A., Patterson, M. D., Rothhaar, P. M., "An Exploration of the Performance and Acoustic Characteristics of UAV-Scale Stacked Rotor Configurations", AIAA SciTech 2019, https://doi.org/10.2514/6.2019-1071*

Hover Tests – Experimental Setup

- Fourteen rotor configurations tested
- Load cell used to collect thrust data

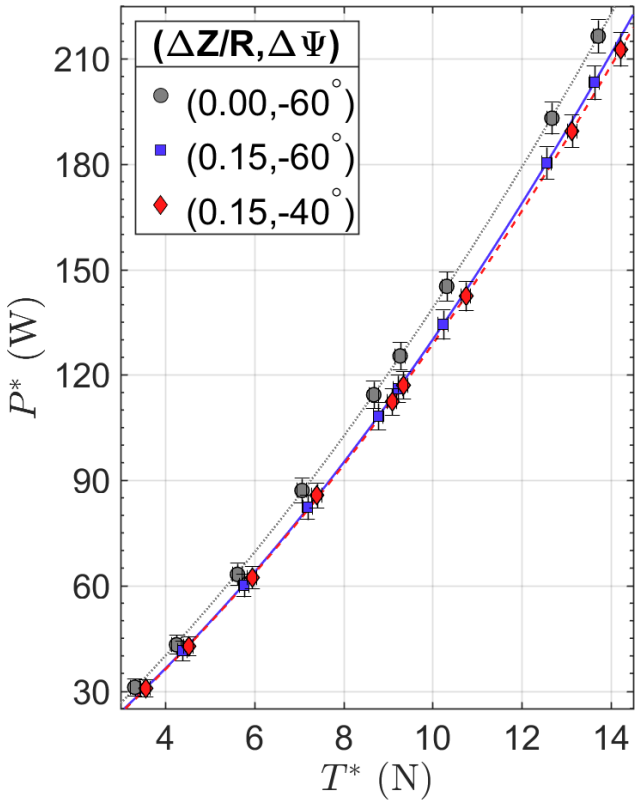
- Three configurations will be presented here, at 9N (2 lb) thrust condition
- Post-Process: spectra at M5 ($\theta = -35°$) and A-Weighted OASPL (L_A)



Configuration→ Parameter ↓	Coplanar	Stacked, Symmetrically Offset	Stacked, Asymmetrically Offset
Axial Spacing ($\Delta Z/R$)	**0.0**	0.08, **0.15**, 0.20, 0.25	**0.15**
Azimuthal Spacing ($\Delta\psi$)	**-60°**	**-60°**	+/- 10°,+/- 20°, +/- 30°,+/- **40°**

Results - Hover

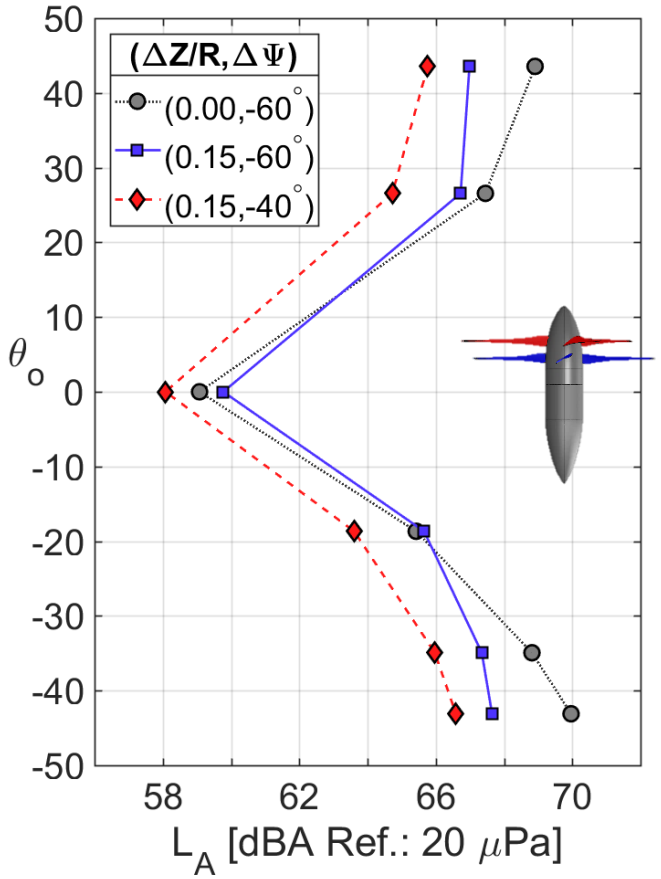
Performance



For T = 9 N (2 lb), rotor mechanical power **savings** of:

- 6.9% for stacked rotor ($\Delta Z/\mathrm{R} = 0.15, \Delta\Psi = -60°$)
- 7.6% for azimuthally offset rotor ($\Delta Z/\mathrm{R} = 0.15, \Delta\Psi = -40°$)

