Acoustic and Performance Measurements Obtained in the NASA Langley Small Hover Anechoic Chamber

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Personal Background

Where I'm From Houston, TX

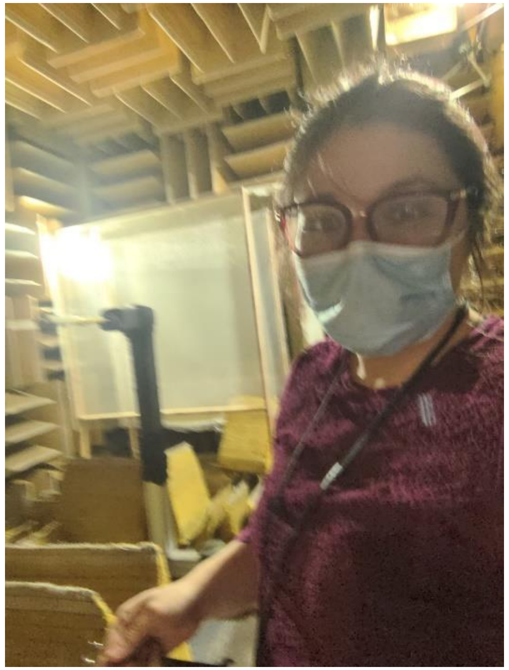
Where I Studied

- B.S. Mechanical Engineering, Lafayette College, Class of 2014
- M.S. Aerospace Engineering, Virginia Tech, Class of 2017

Where I Work Aeroacoustics Branch, NASA Langley Research Center

What I Do Research rotor noise for small Unmanned Aircraft Systems (sUAS), and electric Vertical Takeoff and Landing (eVTOL) aircraft

Interests Painting, slowpitch softball, cats, roller skating

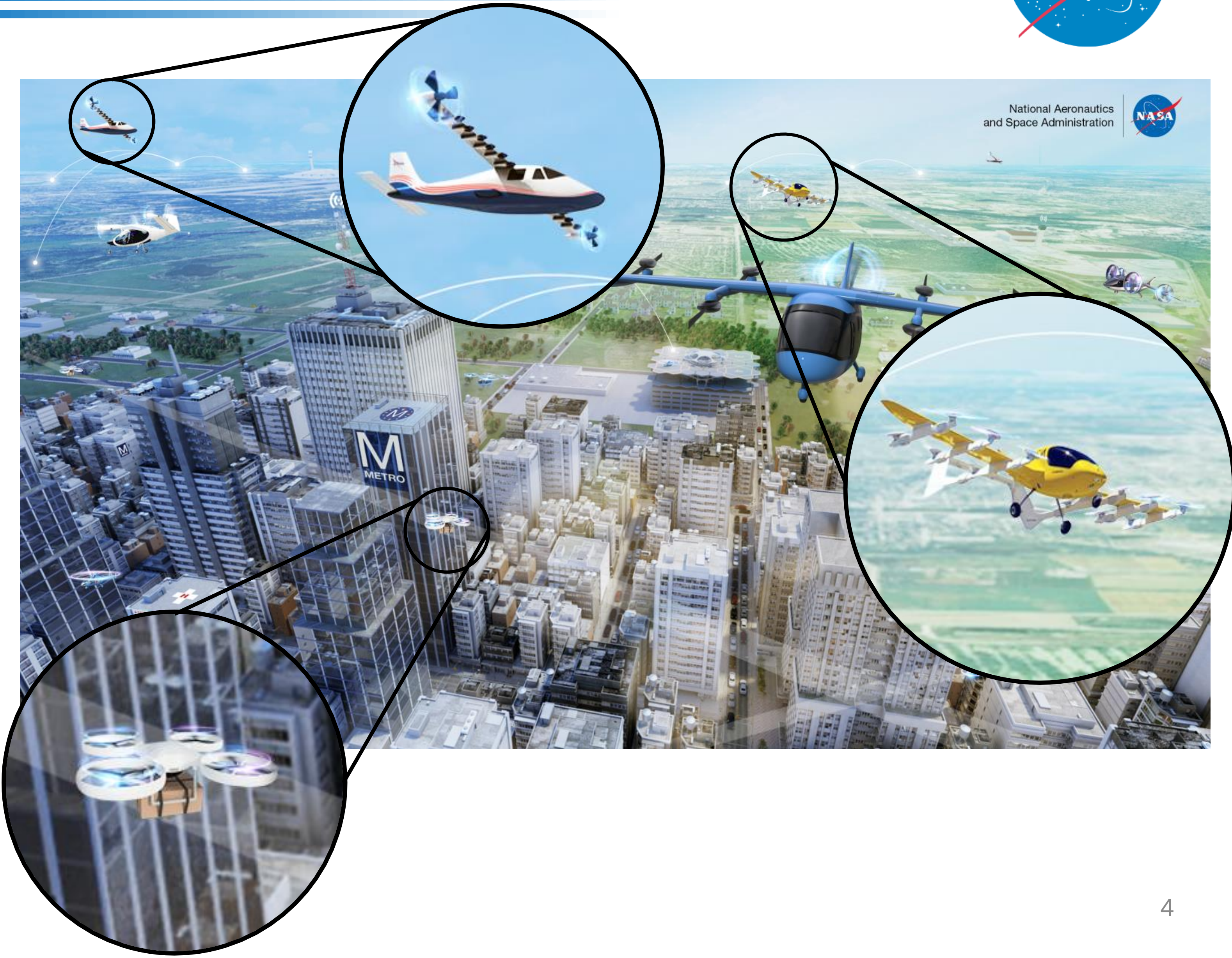


Presentation Outline

- Introduction and motivation for hover experiments
- Summary of tests in the SHAC
- Ideal Twist Experiment
  - Facility and hardware set up
  - Performance and Acoustic Data
- Additional tests

Introduction

- ***Advanced Air Mobility (AAM)*** is working to create ***safe***, ***sustainable***, ***accessible***, *and* ***affordable*** aviation to move ***people*** and ***packages***.
- Rotary-wing vehicles now include traditional ***helicopters***, ***urban air mobility (UAM)*** vehicles, and ***small unmanned aerial systems (sUAS).***
- ***Noise*** may be a ***key barrier*** for ***community acceptance,*** and ***rotors*** contribute significantly to the noise signature of these vehicles.
- The AAM industry motivates us to ***characterize noise sources*** to assess the ***community impact*** of these new vehicle concepts.
- ***Hover chamber tests*** of small rotors are beneficial in assessing the ***potential noise impact*** of small unmanned aerial vehicles (sUAS) and urban air mobility (UAM) vehicles

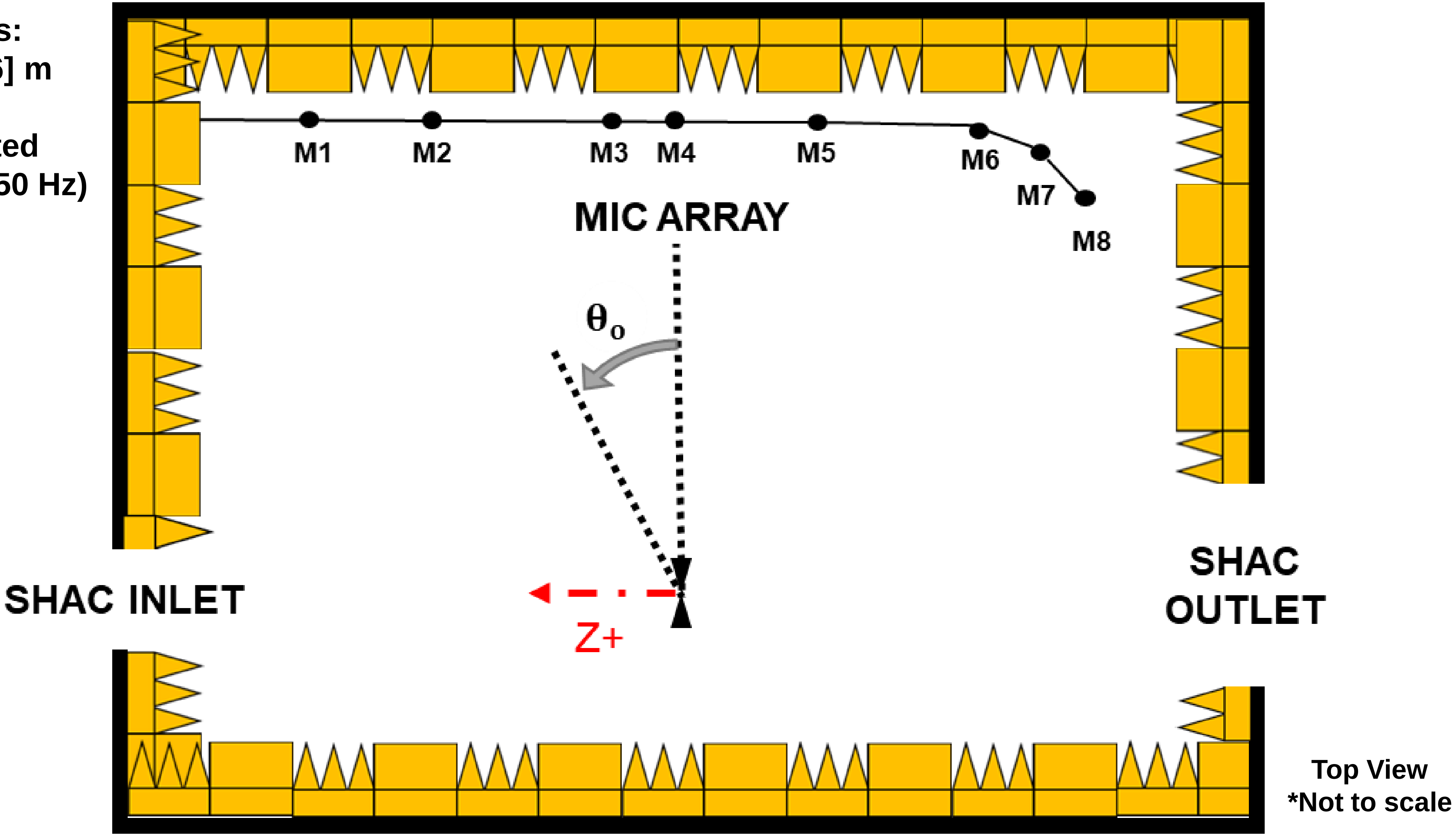


Small Hover Anechoic Chamber

SHAC

Room dimensions:
[3.87 x 2.56 x 3.26] m

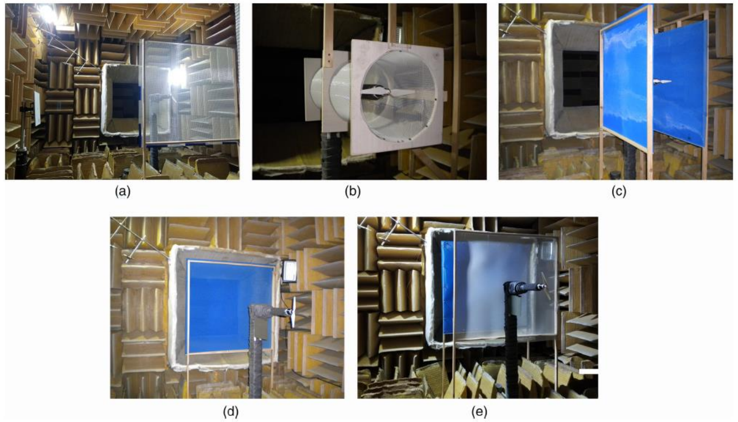
Acoustically treated
(cutoff down to 250 Hz)



SHAC Tests

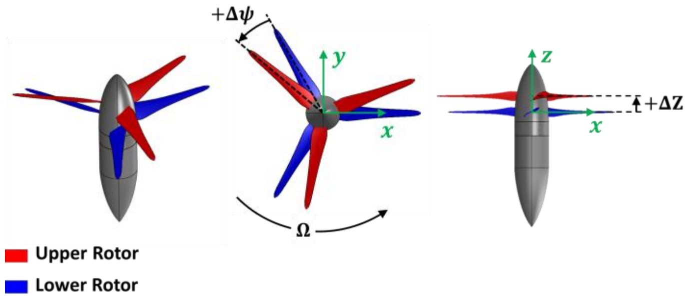
1. Recirculation in chamber:

Weitsman, D., Stephenson, J. H., & Zawodny, N. S. “Effects of flow recirculation on acoustic and dynamic measurements of rotary-wing systems operating in closed anechoic chambers.” *The Journal of the Acoustical Society of America*, Vol. 148, No. 3, 2020, pp. 1325–1336. https://doi.org/10.1121/10.0001901


(a) (b) (c)
(d) (e)

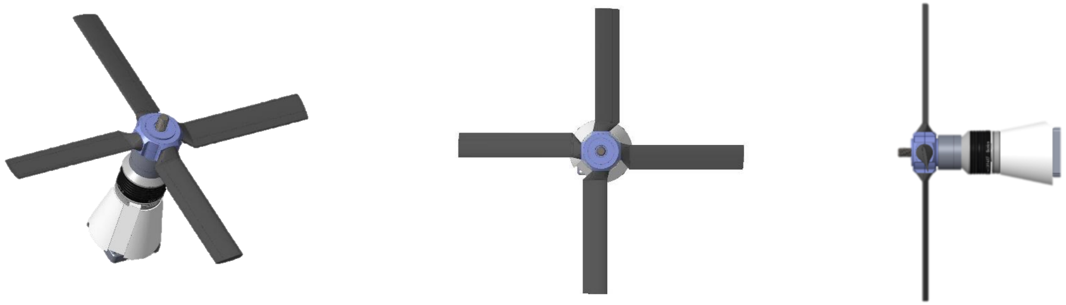
2. Stacked rotors:

Whiteside, S., Zawodny, N., Fei, X., Pettingill, N. A., Patterson, M. D., and Rothhaar, P., “An Exploration of the Performance and Acoustic Characteristics of UAV-Scale Stacked Rotor Configurations,” *AIAA Scitech 2019 Forum*, San Diego, CA, Jan. 2019, https://doi.org/10.2514/6.2019-1071

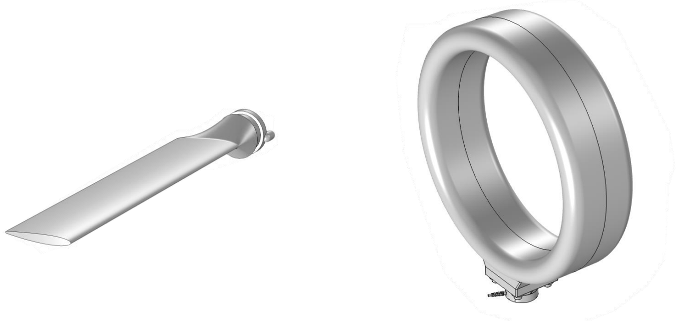


3. Ideally twisted rotors:

Pettingill, N. A., Zawodny, N. S., Thurman, C., & Lopes, L. V. “Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover.” *AIAA Scitech 2021 Forum*, Virtual, Jan. 2021, https://doi.org/10.2514/6.2021-1928

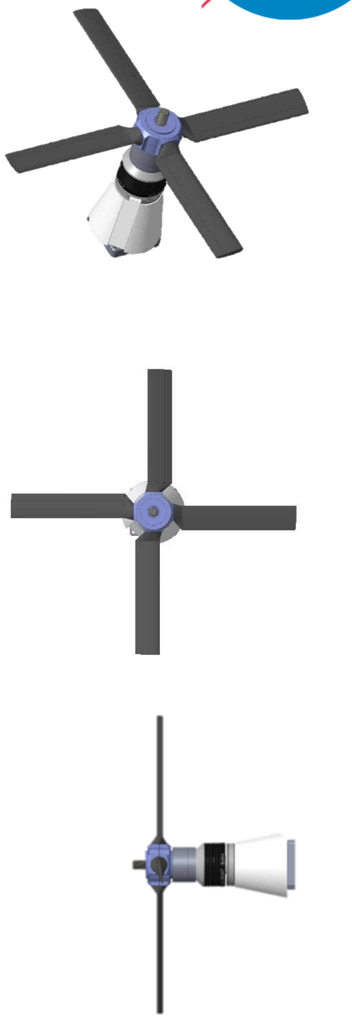


4. Ducted propellers (recent work)



Ideally Twisted Rotor Test

Ideally Twisted Rotor Test



A series of experiments were conducted in an anechoic hover chamber to investigate the noise and performance of an ideally twisted rotor design. The results of this test were compared with those of noise prediction tools.