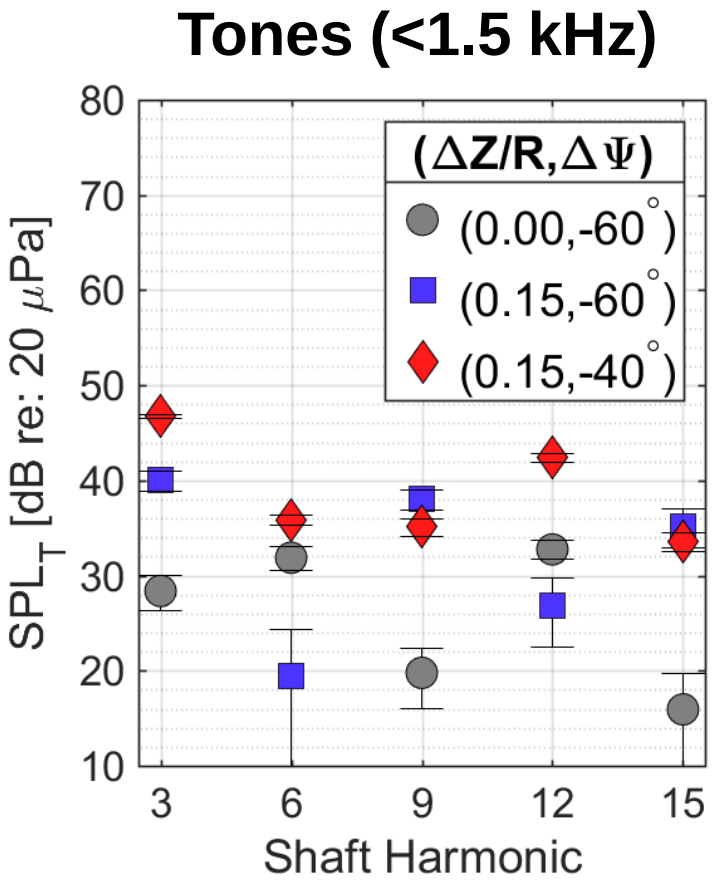
Acoustics

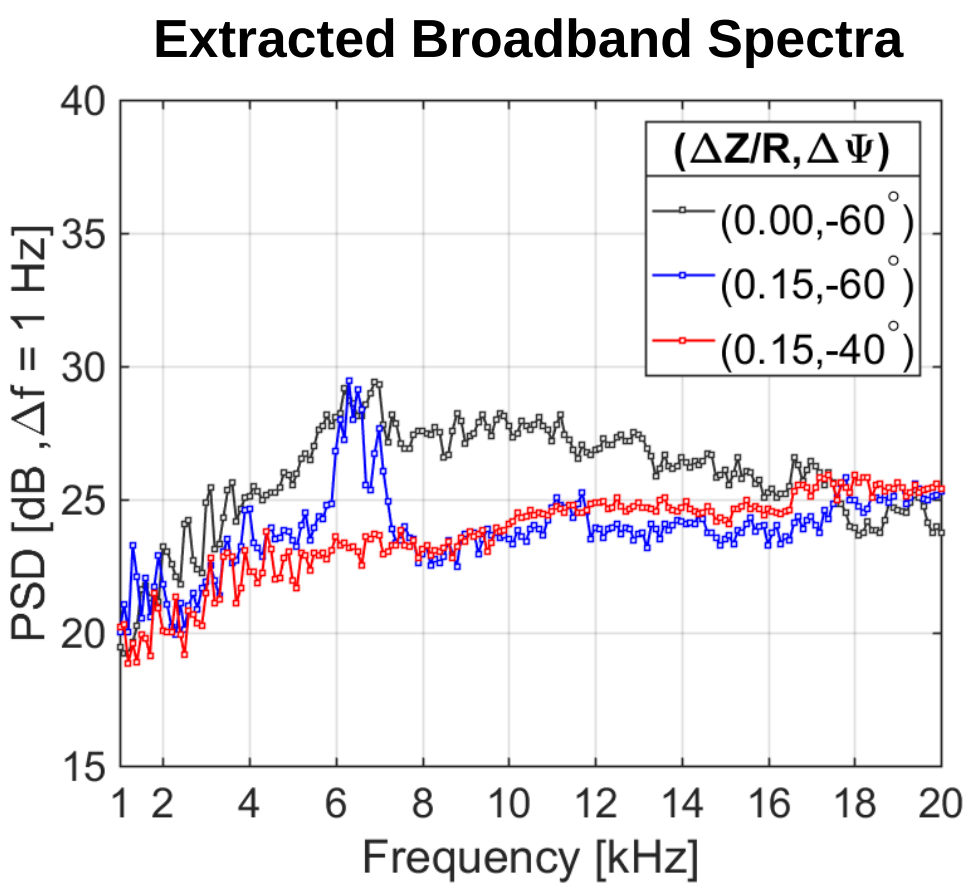


For asymmetrically stacked configuration ($\Delta Z/\mathrm{R} = 0.15, \Delta\Psi = -40°$):

- Noise **reduction** up to 3.4 dBA

Results - Hover





Stacking Effect

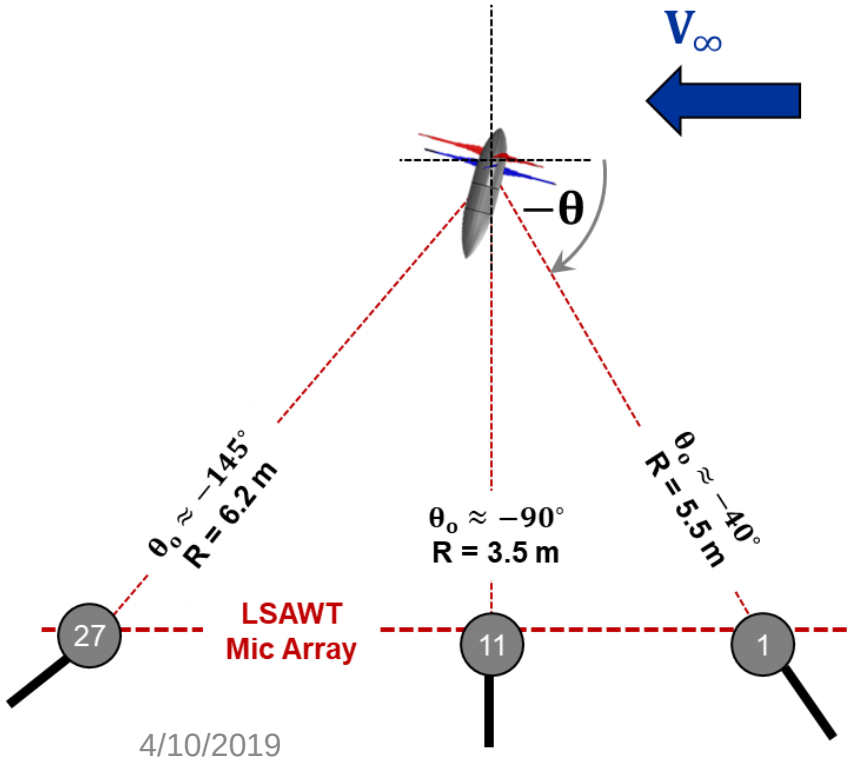
- Low frequency tonal noise increases with stacking
- High frequency broadband noise always less than baseline with stacking

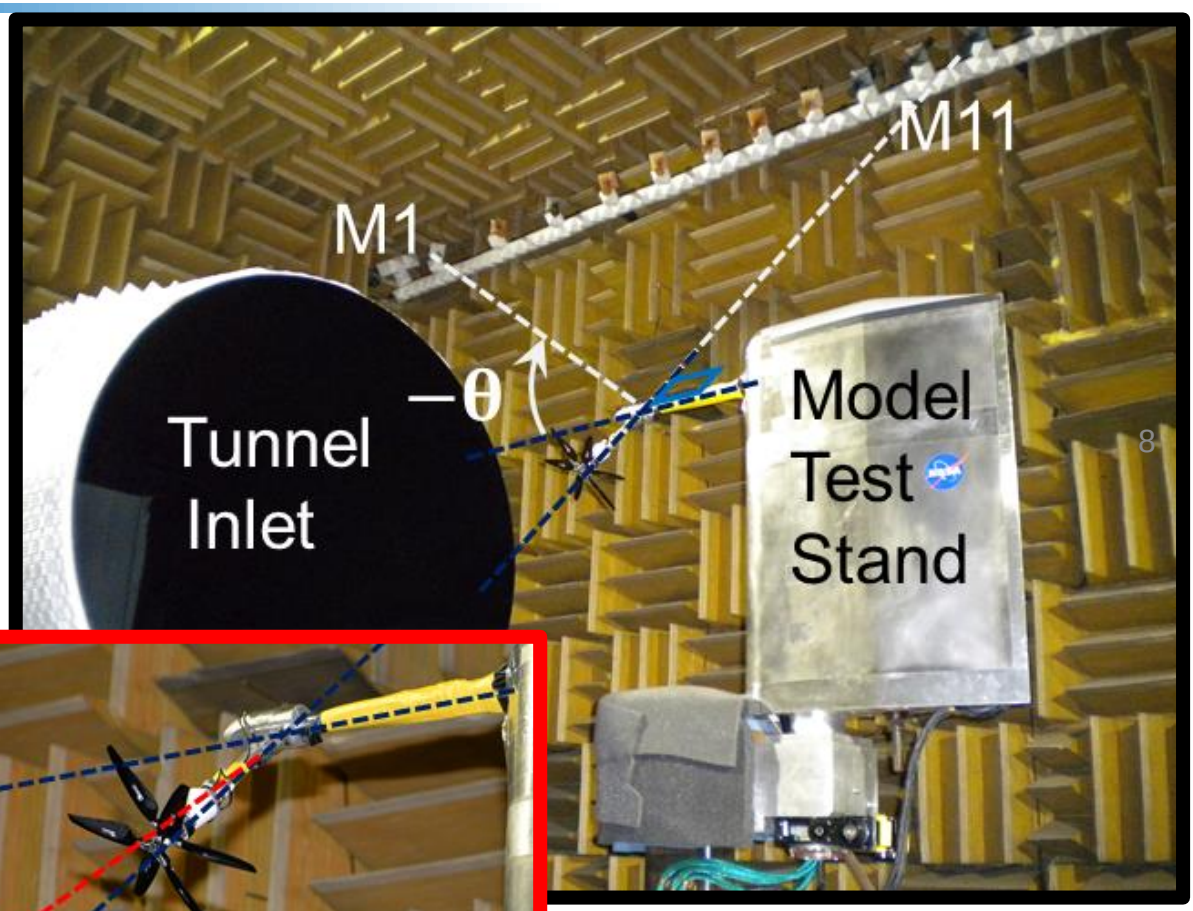
Azimuthal Offset Effect

- Tonal noise increases with reduction of $\Delta\Psi$

Forward Flight Tests – Experimental Setup

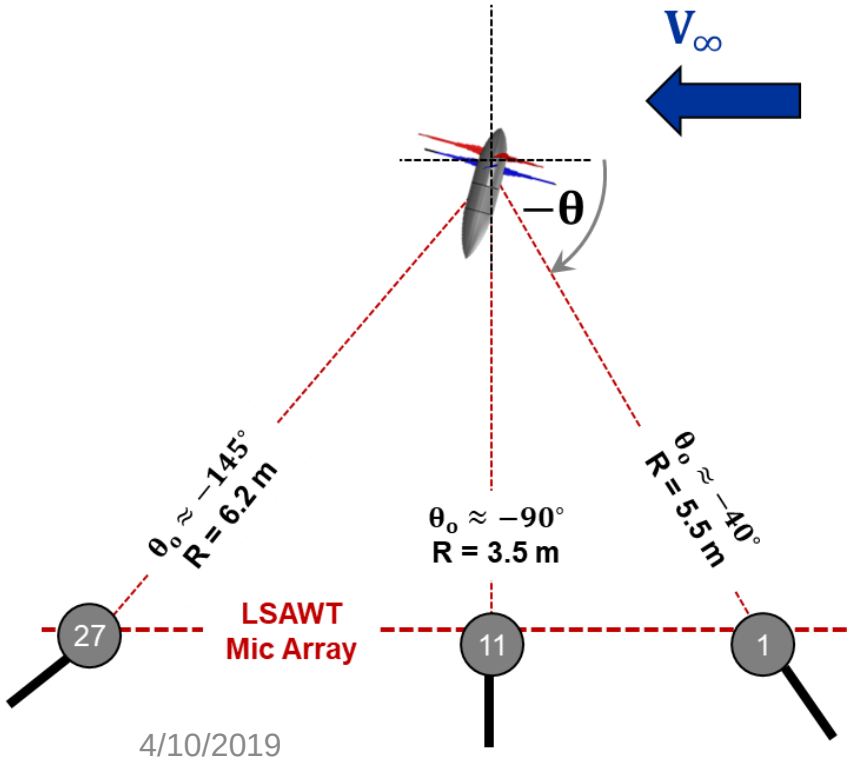
- Data recently taken at the Langley Low Speed Aeroacoustic Wind Tunnel (LSAWT)
- Rotors pitched forward $\alpha = -10°$
- Tunnel flow speed of $V_\infty \approx 16\, m/s$

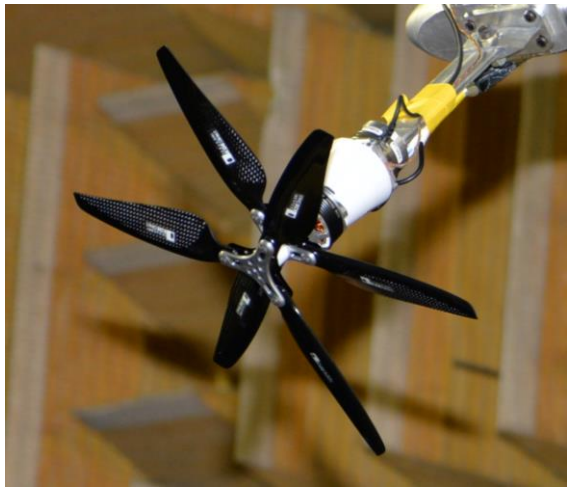




Forward Flight Tests – Experimental Setup

- Three rotor configurations tested
- Load cell used to collect thrust data
- Post-Process: spectra at M7 ($\theta \approx -70°$) , and A-Weighted OASPL (L_A)





Configuration→ Parameter ↓	Coplanar	Stacked, Symmetrically Offset	Stacked, Asymmetrically Offset
Axial Spacing $(\Delta Z/R)$	$\mathbf{0.0}$	$\mathbf{0.15}$	$\mathbf{0.15}$
Azimuthal Spacing $(\Delta\psi)$	$\mathbf{-60°}$	$\mathbf{-60°}$	$\mathbf{-40°}$

Acoustics Results – Forward Flight

Performance

For T = 9 N (2 lb), rotor mechanical power **savings** of:

- 9.6% for stacked rotor ($\Delta Z/\mathrm{R} = 0.15, \Delta\Psi = -60°$)
- 15.4% for azimuthally offset rotor ($\Delta Z/\mathrm{R} = 0.15, \Delta\Psi = -40°$)

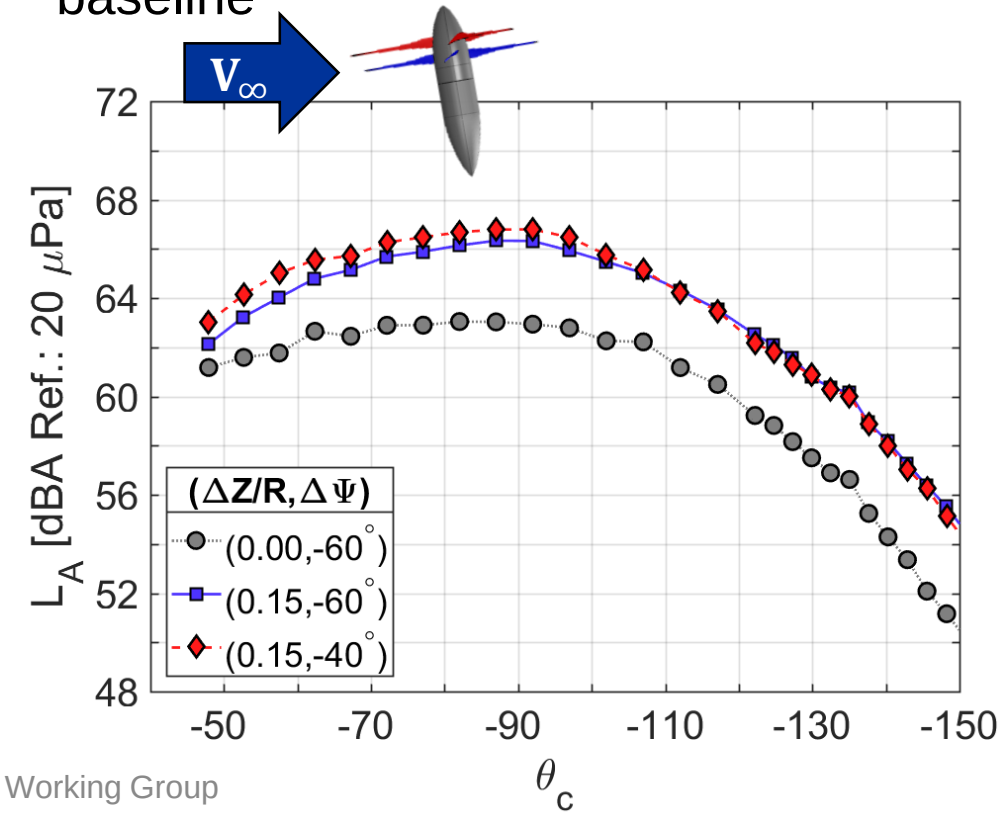
Config. $(\Delta Z/R, \Delta\psi)$	Ω (RPM)	P_{mech} (W)	P_{elec} (W)	ΔP_{mech}* (%)	ΔL_A** (dBA)
$(0.0, -60°)$	4828	105.5	137.2	-	-
$(0.15, -60°)$	4715	95.4	124.5	-9.6	+3.4
$(0.15, -40°)$	4511	89.3	117.4	-15.4	+3.9