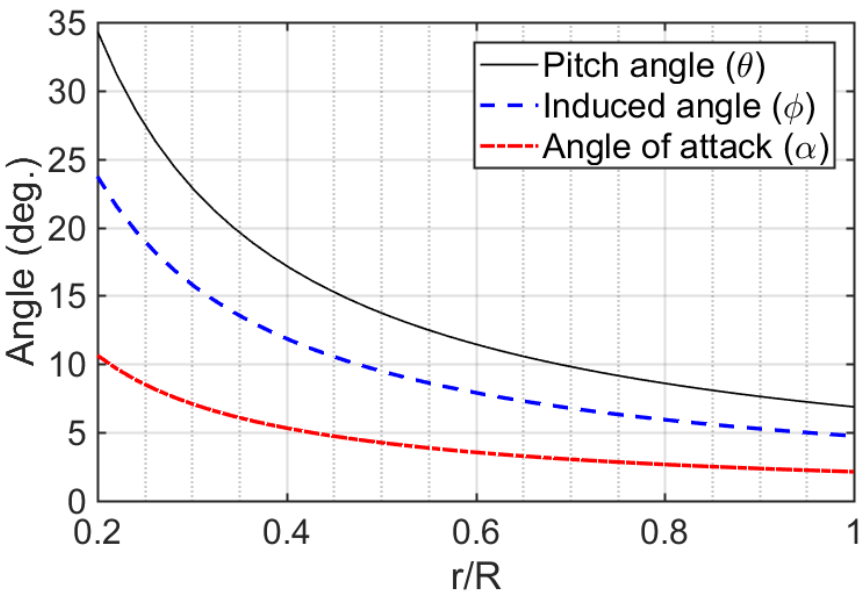
- With commercial off the shelf (COTS) rotors, it is not always possible to know the **exact geometric properties** or the ***complexity of the inflow***
- A rotor with an ideal twist distribution ***theoretically*** has ***uniform inflow,*** which may be simpler to predict using low-fidelity tools

Ideally Twisted Rotor Design

Blade element momentum theory (BEMT)

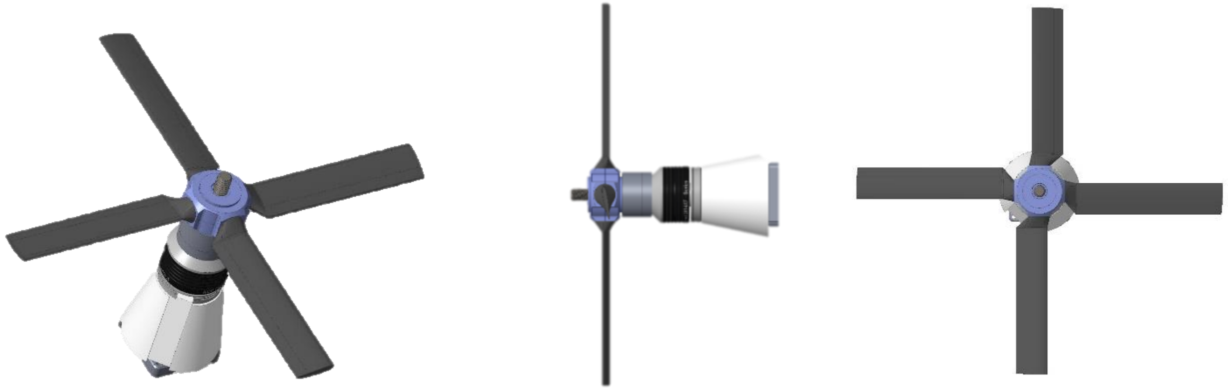
- Target thrust = 11.12 N
- Tip angles
  - Pitch $\theta = 6.9°$
  - Induced $\phi = 4.7°$
  - Angle of attack $\alpha = 2.1°$

	Parameter	Value
Geometry	R (m)	0.1588
	c/R	0.20
	Θ_{tip} (°)	6.9
	N_b	4
	σ	0.255
Operating Condition	C_T	0.0137
	M_{tip}	0.27
	Ω_c (RPM)	5500



Additional design features

- NACA 0012 airfoil

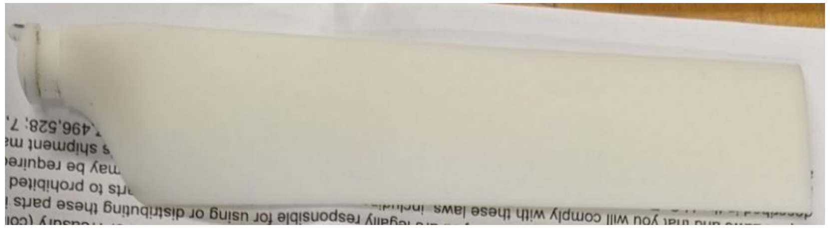


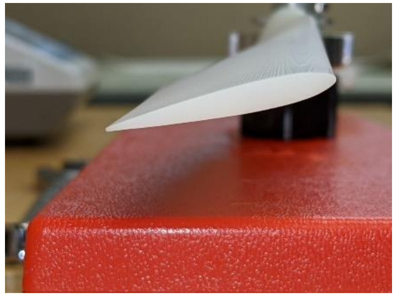
Blade sets

In-house Markforged blades

- Onyx material: microcarbon fiber filled nylon plastic
- Aluminum ejector pin inserted span-wise to improve stiffness

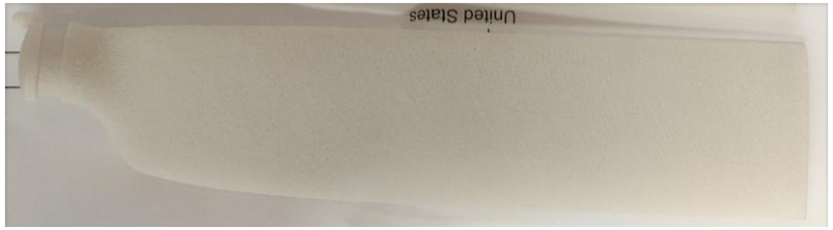
Protolabs SLA “smooth” blades

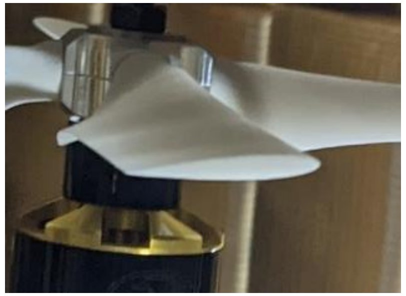




- Accura Xtreme White 200 material: similar to injection molded resin (“ABS-like”)
- Manufactured via stereolithography (SLA)

Protolabs SLS “rough” blades





- PA 12 material: 25% mineral-filled nylon
- Manufactured via selective laser sintering (SLS)

COTS varioPROP hub

Experiment: Facility and Setup

Small Hover Anechoic Chamber (SHAC)*

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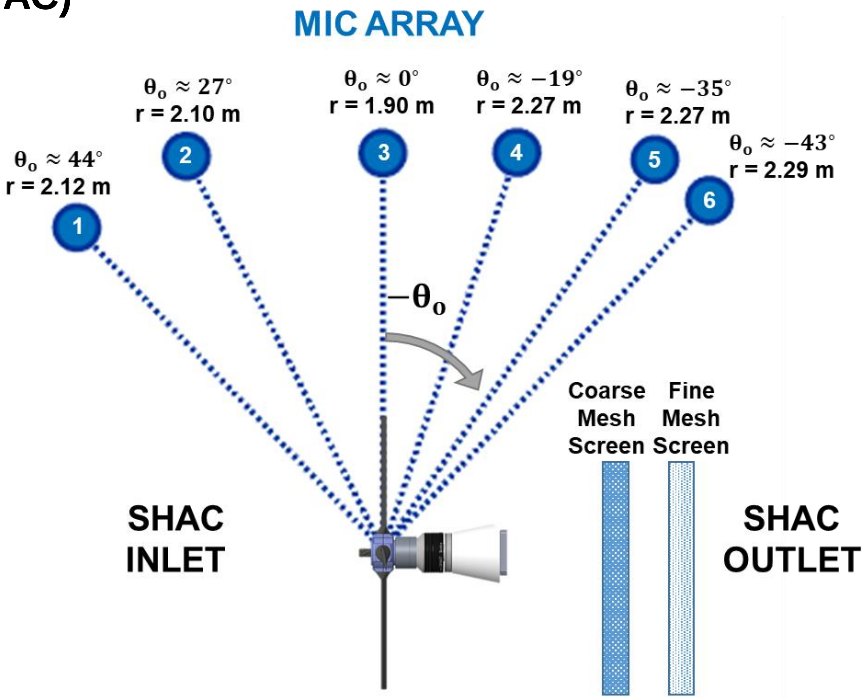
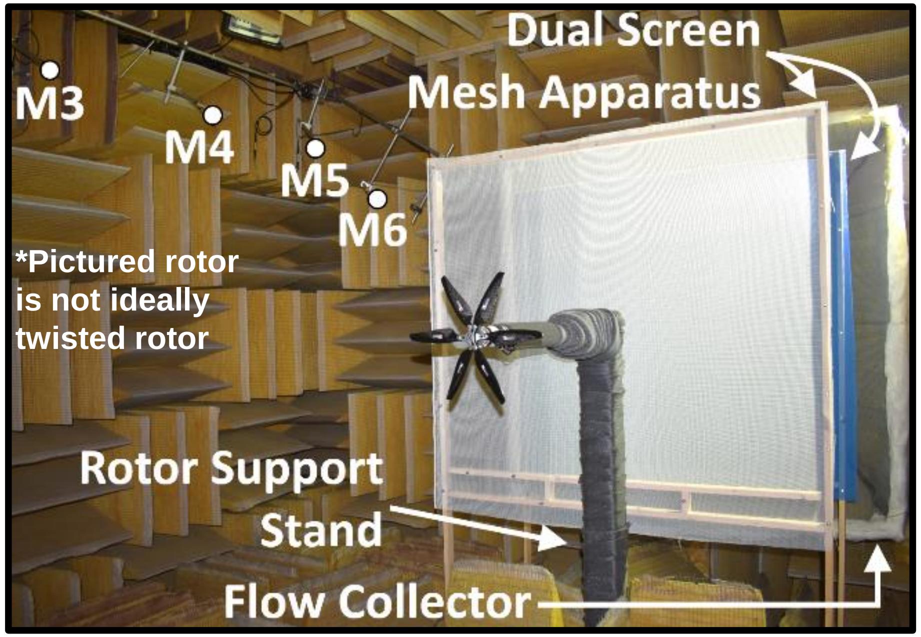
- Acoustically treated (cutoff down to 250 Hz)
- DAS: Brüel & Kjær (BK) LAN-XI DAQ and BK Connect Software
    - 6 B&K Type 4939 Free-Field microphones
    - Laser sensor tachometer
    - 6-Component AI-IA mini40 multiaxis load cell
- Scorpion Motor



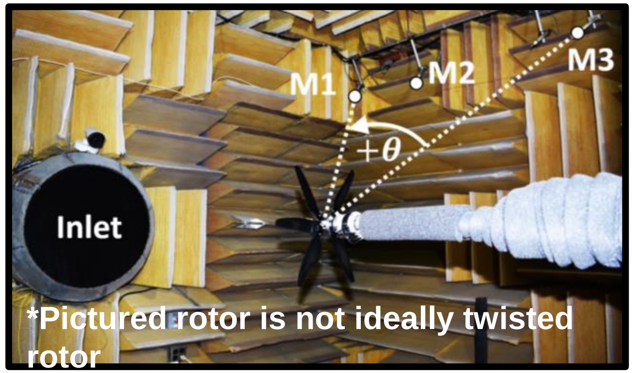


*Pictured rotor is not ideally twisted rotor

Experiment Target Conditions

Parameter Sweep	Ω (RPM)	Θ_{tip} (°)
Rotation Rate (Ω)	3000⇒5800* †	6.9
Rotor Collective (A_0)	5500*	3.9, 6.9, 9.9

*Values are approximate.
†Tested in approximate increments of 500 RPM.



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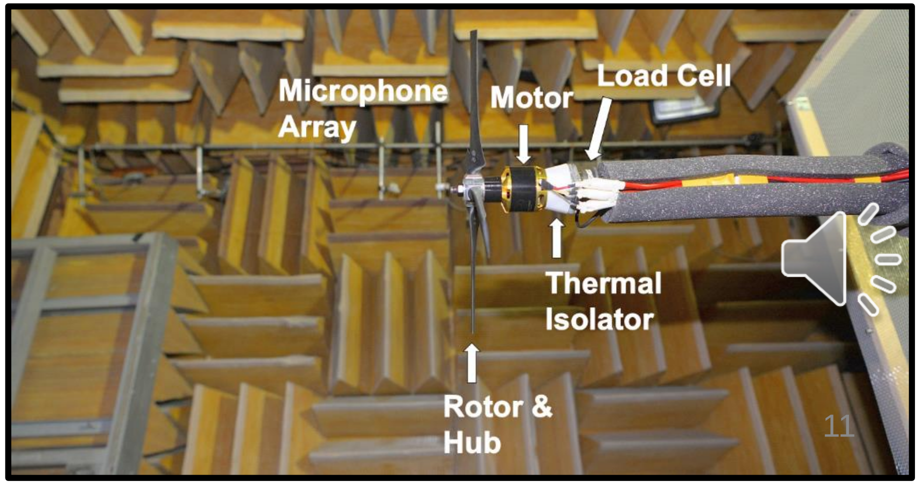


* Whiteside, S. K. S., Zawodny, N. S., Fei, X., Pettingill, N. A., Patterson, M. D., Rothhaar, P. M., *"An Exploration of the Performance and Acoustic Characteristics of UAV-Scale Stacked Rotor Configurations", AIAA SciTech 2019,* https://doi.org/10.2514/6.2019-1071

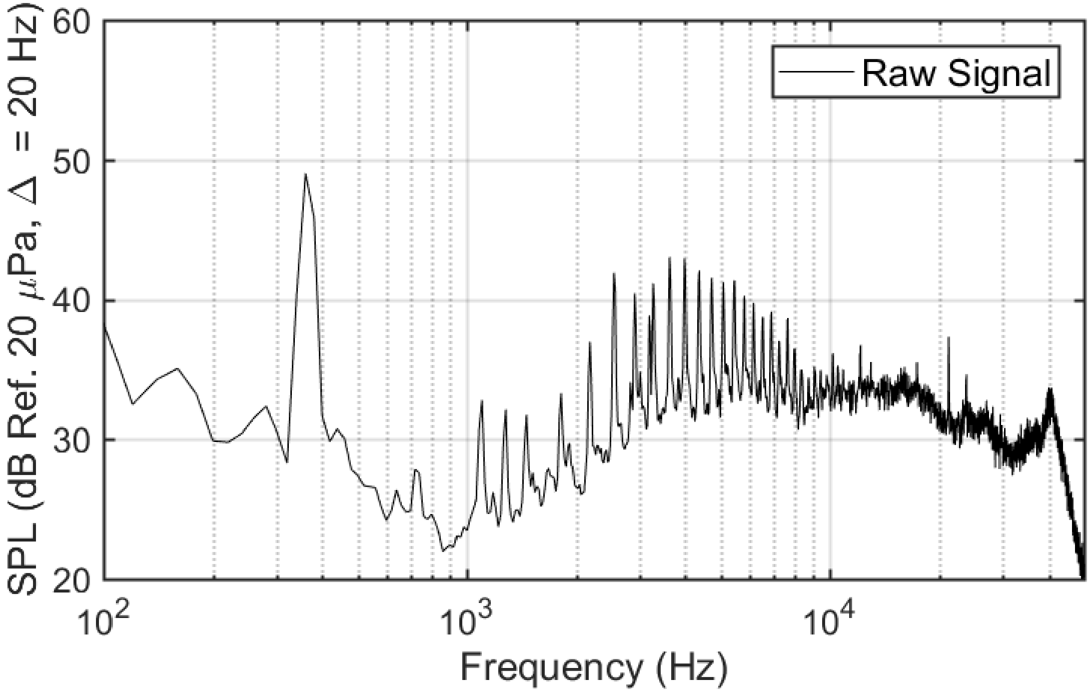
Experimental Data Processing

Extracting Broadband Noise

1. **Data treated as random data sets**
    - **Narrowband acoustic spectra computed using fast Fourier Transform (FFT)**
2. Separate periodic and random noise components in the time domain
    - Compute mean rotor revolution time history
    - Subtract from time record to retain random noise components
    - Use FFT to compute periodic and broadband spectra from the mean and residual time series
3. Remove signal peaks that remain in broadband spectra

Resultant broadband noise spectra are compared to broadband noise predictions

Raw Noise Spectra



Additional Resources:

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Zawodny, N. S., & Pettingill, N. A. (2018). "Acoustic Wind Tunnel Measurements of a Quadcopter in Hover and Forward Flight Conditions". Internoise.

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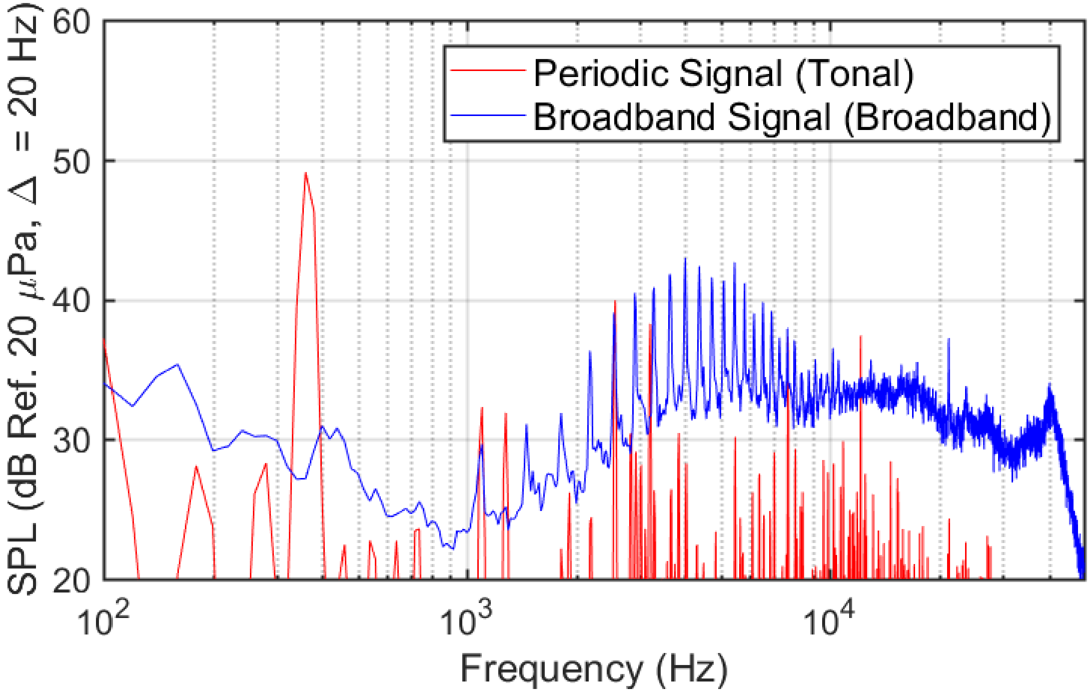
Periodic and Broadband Noise Spectra



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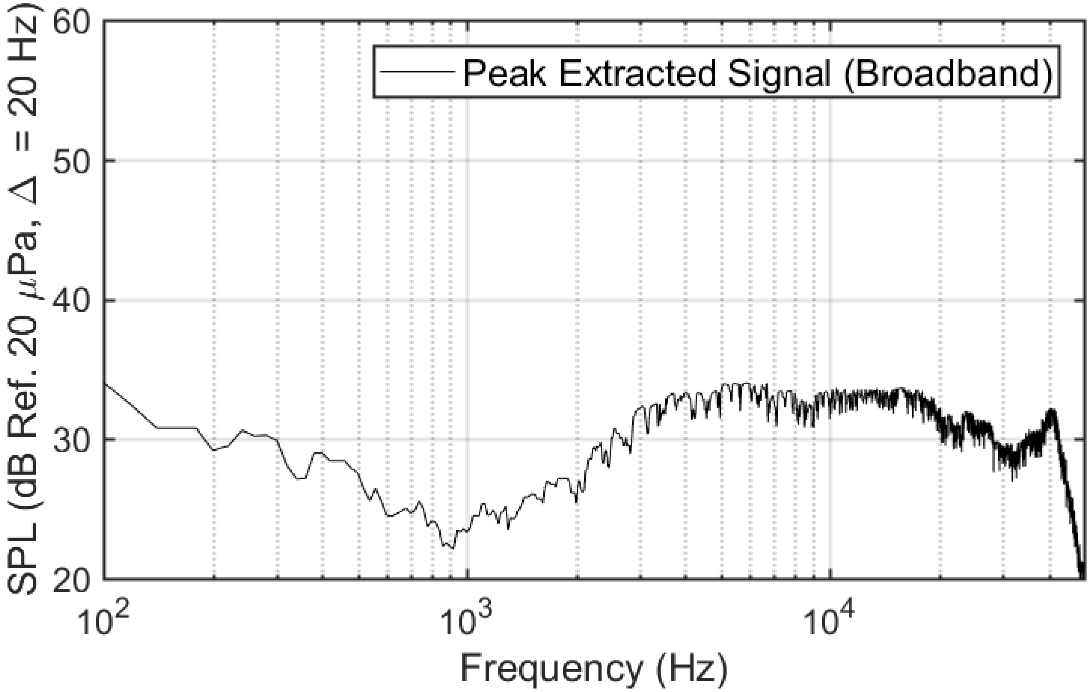
Broadband Noise Spectra



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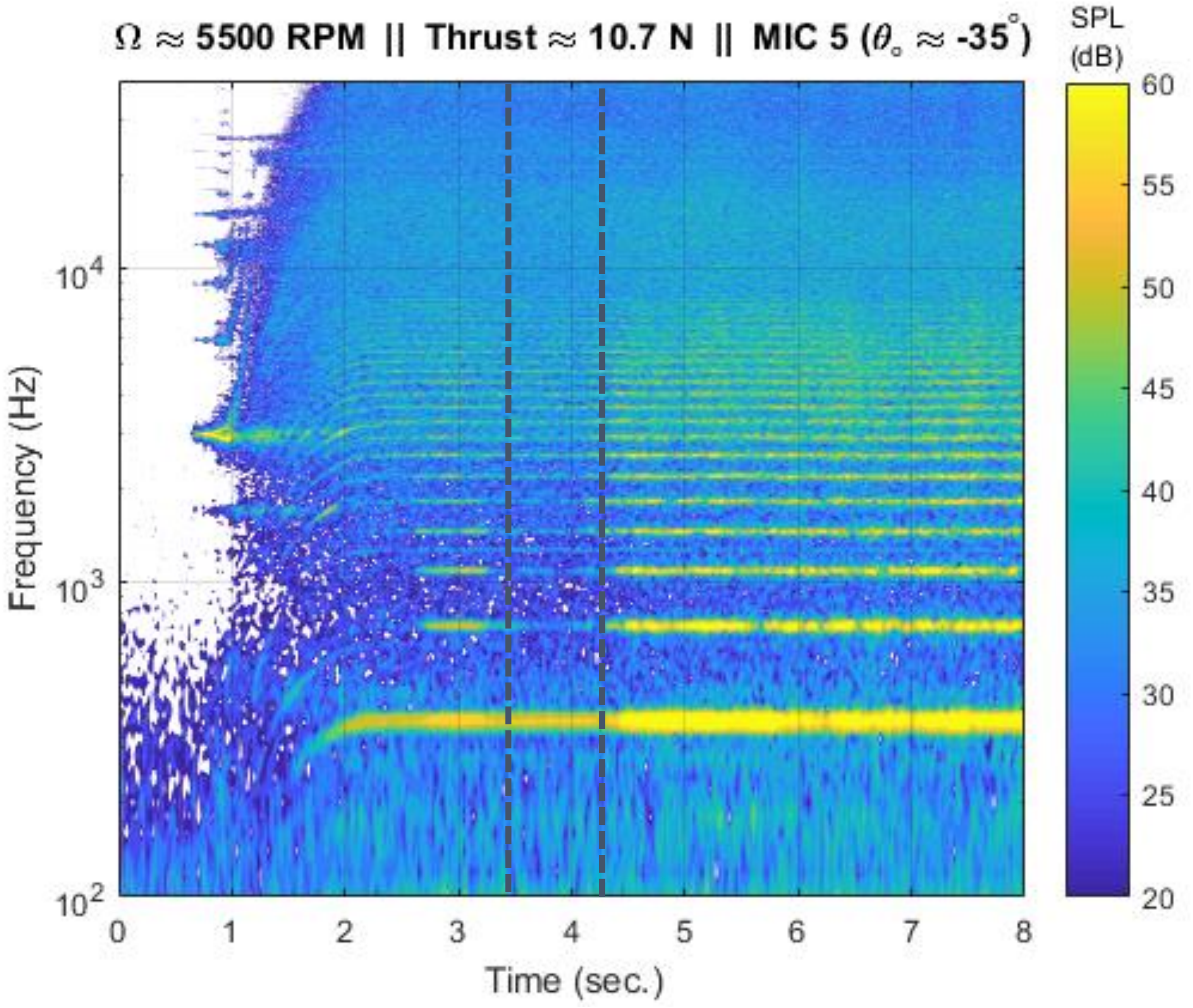
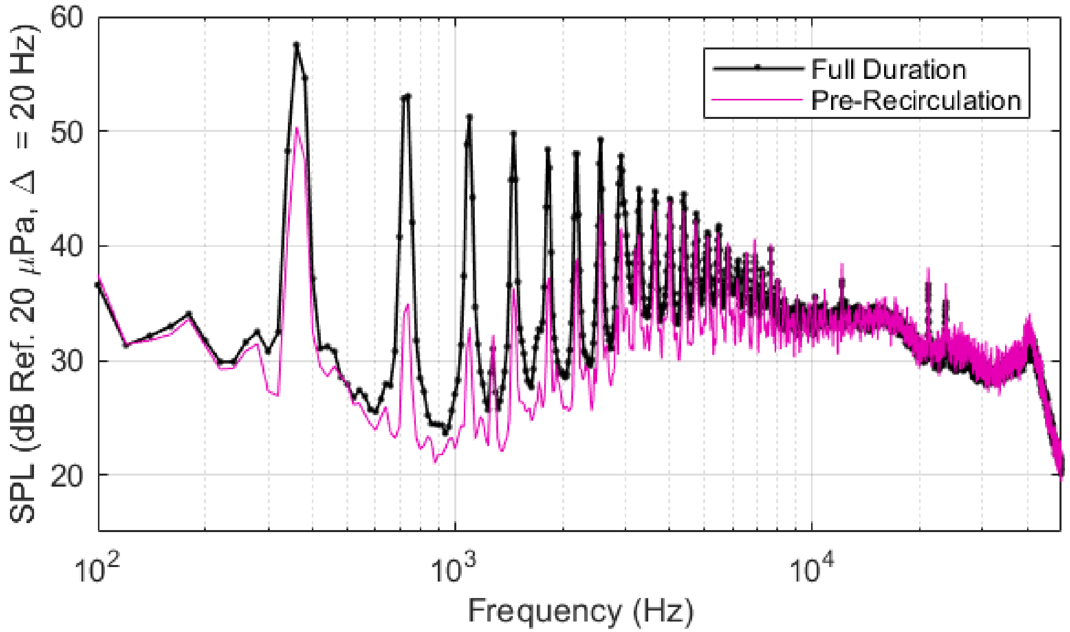
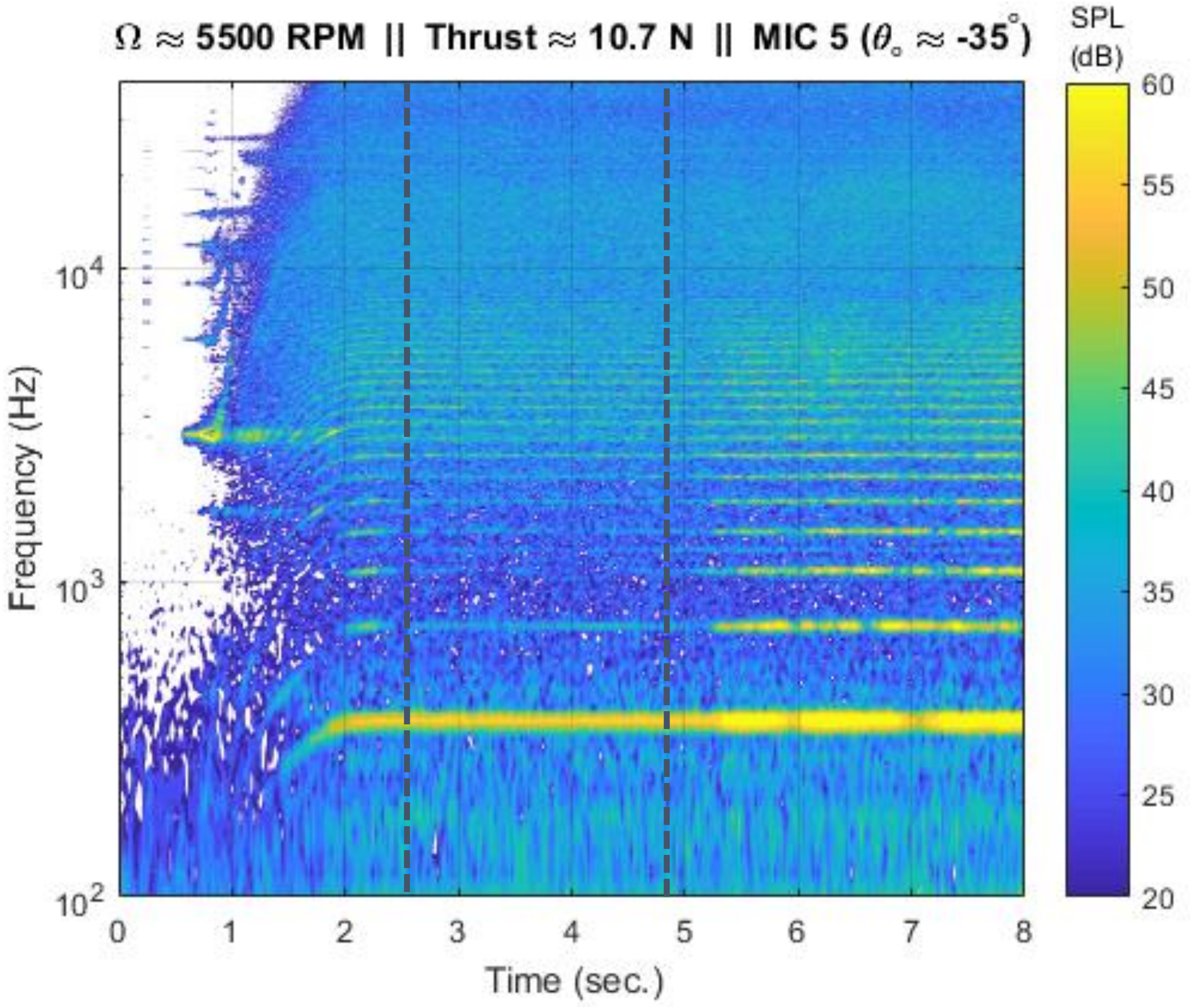
Experiment: Without Mesh Screens