*Relative to baseline configuration

**Computed at polar flyover angle of $\theta = 90°$

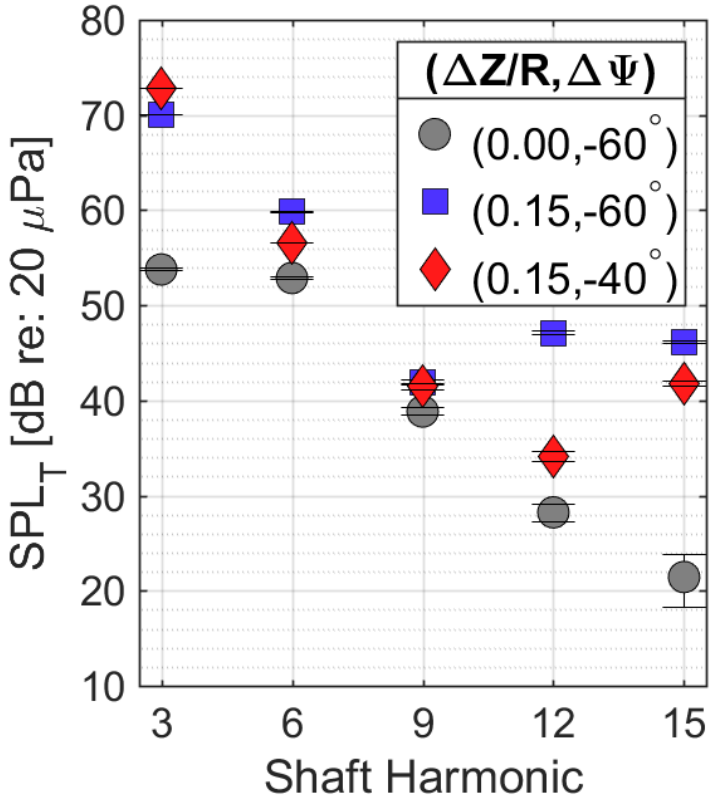
Acoustics

Stacked rotors yield noise **detriments** of 3.4/3.9 dB (sym./asym) when compared to baseline

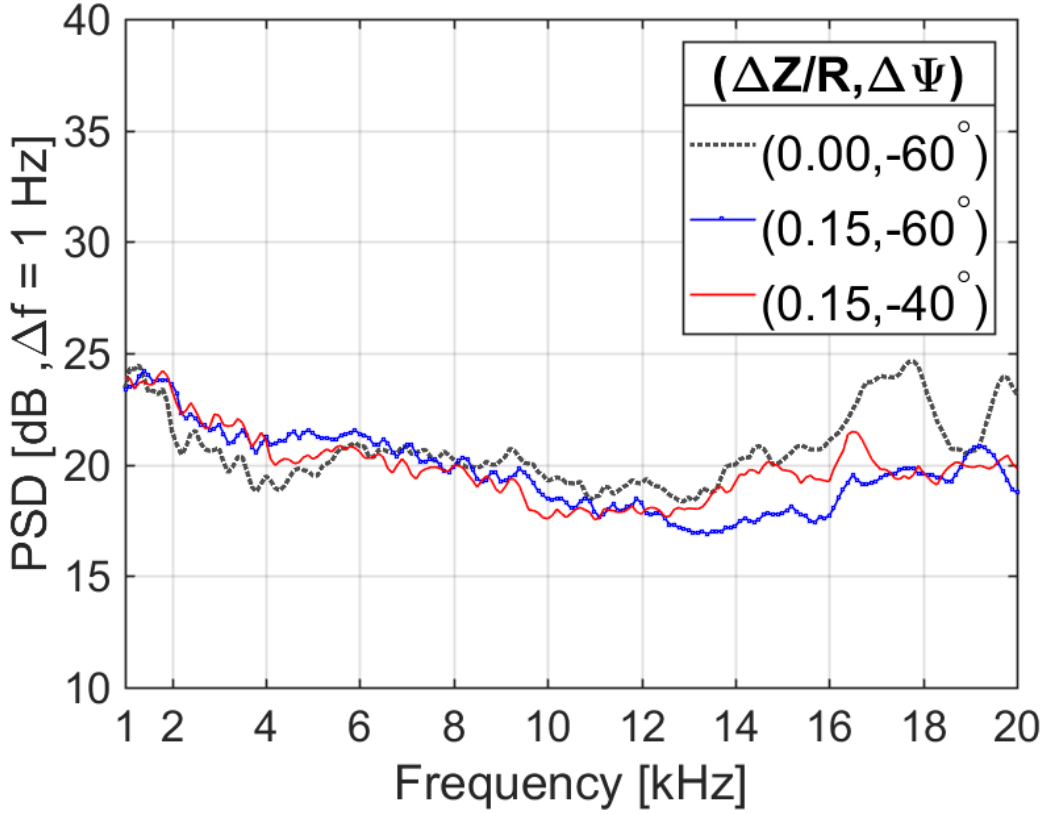


Results – Forward Flight

Tones (<1.5 kHz)



Extracted Broadband Spectra



Stacking Effect

- Low frequency tonal noise increases with stacking
- High frequency broadband noise less than baseline with stacking (but not enough to make up for tonal noise)

Azimuthal Offset Effect

- Third shaft harmonic increases with reduction of $\Delta\Psi$
- Not enough cases to see the effects on broadband noise

Results Summary

Hover

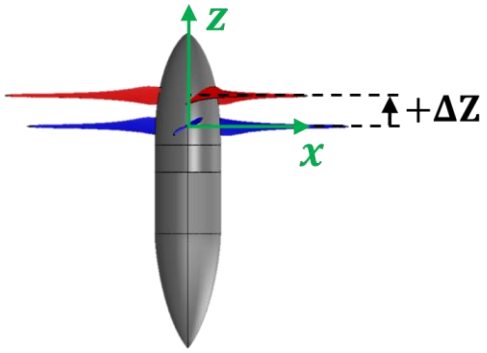
- Best Performance Cases
  - Axially offset and asymmetric configurations
  - $\Delta Z = 0.15R, \Delta\Psi = -60°$
  - $\Delta Z = 0.15R, \Delta\Psi = -40°$
  - **6.9% and 7.6%** less power to achieve 2 lb of thrust
- Best Acoustics Case
  - $\Delta Z = 0.15R, \Delta\Psi = -40°$
  - Noise ***reduction*** of 3.4 dBA from baseline

Forward Flight

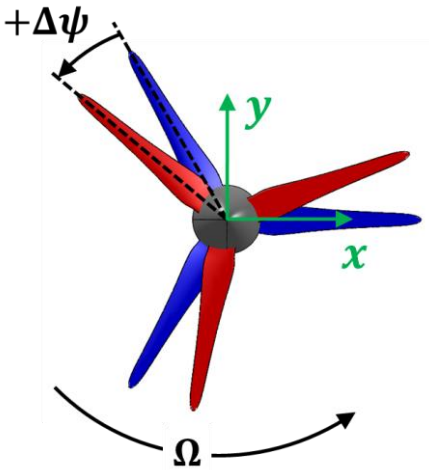
- Best Performance Cases
  - Axially offset and asymmetric configurations
  - $\Delta Z = 0.15R, \Delta\Psi = -60°$
  - $\Delta Z = 0.15R, \Delta\Psi = -40°$
  - **9.6% and 15.4%** less power to achieve 2 lb of thrust
- Best Acoustics Case
  - Baseline
  - Noise ***gain*** of 3.4 and 3.9 dBA for other two configurations

Initial conclusion: Stacked rotors provide performance benefits for hover and forward flight cases, but may not be effective concept for forward flight conditions with regards to noise

Stacking Offset ΔZ



Azimuthal Offset Δψ



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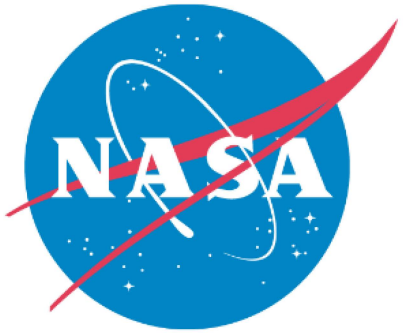
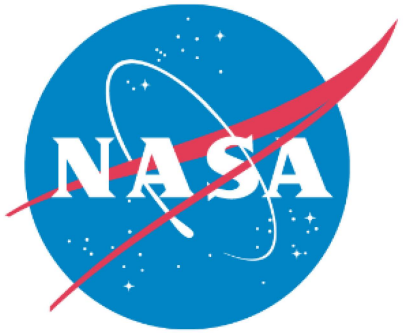
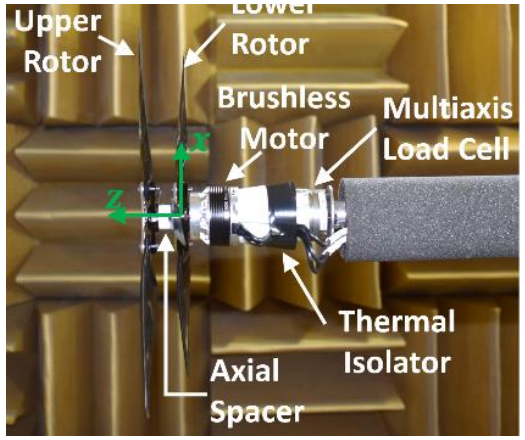
Thank you