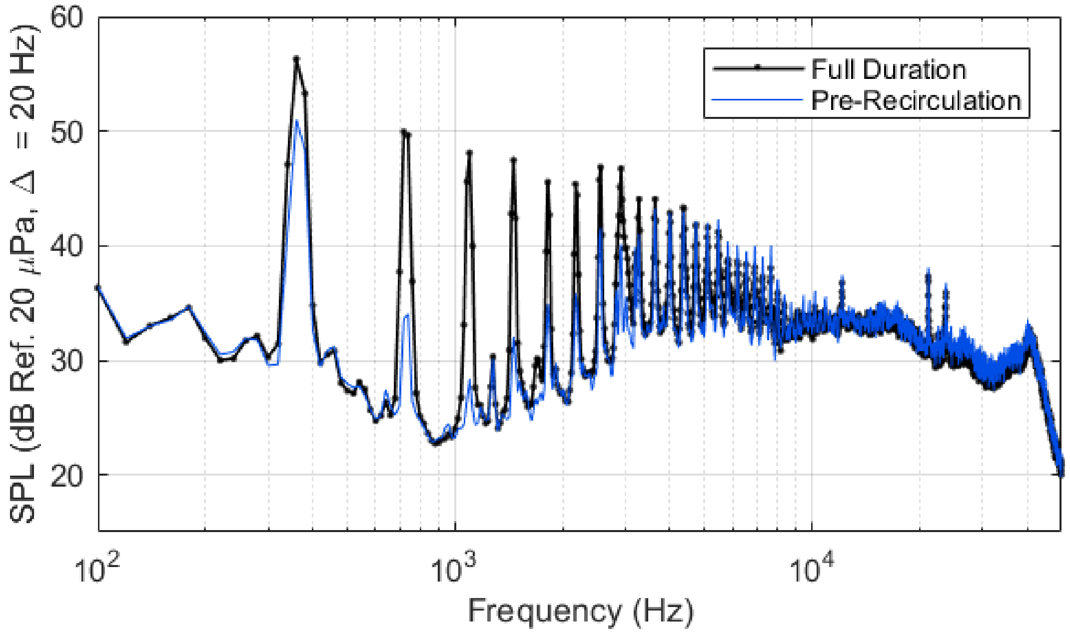




Without mesh screens, "clean data" duration is **< 1 second**

Experiment: With Mesh Screens

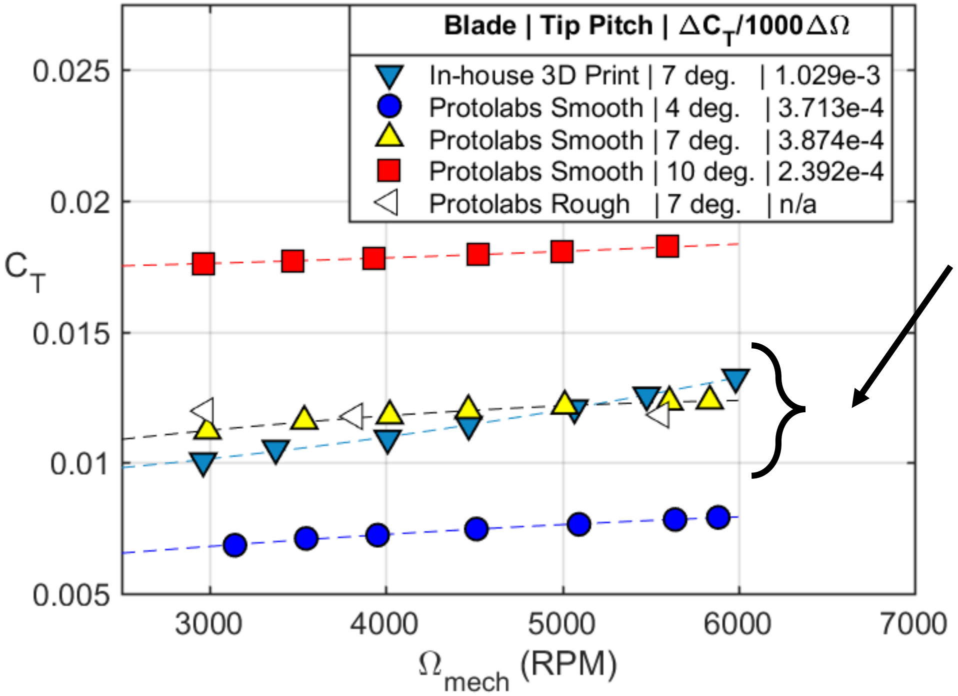




With mesh screens, "clean" data duration is **> 2 seconds**

Performance Results

- Performance data for three blade sets compared
  - Thrust coefficient (C_T) expected to be constant if only rotation rate is varied
  - In-house blades showed high variance in C_T
- Protolabs smooth blades chosen to be tested for additional tip pitch conditions
  - Produced 9.26% less thrust than design thrust of 11.12 N



In-house Markforged blades

Protolabs SLA “smooth” blades

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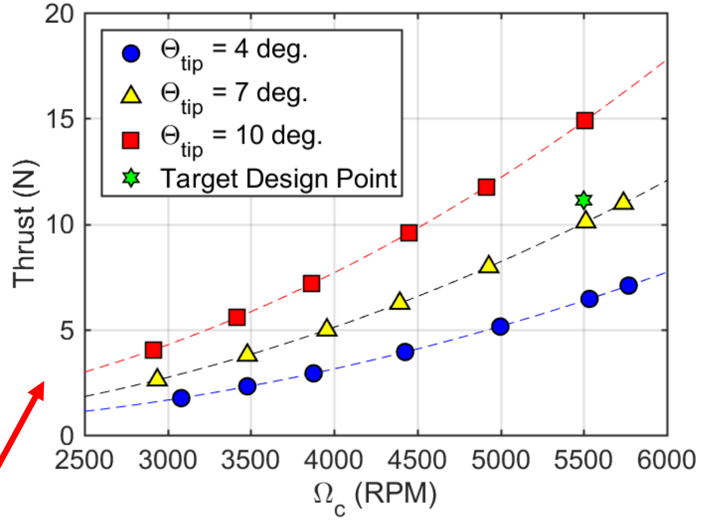
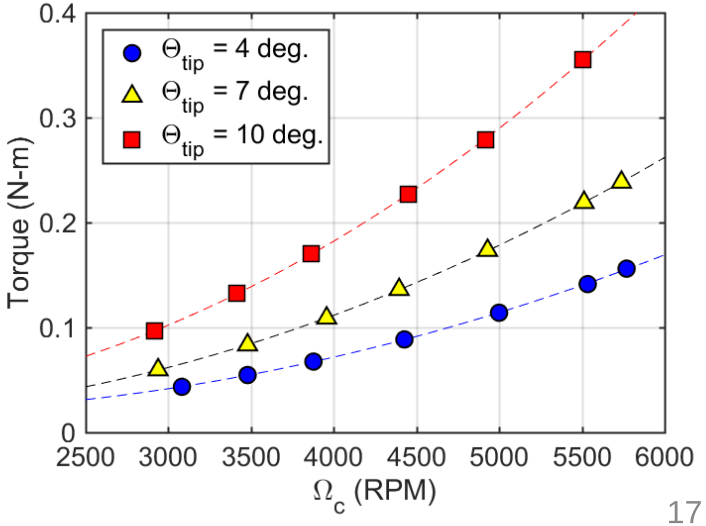




Noise Trends

Self-noise source abbreviations

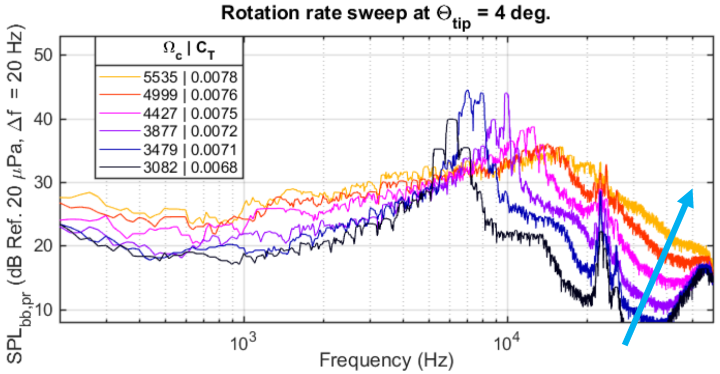
LBLVS = laminar boundary layer vortex shedding

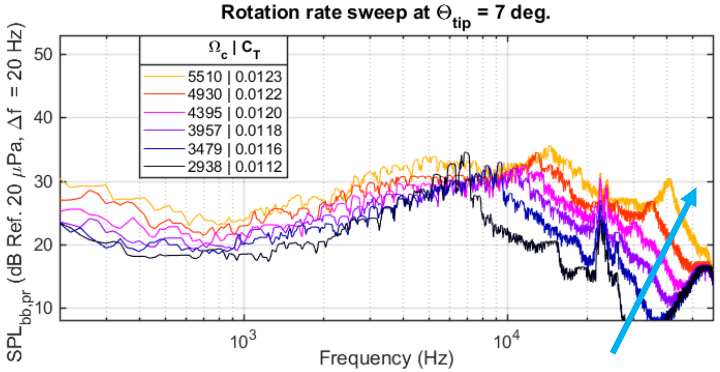
BVS = bluntness vortex shedding

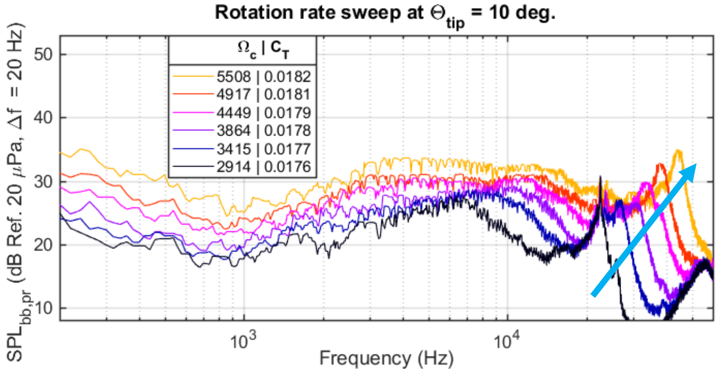
TBLTE = turbulent boundary layer trailing edge

Acoustic spectra for smooth blade experiments at microphone 5 (-35 deg. below the plane of the rotor)

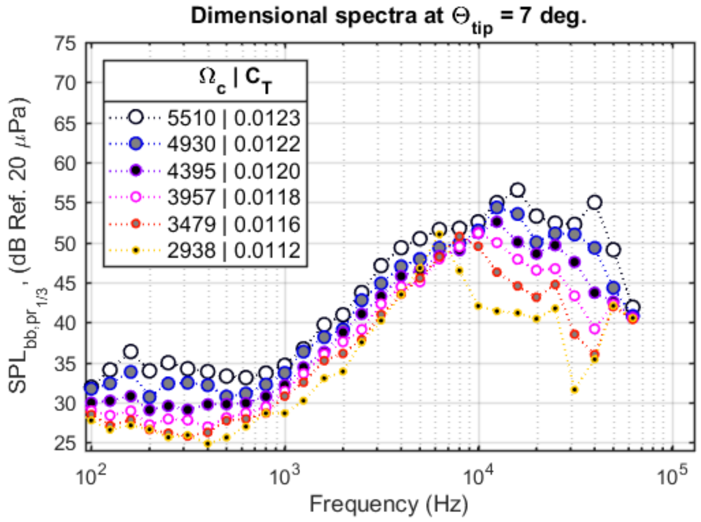
Increasing blade tip pitch

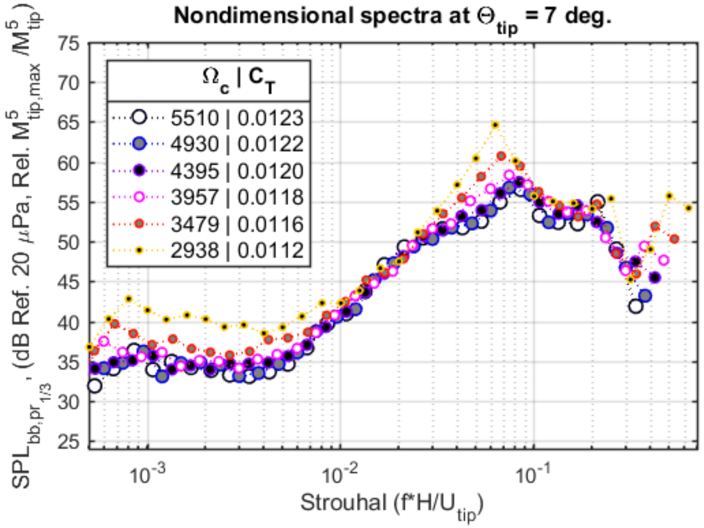






Increasing rotation rate





Spectral scaling

- Strouhal number ($St = fH/U_{tip}$) with bluntness thickness H as length scale
- Tip Mach number to the 5th power as velocity scale