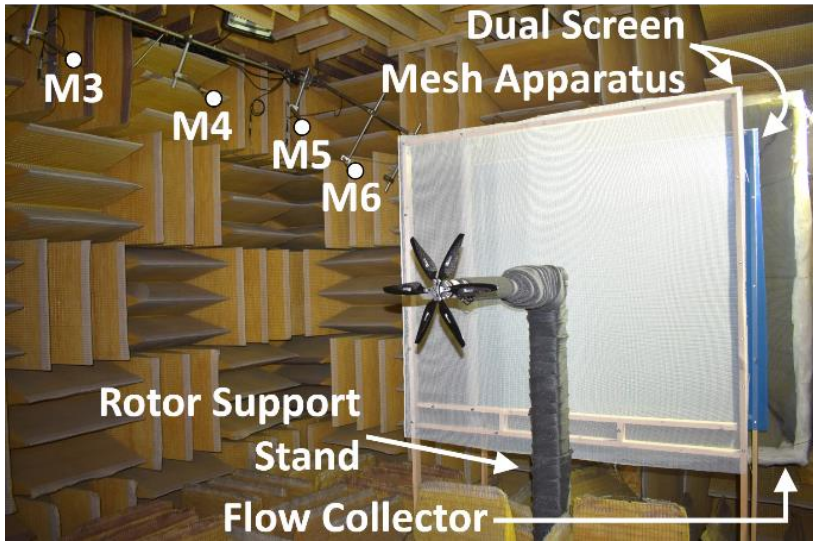


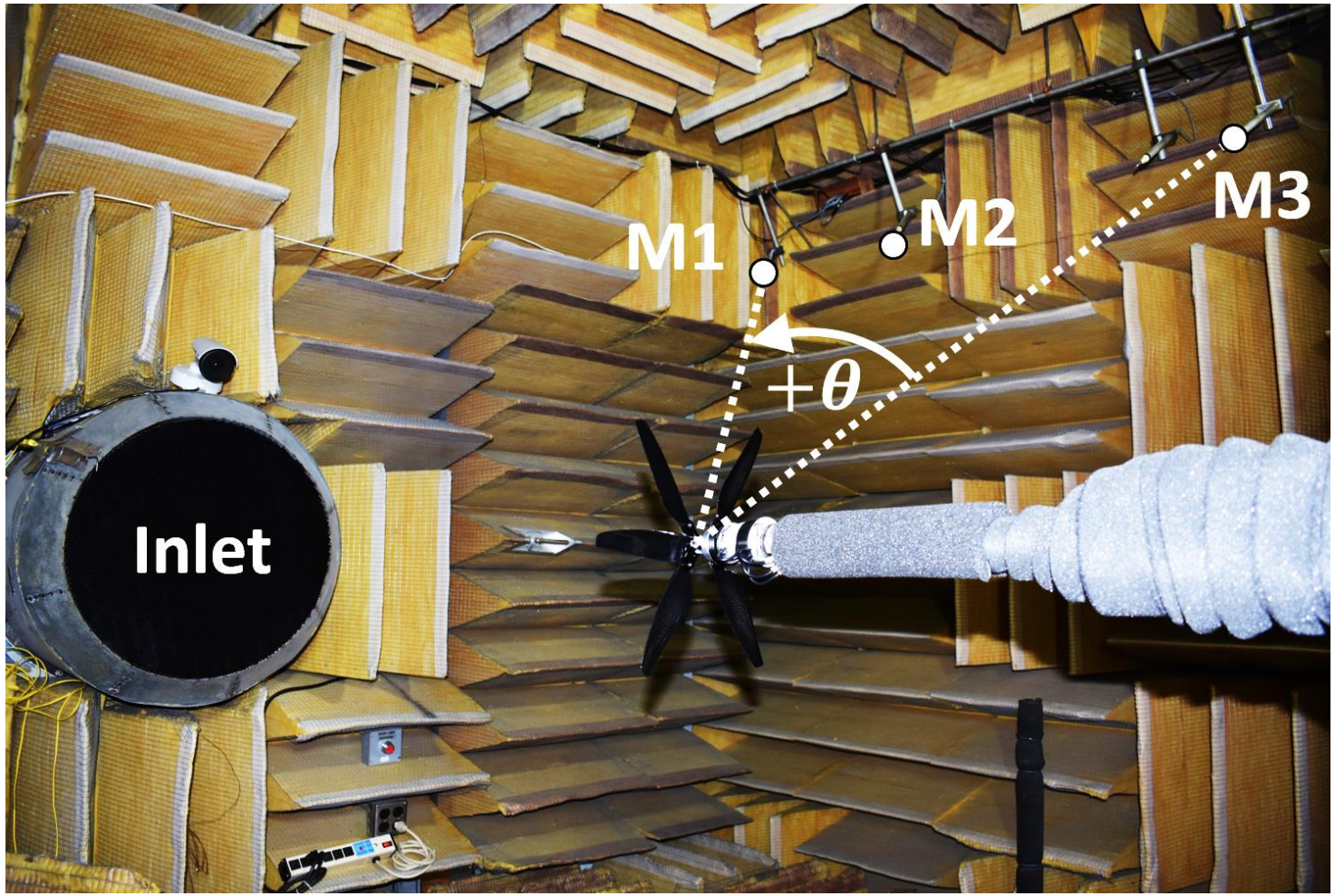
Extra Slides



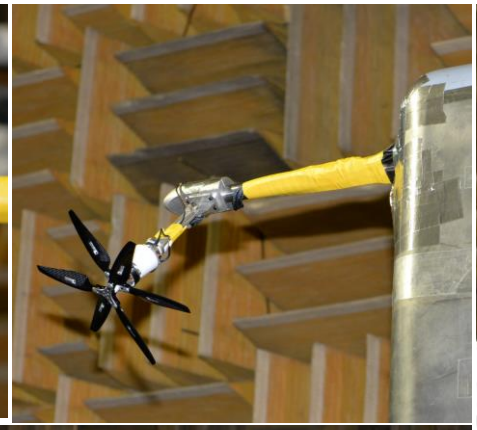
Hover Tests – Experimental Setup

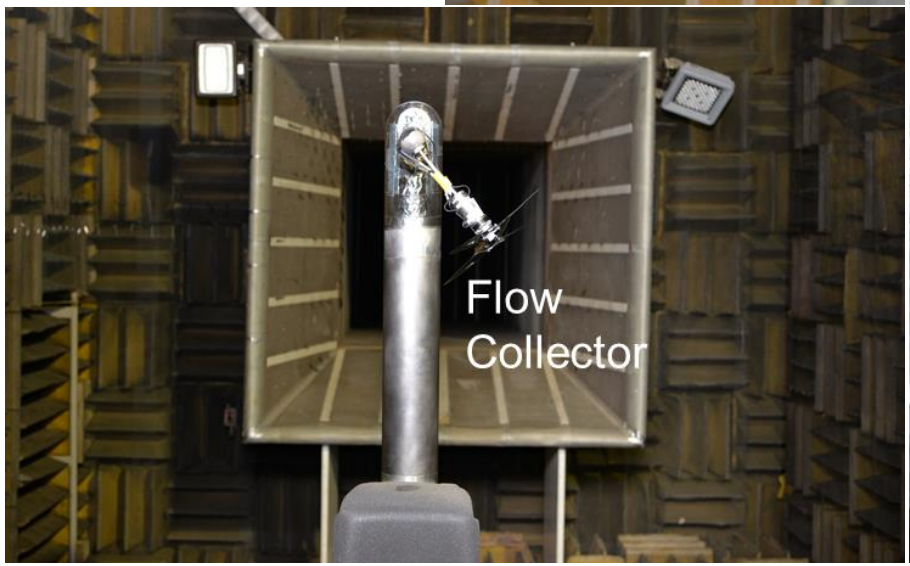


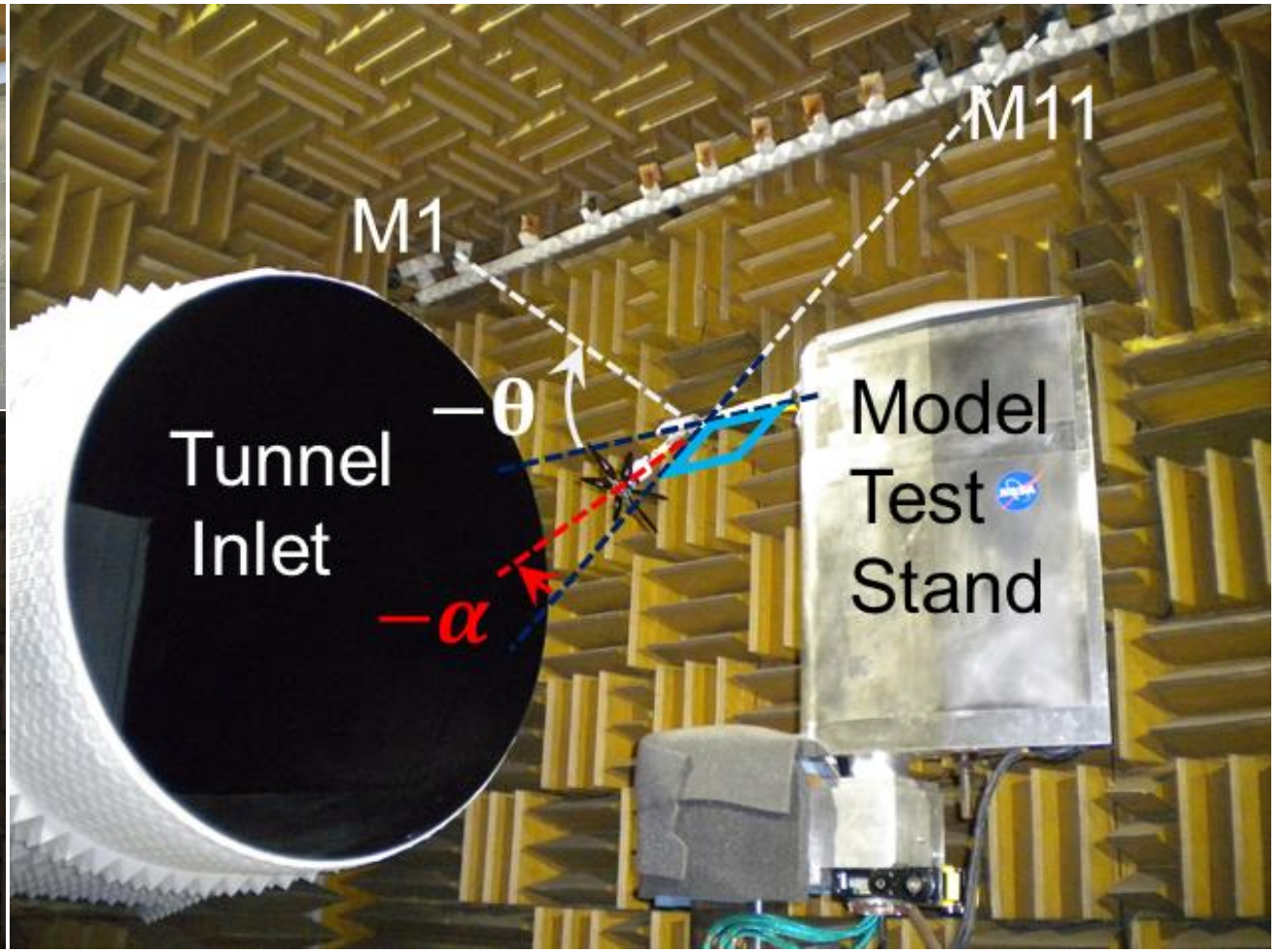




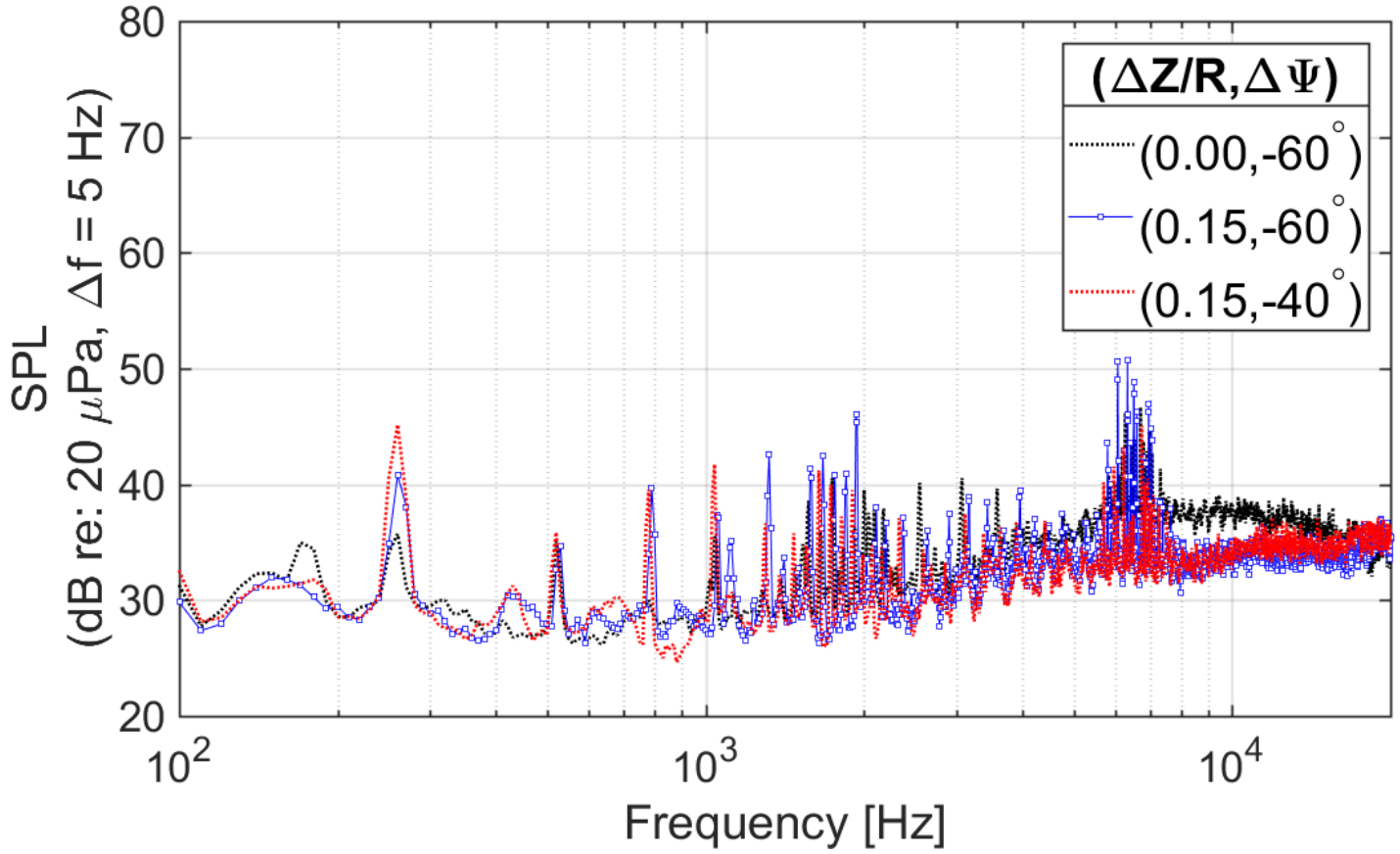
Forward Flight Tests – Experimental Setup