Rough Blade Comparison

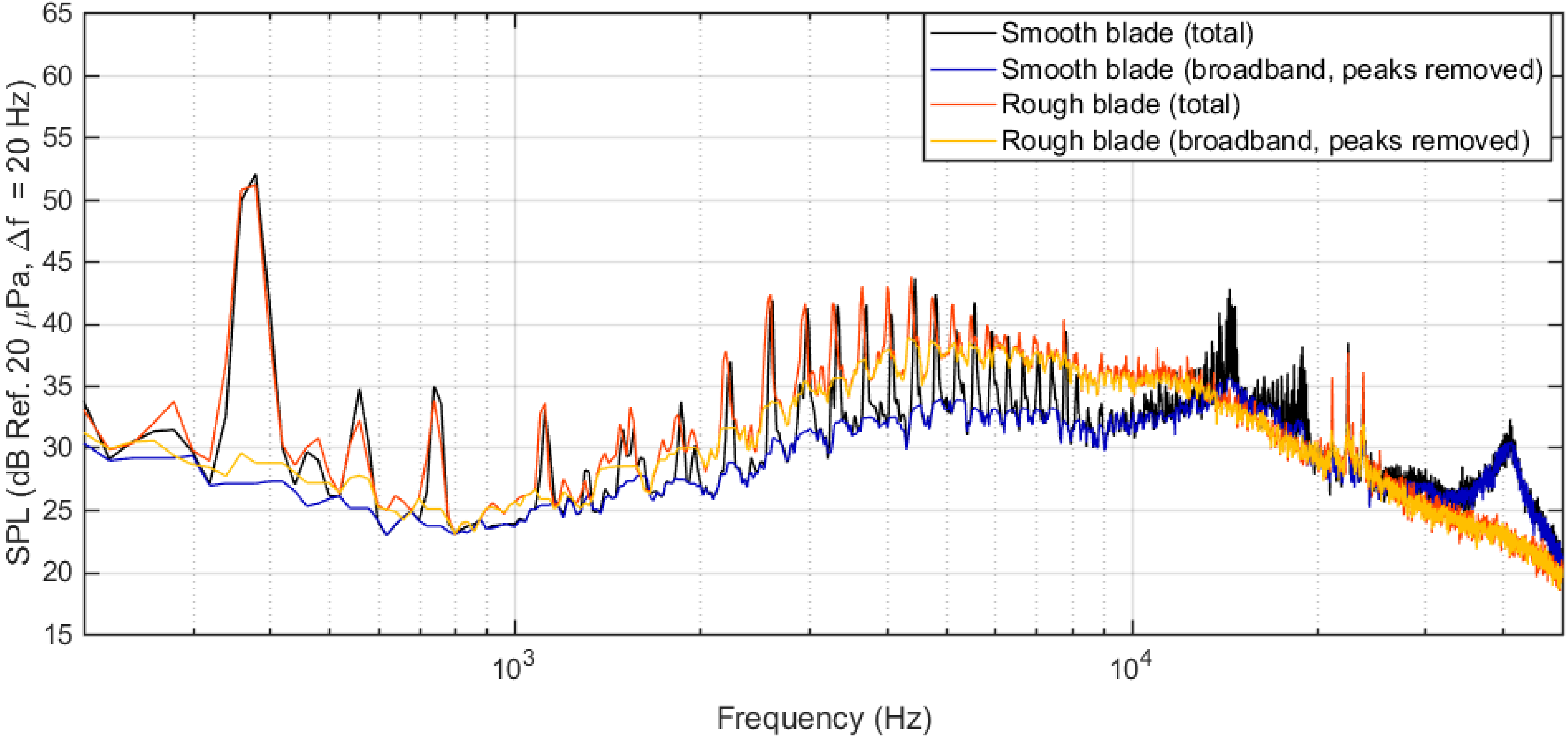
Self-noise source abbreviations

LBLVS = laminar boundary layer vortex shedding

BVS = bluntness vortex shedding

TBLTE = turbulent boundary layer trailing edge

5500 RPM at 7 deg. blade tip pitch



Rough Blade Comparison

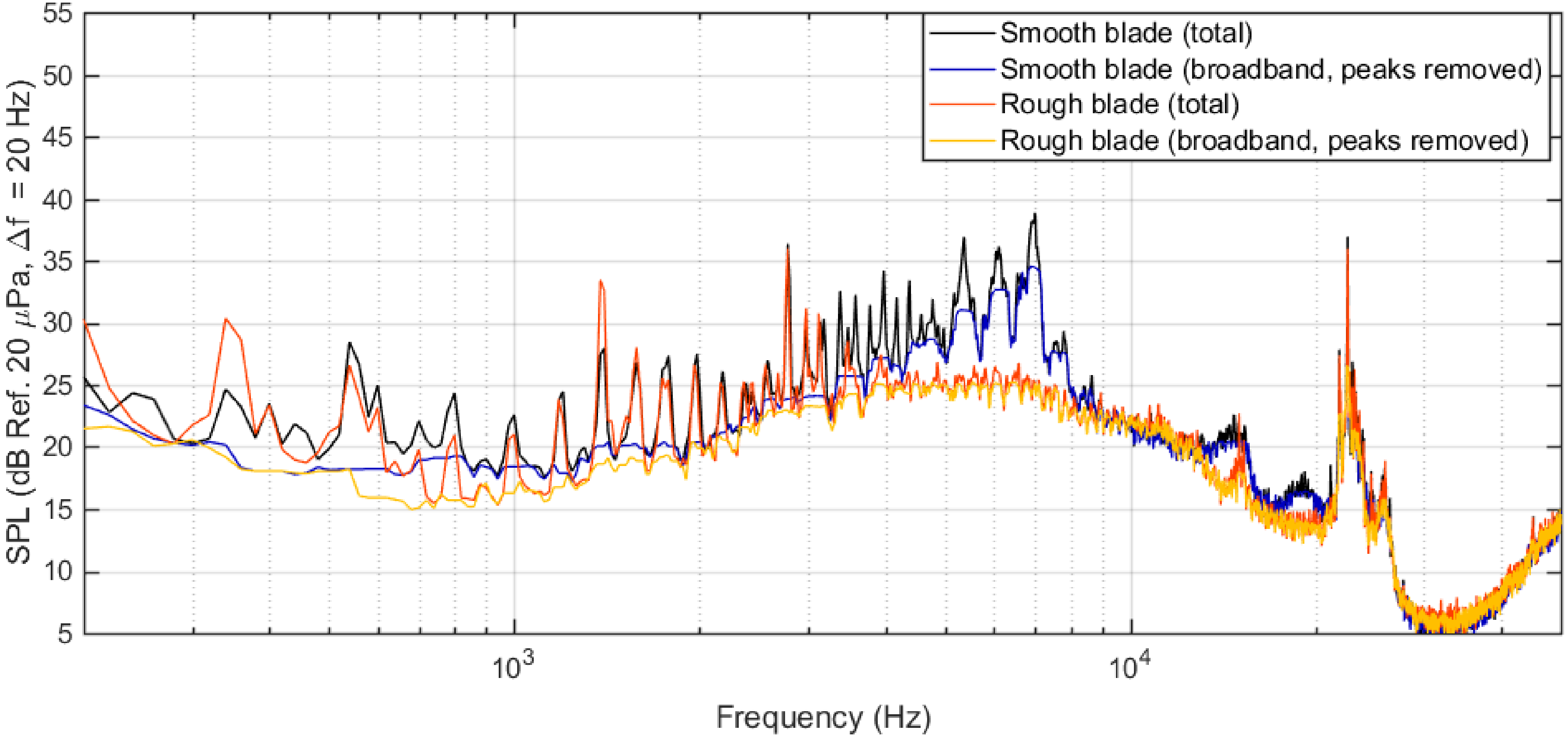
Self-noise source abbreviations

LBLVS = laminar boundary layer vortex shedding

BVS = bluntness vortex shedding

TBLTE = turbulent boundary layer trailing edge

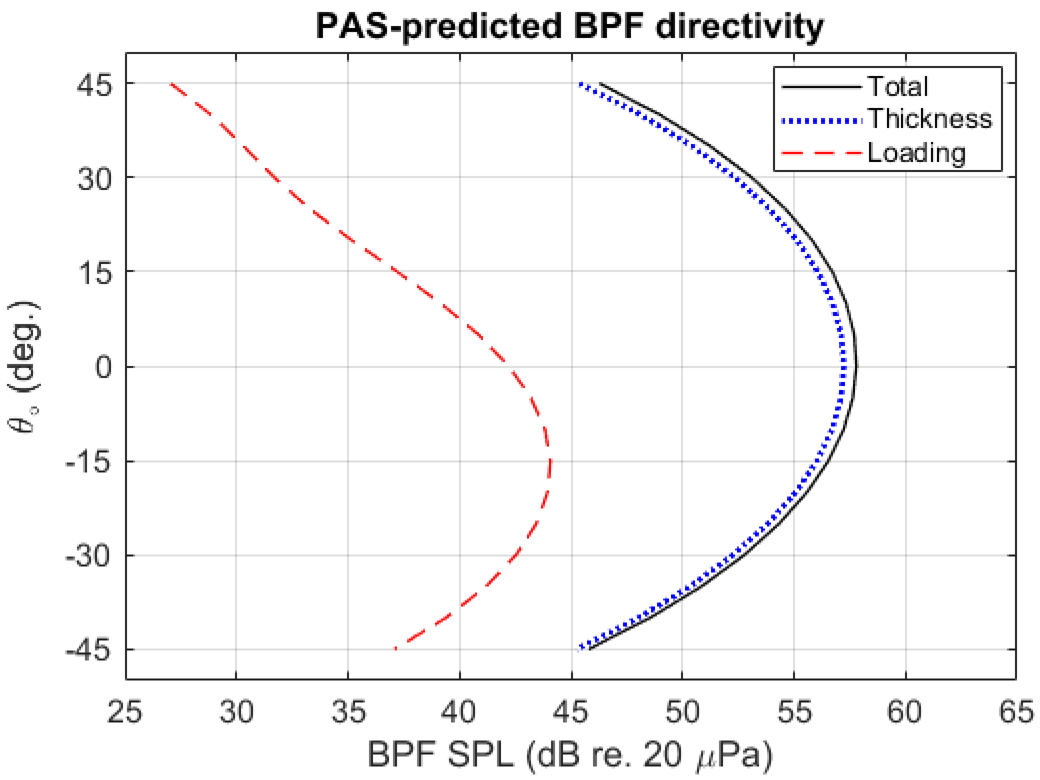
3000 RPM at 7 deg. blade tip pitch

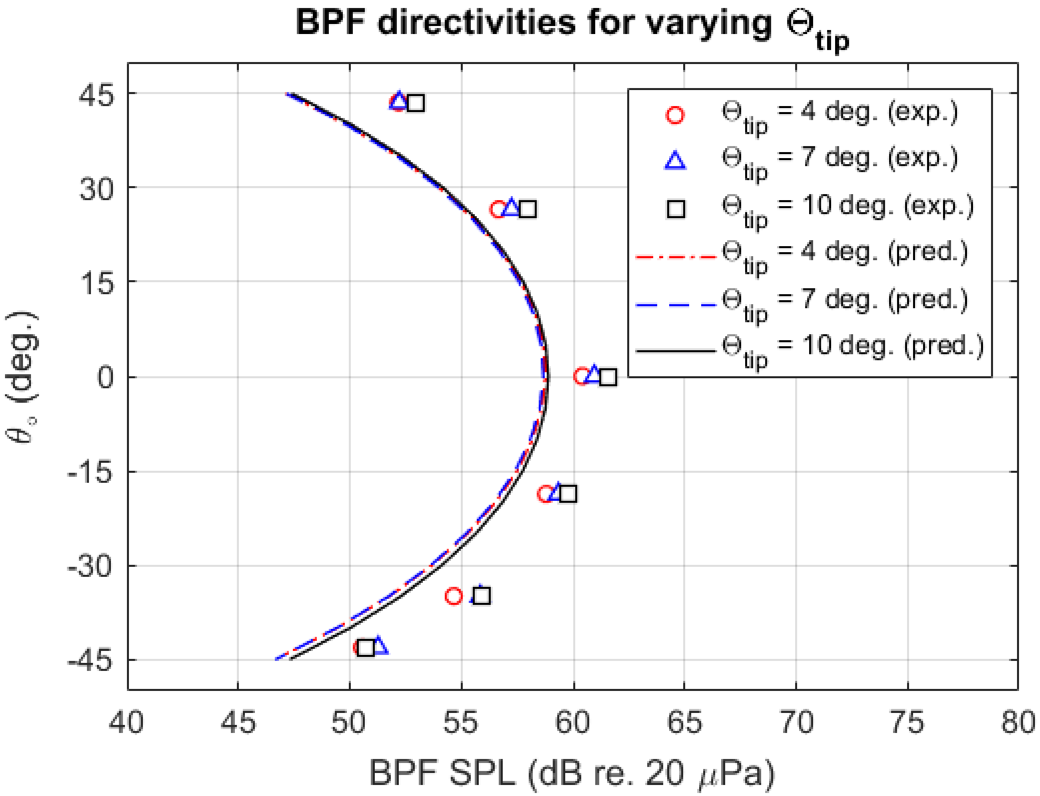


Tonal Noise

- PAS is used to perform a tonal noise prediction at the target design condition
- Thickness noise dominated

- Little difference in tonal amplitudes between lowest and highest blade tip pitch settings (max deviation between cases was 1.3 dB)





Ideally Twisted Rotor Test Conclusions

- Examining acoustic data for rotation rate sweeps at different design blade tip pitch conditions $(4°, 7°, 10°)$ helped identify **noise trends with performance**

- Please see paper for additional work*
  - Low-fidelity tools were able to predict some of the **tonal and broadband noise characteristics** of this tested rotor
  - TBLTE-suction, LBLVS, and BVS were predicted to be prominent self-noise sources
  - Broadband noise predictions provided great comparison for some cases, but required modifications for other cases
  - **Higher fidelity inflow modeling** may be necessary for off-design conditions