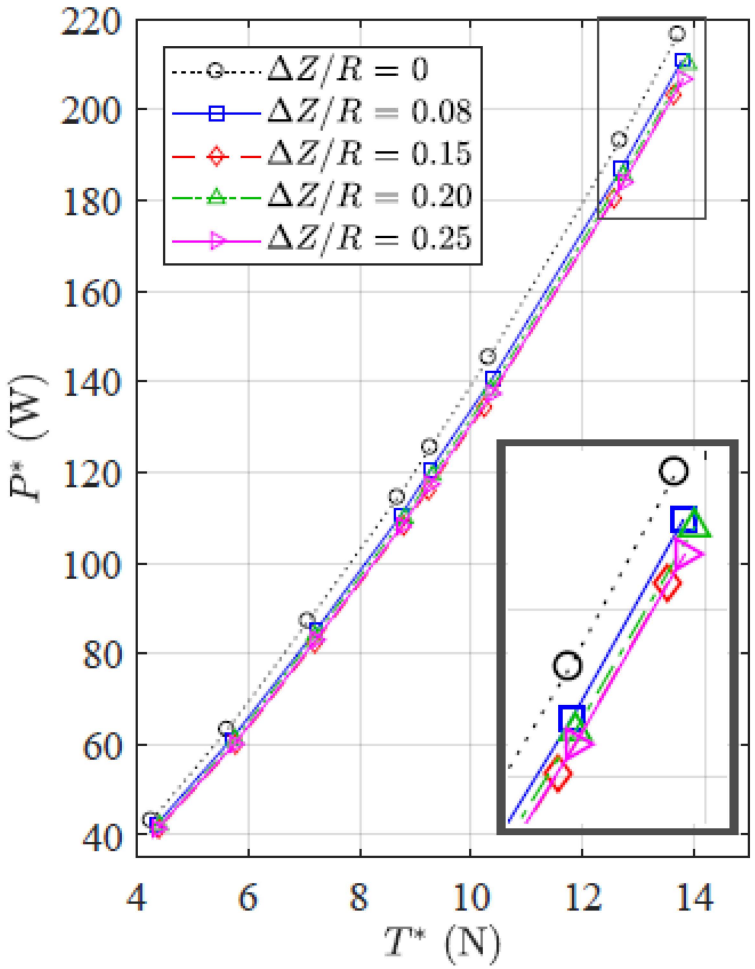


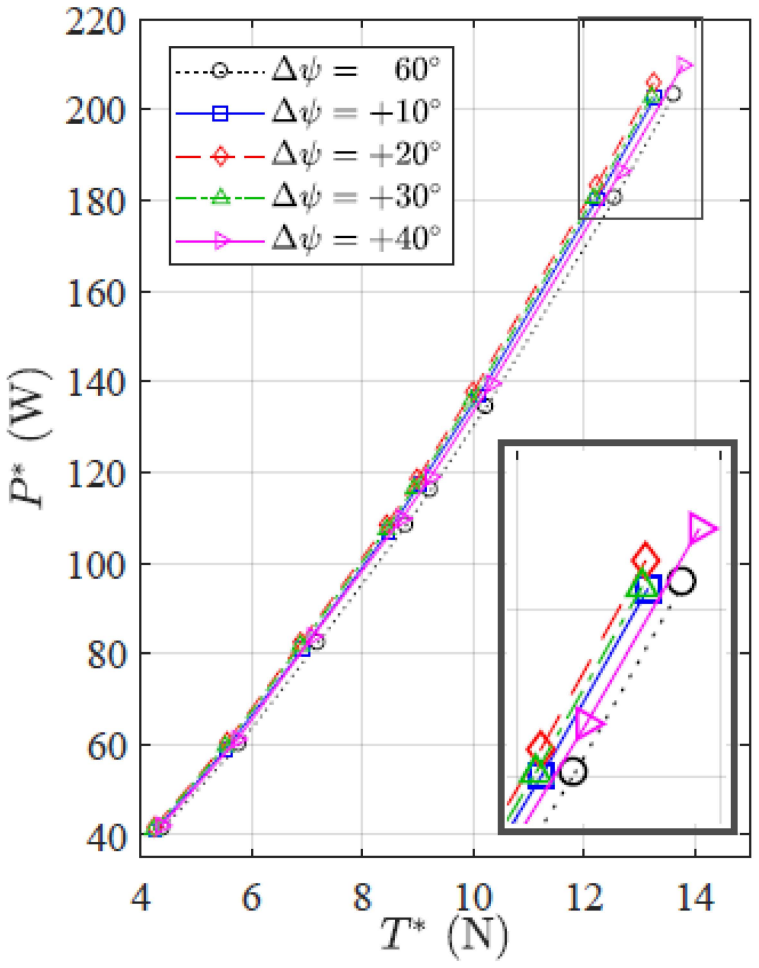


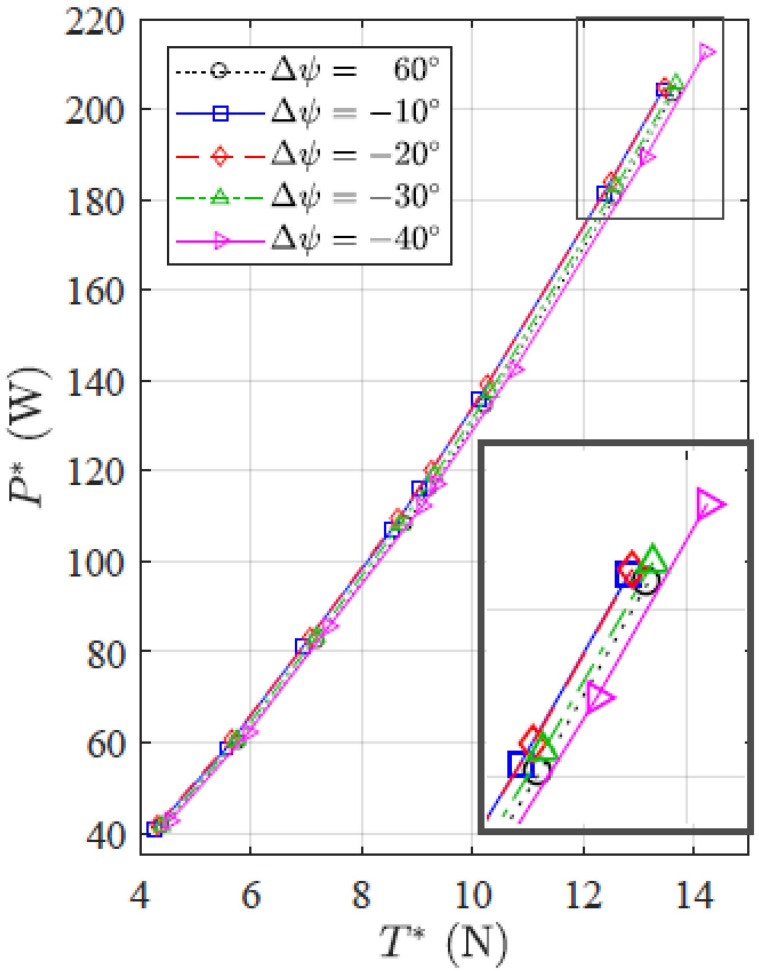
Results - Hover



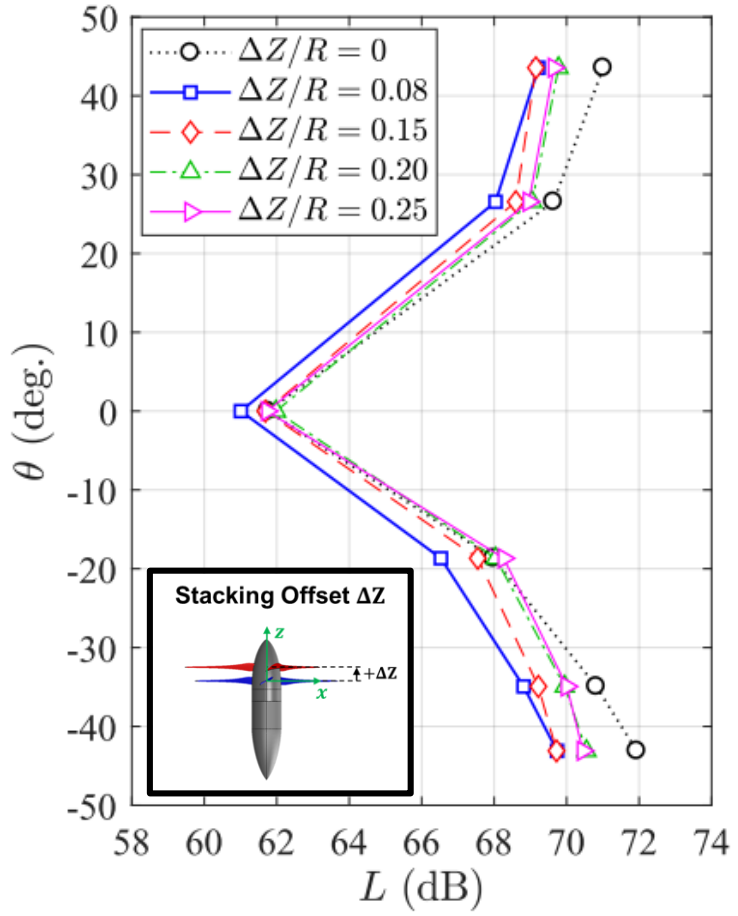
Results - Hover

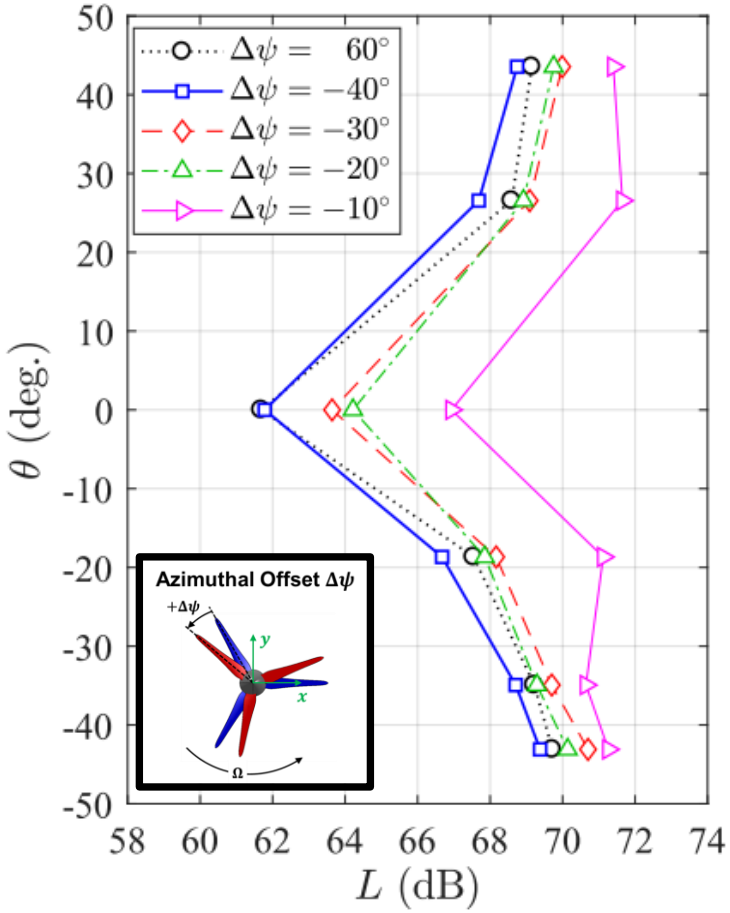






Results - Hover





Results – Forward Flight