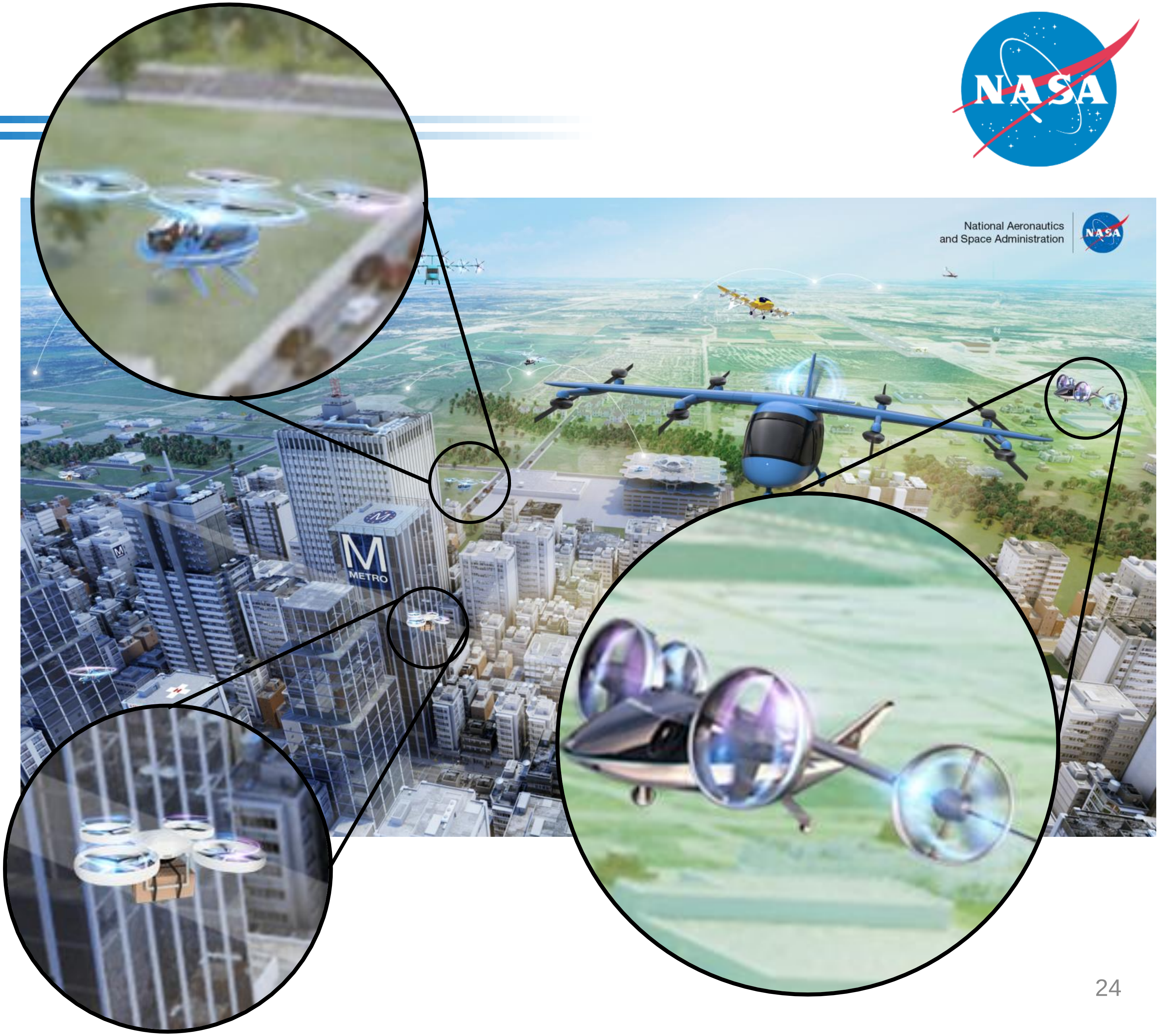
*Pettingill, N. A., Zawodny, N. S., Thurman, C., & Lopes, L. V. “Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover.” *AIAA Scitech 2021 Forum*, Virtual, Jan. 2021, https://doi.org/10.2514/6.2021-1928

Ducted Propeller Test

Recent Work

Ducted Propellers

Many AAM aircraft configurations are being considered, some of which have ducted propulsors



Experiment: Facility and Setup

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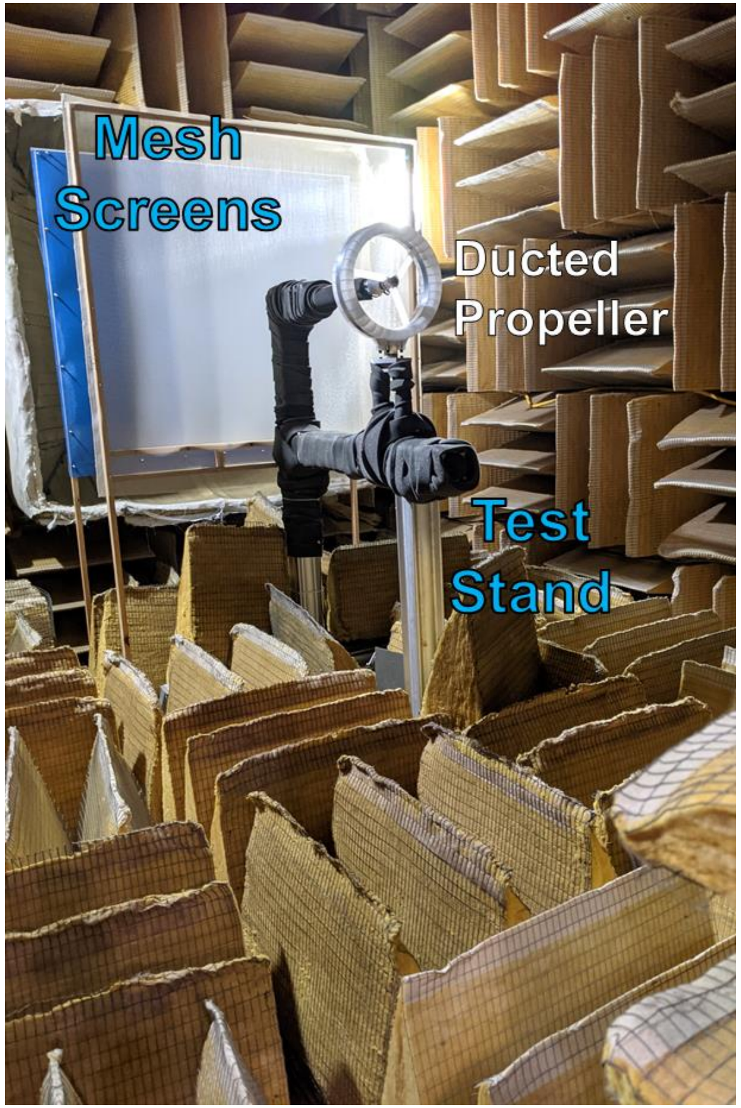
Small Hover Anechoic Chamber (SHAC)*



- Room dimensions = [3.87 x 2.56 x 3.26] m
  - Acoustically treated (cutoff down to 250 Hz)
  - Mesh screens reduce the onset of recirculation
- Hardware
  - KDE 2814XF-515 motor
  - Duct mounted on 1" 8020 axial track (~6" below rotor loadcell)

- DAS: Brüel & Kjær (BK) LAN-XI DAQ and BK Connect Software
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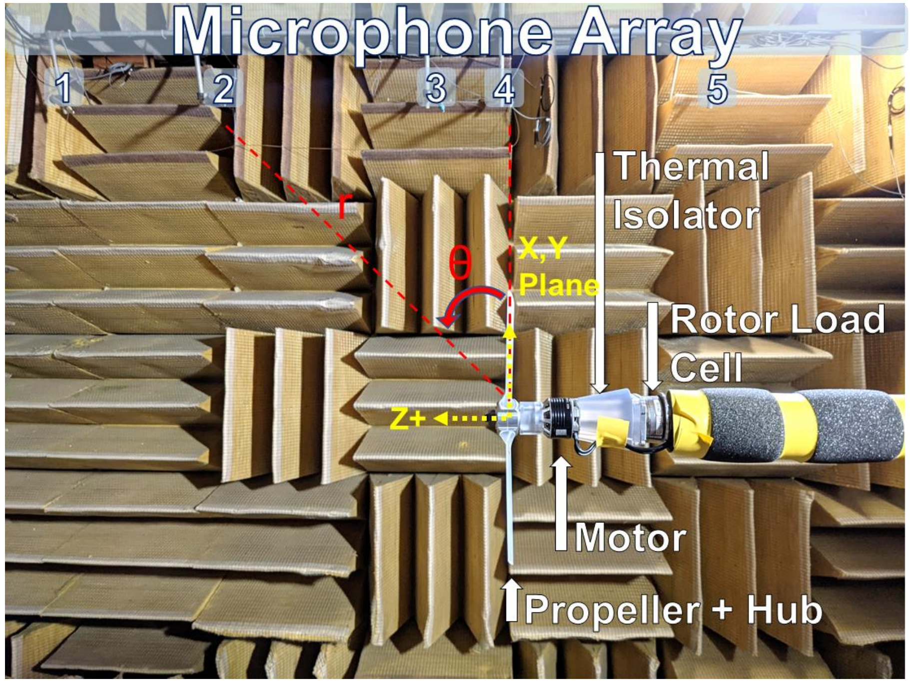
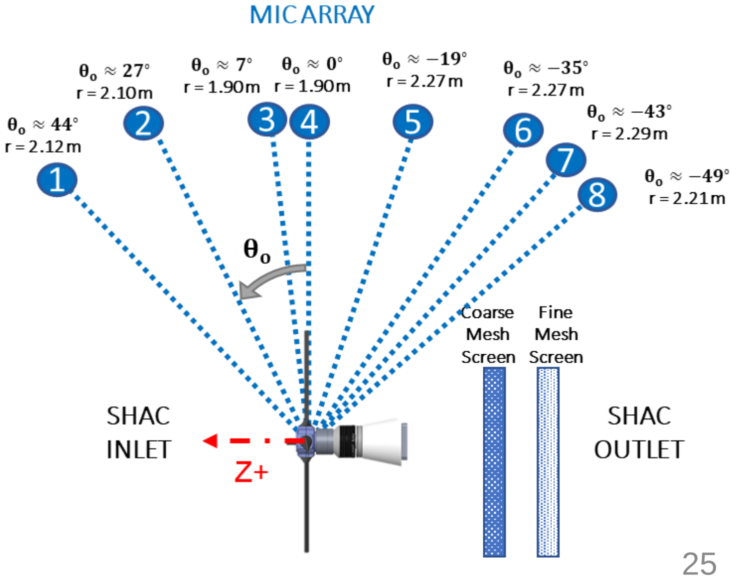
  - 2x 6-Component AI-IA mini40 multiaxis load cell
  - Hot Wire Probe + Thermistor





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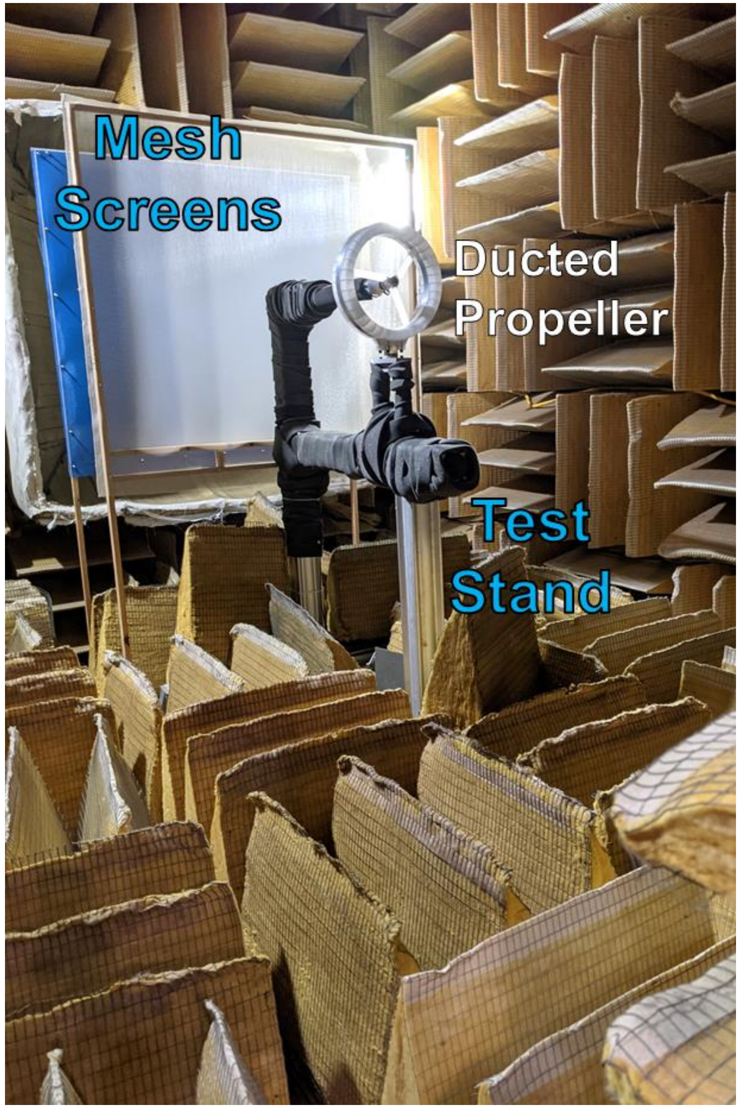

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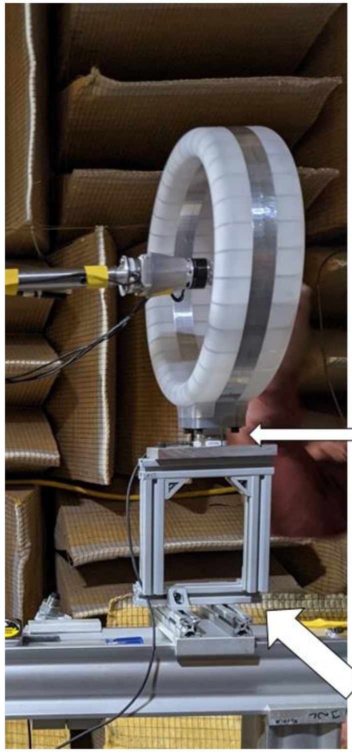
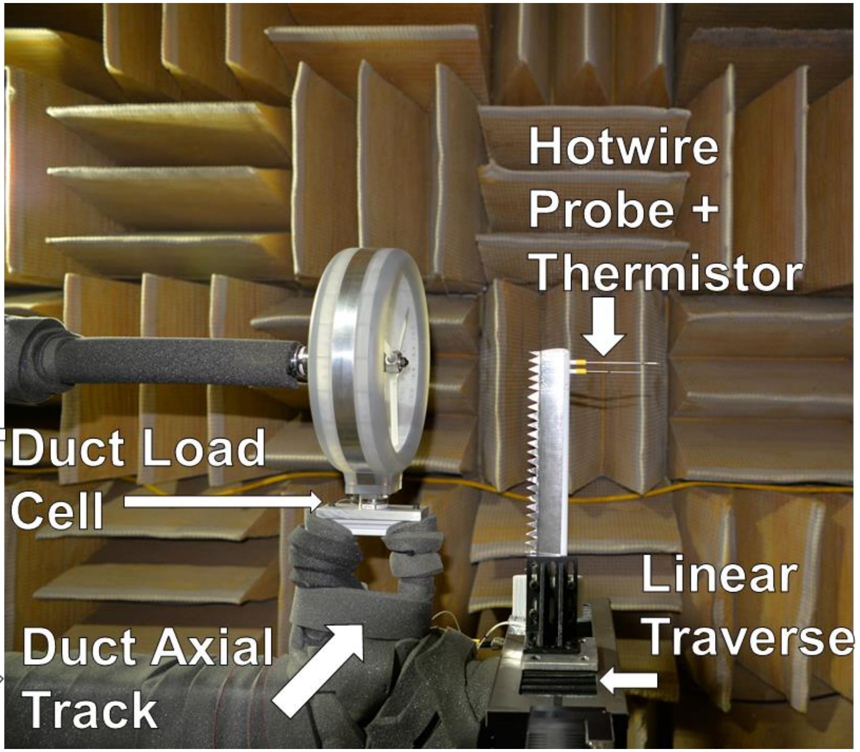
  - Hot Wire Probe + Thermistor

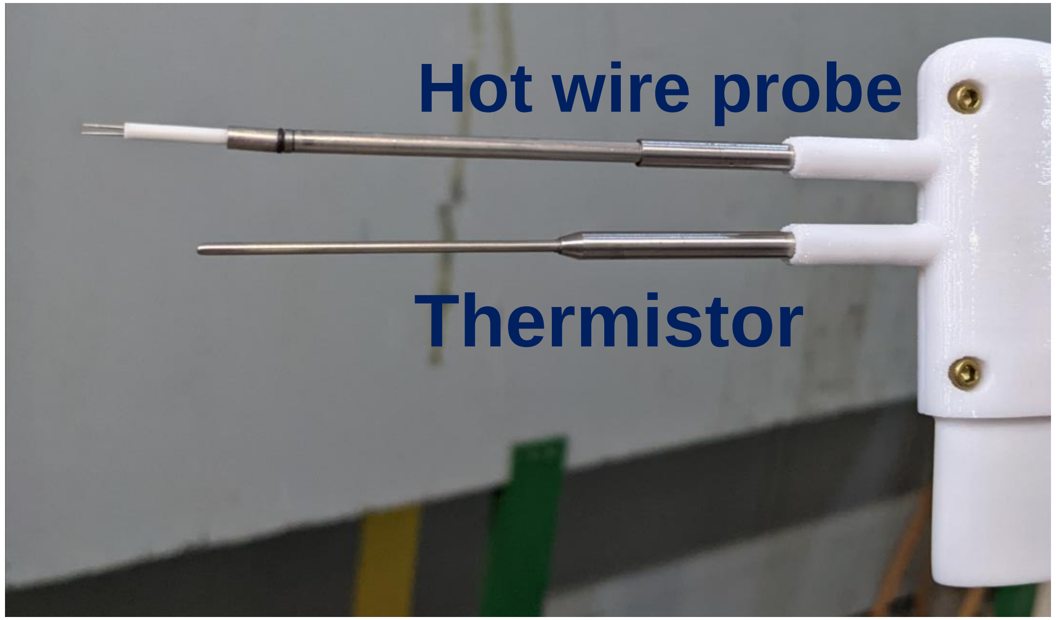




* Whiteside, S. K. S., Zawodny, N. S., Fei, X., Pettingill, N. A., Patterson, M. D., Rothhaar, P. M., "An Exploration of the Performance and Acoustic Characteristics of UAV-Scale Stacked Rotor Configurations", AIAA SciTech 2019, https://doi.org/10.2514/6.2019-1071

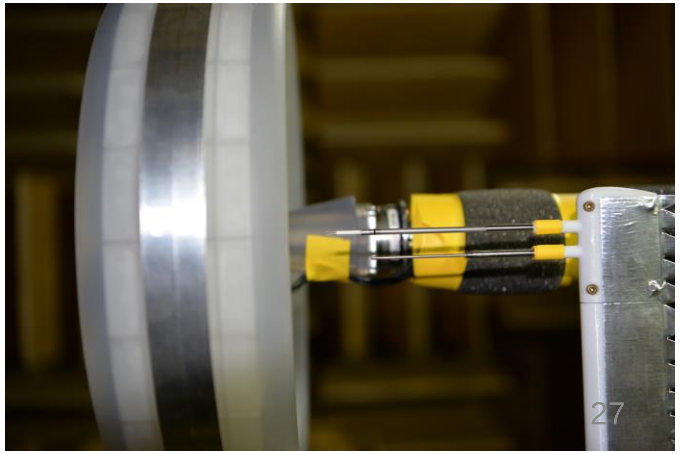
Hot Wire Probe

- Motivation
    - To diagnose flow separation near inlet lip
    - To get a better sense of hydrodynamics responsible for large increase in broadband noise
- Two surveys
    - Freestream hot wire survey
    - Wake survey
- Two probes
    - Mini CTA Anemometer 54T42 with 55P16 hot wire probe
    - 90P10 thermistor



Free Stream Survey

Wake Survey



Conclusions

- The SHAC is a facility that helps us characterize performance and acoustics of small rotors, as well as more complex configurations such as the ducted propellers or stacked rotors.
- For static measurements, mitigation techniques are necessary to delay the onset of recirculation
- Hot wire probe capability will help characterize freestream and wake behavior of current and future tests.

*Pettingill, N. A., Zawodny, N. S., Thurman, C., & Lopes, L. V. “Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover.” *AIAA Scitech 2021 Forum*, Virtual, Jan. 2021, https://doi.org/10.2514/6.2021-1928

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LaRC Center Innovation Fund (CIF)

Revolutionary Vertical Lift Technology (RVLT) Project

Funding - Ducted Propeller

Revolutionary Vertical Lift Technology (RVLT) Project

ONERA

Thank you, any questions?

https://intern.nasa.gov/

Internships

Pathways

Fellowships

Contractors

Extra Slides

Low-Fidelity Prediction Tools

- ***ROTONET*** (Rotorcraft Noise Prediction System[1]) and ***PAS*** (Propeller Analysis System)[2] are subsystems of NASA Aircraft Noise Prediction Program (ANOPP) and are lower fidelity tools with simple inflow models
- ***BARC*** (Broadband Acoustic Rotor Codes[3]) is a semiempirical, blade element method for predicting self-noise
  - Uses inflow conditions and airfoil geometry as inputs, and NACA0012 empirical BL data
  - **Predicts broadband noise due to self-noise sources and incorporates into a rotational reference frame**
- TIN and BWI cannot be modeled with these tools, but companion paper[5] uses higher-fidelity tools to predict these noise sources

Predicted with PAS →

Tonal noise sources

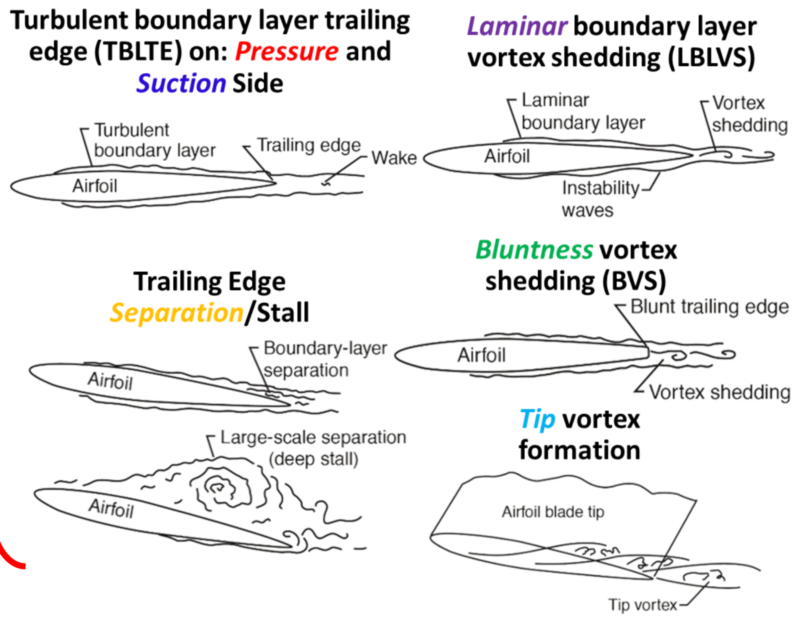
- **Thickness noise**
- **Loading noise**
- Blade vortex interaction (BVI) noise

Predicted with ROTONET and BARC →

Broadband noise sources

- **Airfoil self-generated noise (self noise)** [4]
- Turbulence ingestion noise (TIN)
- Blade-wake interaction (BWI) noise

6 Self-Noise Source Mechanisms



Turbulent boundary layer trailing edge (TBLTE) on: *Pressure* and *Suction* Side

***Laminar* boundary layer vortex shedding (LBLVS)**

Trailing Edge *Separation*/Stall

***Bluntness* vortex shedding (BVS)**

***Tip* vortex formation**

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[1] *Weir, S. D., Jumper, J. S., Burley, C. L., and Golub, A. R., "Aircraft Noise Prediction Program Theoretical Manual: Rotorcraft System Noise Prediction System (ROTONET), Part 4," NASA TM 83199, April 1995.*

[2] Nguyen, L. C. (1991). *The NASA Aircraft Noise Prediction Program Improved Propeller Analysis System*. Hampton.

[3] *Johnson, W., Technology Drivers in the Development of CAMRAD II. American Helicopter Society Aeromechanics Specialists Conference, 1994.*

[3] *Burley, C. L. and Brooks, T. F., "Rotor Broadband Noise Prediction with Comparison to Model Data," Journal of the American Helicopter Society, Vol. 49, (1), January 2004, pp. 28–42.*

[4] *Brooks, T. F., Pope, D. S., and Marcolini, M. A., "Airfoil Self-Noise and Prediction," NASA RP 1218, 1989.*

[5] *Thurman, C. S., Zawodny, N. S., Pettingill, N. A., and Lopes, L. V., "Physics-informed Broadband Noise Source Identificationand Prediction of an Ideally Twisted Rotor," 2021 SciTech Forum, Nashville, TN, Jan. 2021.*

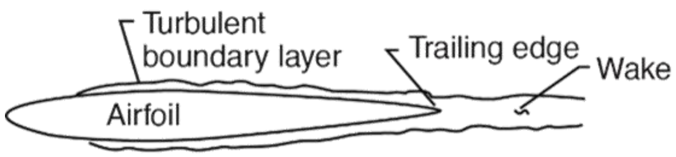
**Source: Brooks, T. F., Pope, D. S., and Marcolini, M. A., “Airfoil Self-Noise and Prediction,” NASA RP 1218, 1989.*

What is self-noise?

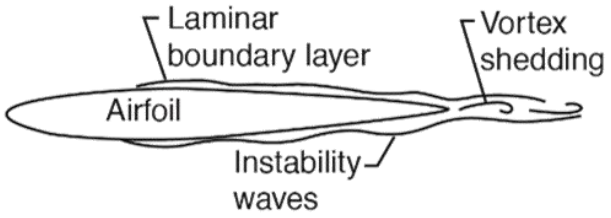
- *Self* generated noise of an airfoil blade encountering smooth flow
- This is a *nondeterministic, broadband* noise source
- In 1989, a NASA Reference Publication (RP1218) was published on the topic of self-noise and a prediction method*

6 Self-Noise Source Mechanisms*

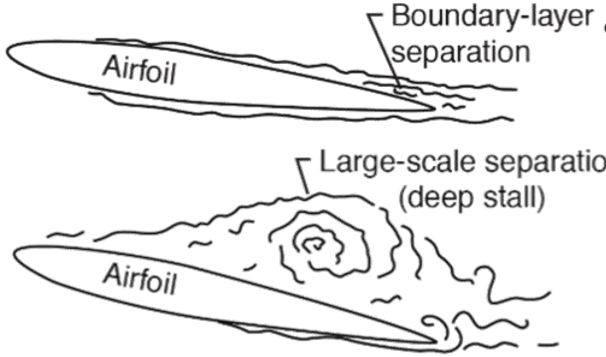
Turbulent boundary layer trailing edge (TBLTE) on: *Pressure* and *Suction* Side



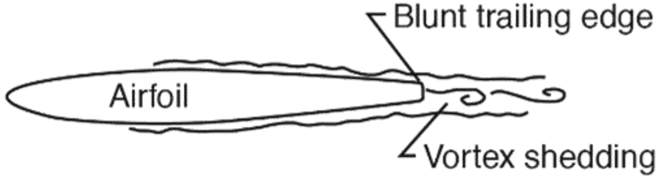
***Laminar* boundary layer vortex shedding (LBLVS)**



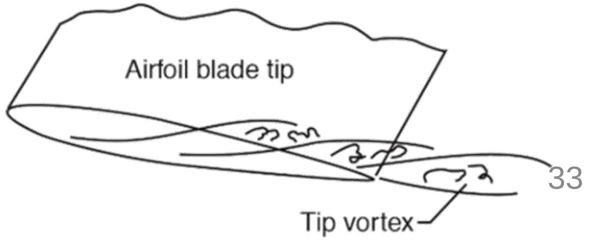
Trailing Edge *Separation*/Stall



***Bluntness* vortex shedding (BVS)**



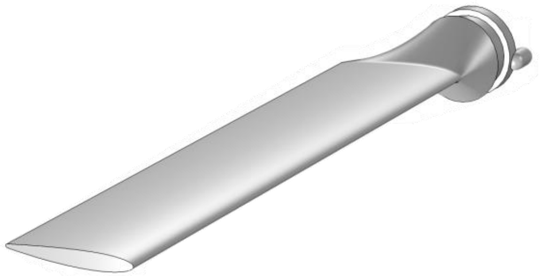
***Tip* vortex formation**



Design and set up

- Blade(s)
    - 9.6” diameter, 3-bladed rotor at 9,000 RPM
    - Target design thrust = 1.9 lbs
    - Tip pitch angle $\theta = 10^\circ$
    - NACA 0012 airfoil, no twist
    - Blades manufactured via Stereolithography (SLA)

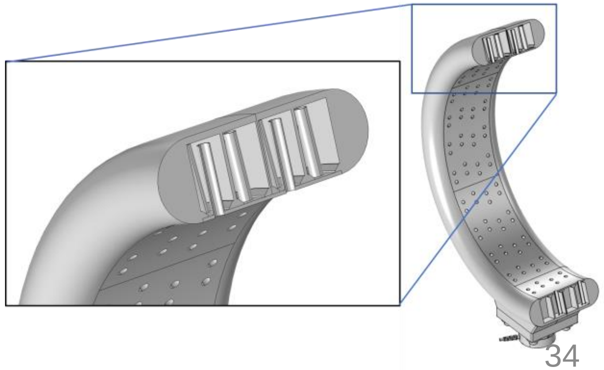
Propeller Blade



- Ducts
    - Two ducts
        - Untreated hardwall duct
        - Low resistance LEONAR lined duct (L02)
    - Straight ducts, 10” inner diameter,1.2” thick, 0.6” inlet and exhaust lip radius, 2.4” axial extent (of the straight duct section), blade tip clearance 4% of duct inner radius
    - Ducts manufactured via stereolithography (SLA)

L02 Duct

Hardwall Duct



Testing configurations

Three propeller configurations

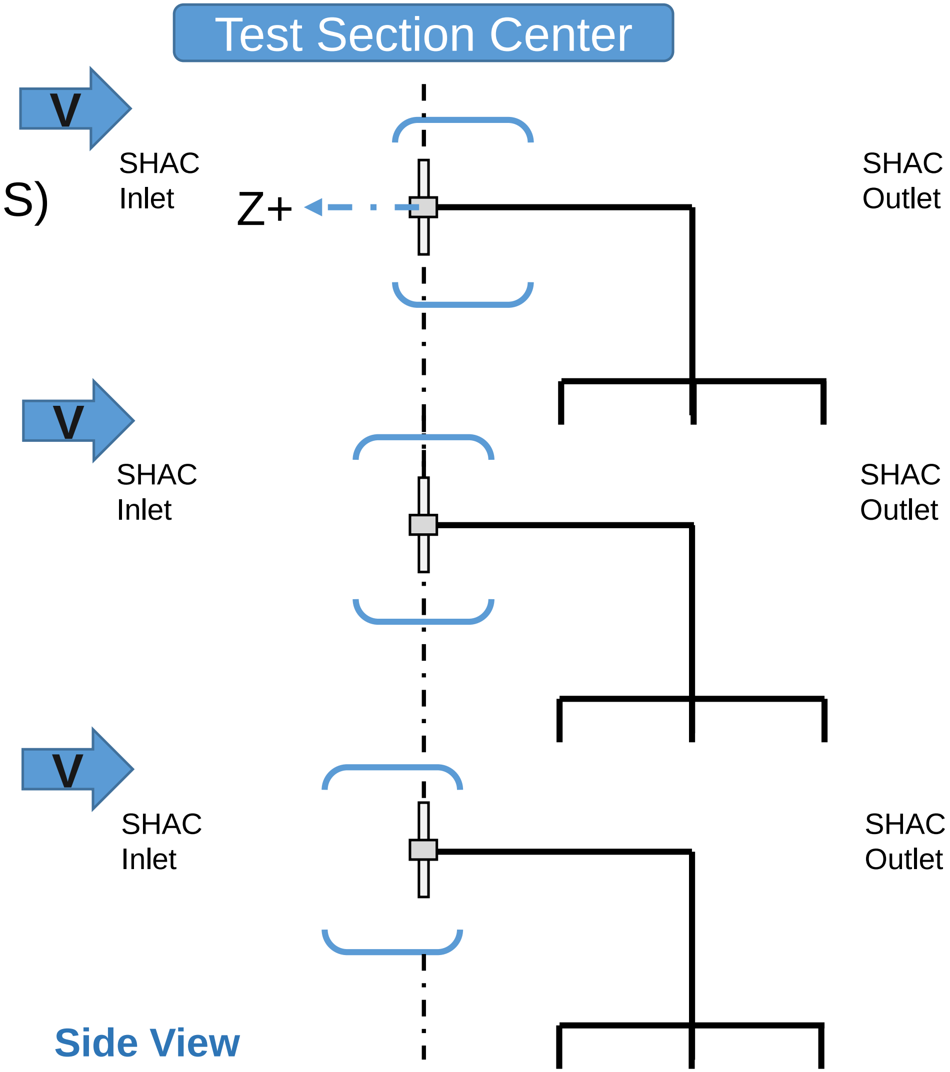
- Isolated propeller (no duct)
- Hardwall untreated ducted propeller →
- L02 treated ducted propeller →

Two flow conditions

- Background flow on (V ~5 m/s)
- Background flow off (V = 0 m/s)

Three duct positions

- Duct downstream (DS)
- Duct centered
- Duct upstream (US)



Side View

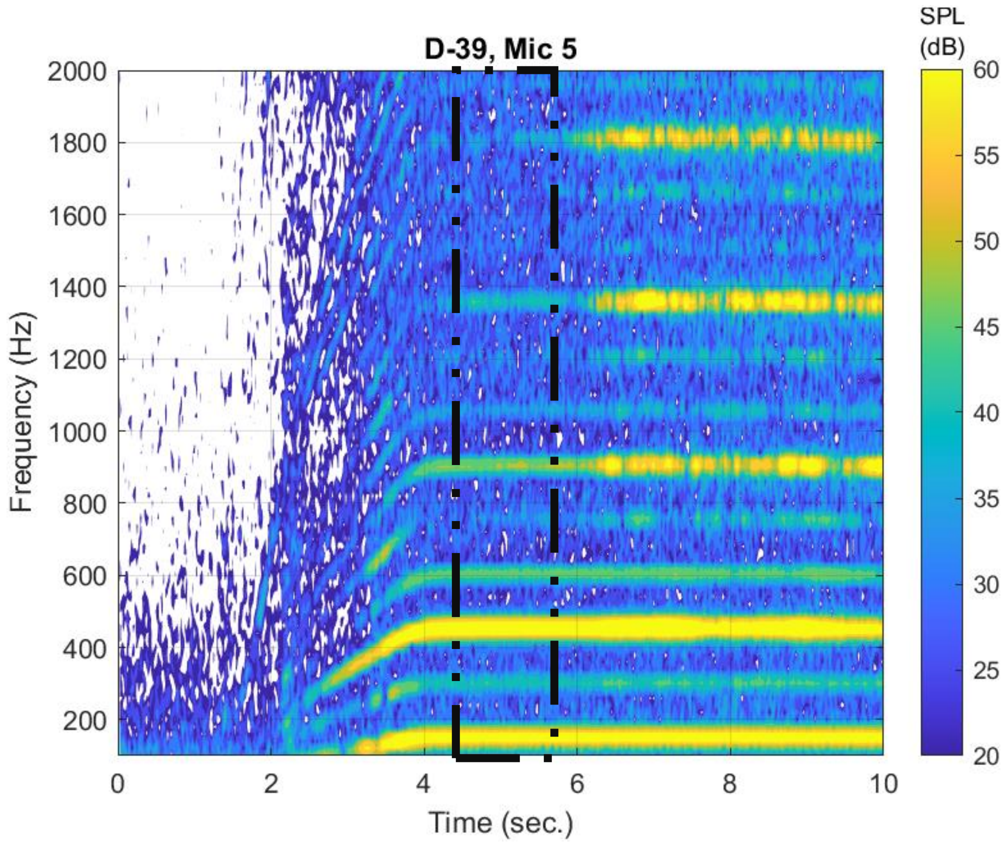
Recirculation in Static Tests – Isolated Propeller

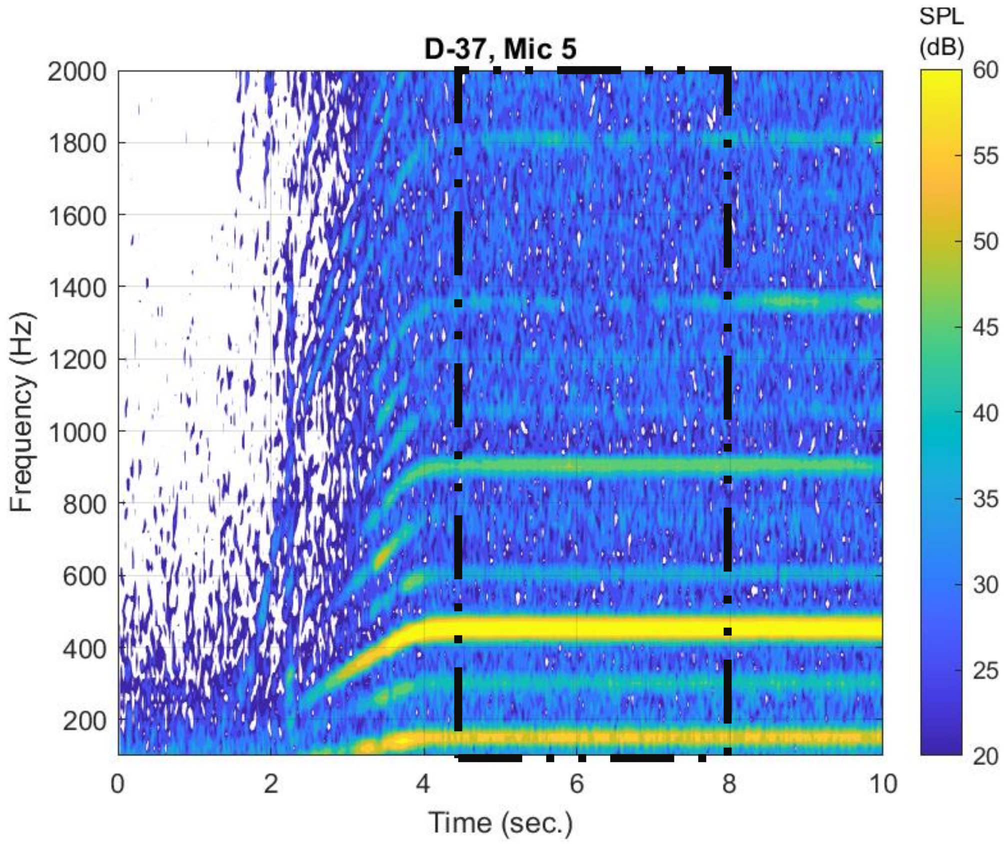
Without Meshscreen Treatment

~1.5 seconds before onset of recirculation

With Meshscreen Treatment

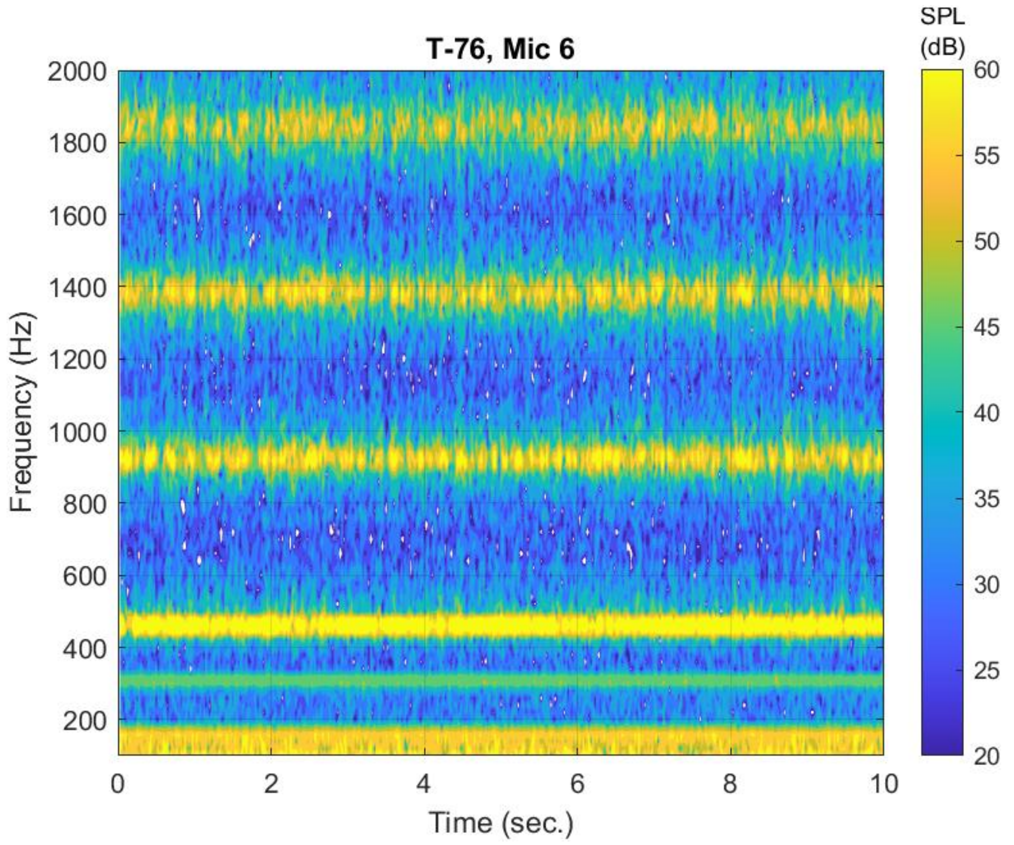
~3.5 seconds before onset of recirculation



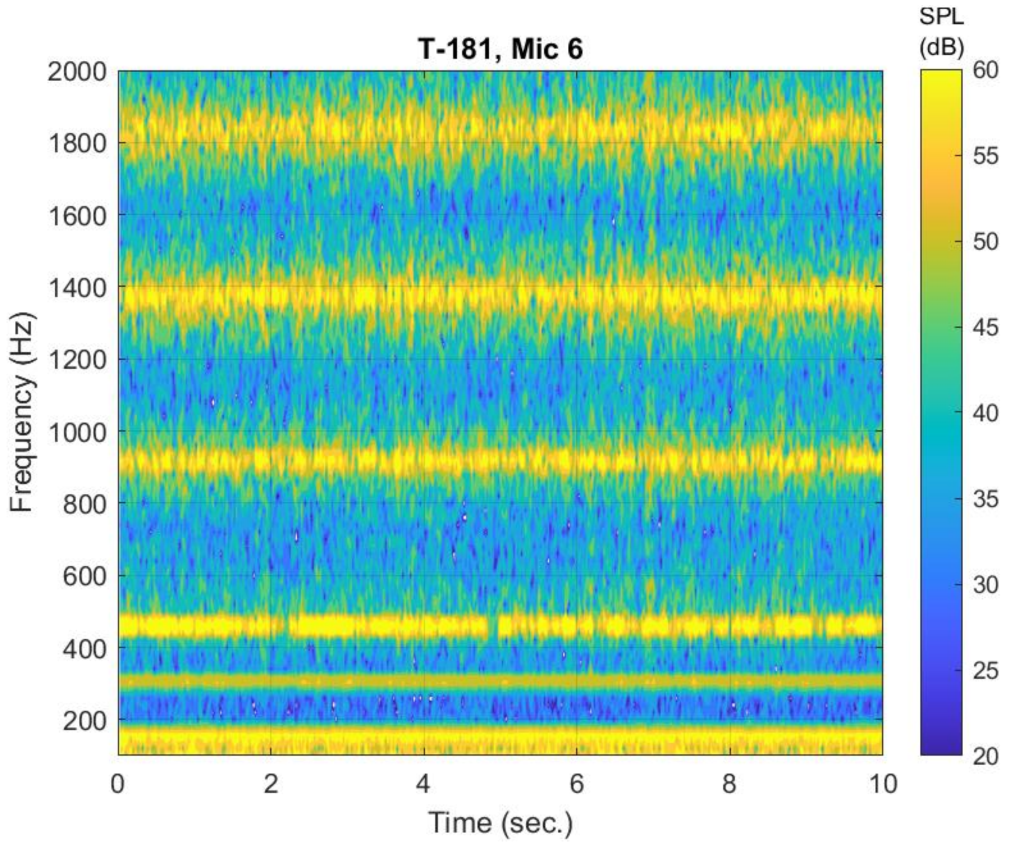


Flow on cases – no recirculation concerns

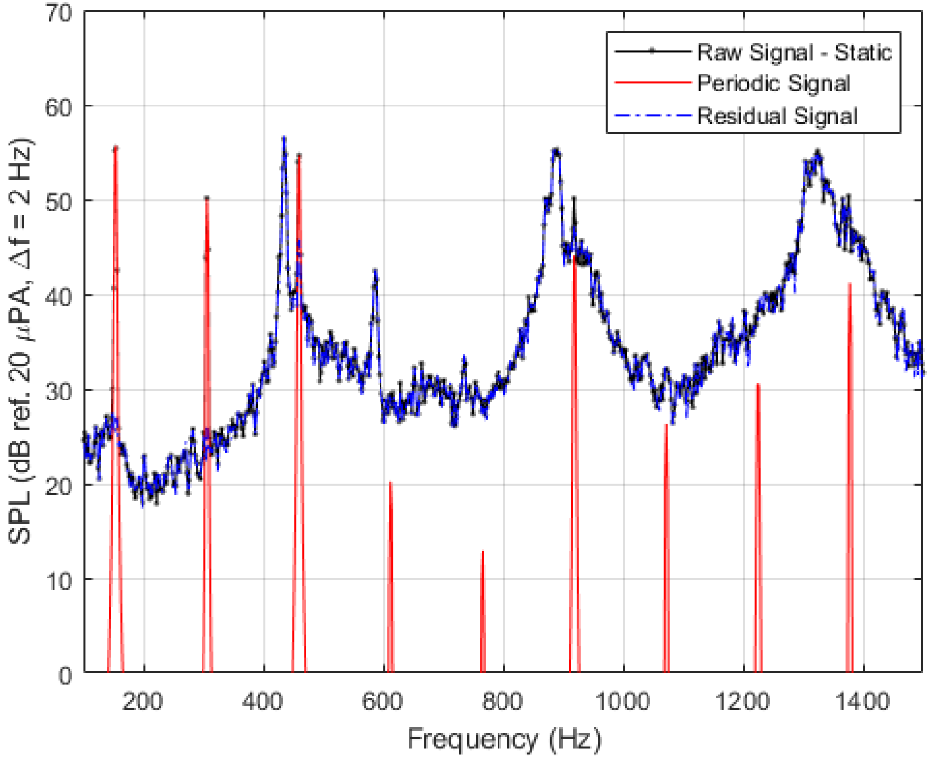
Isolated Propeller



Hardwall Duct

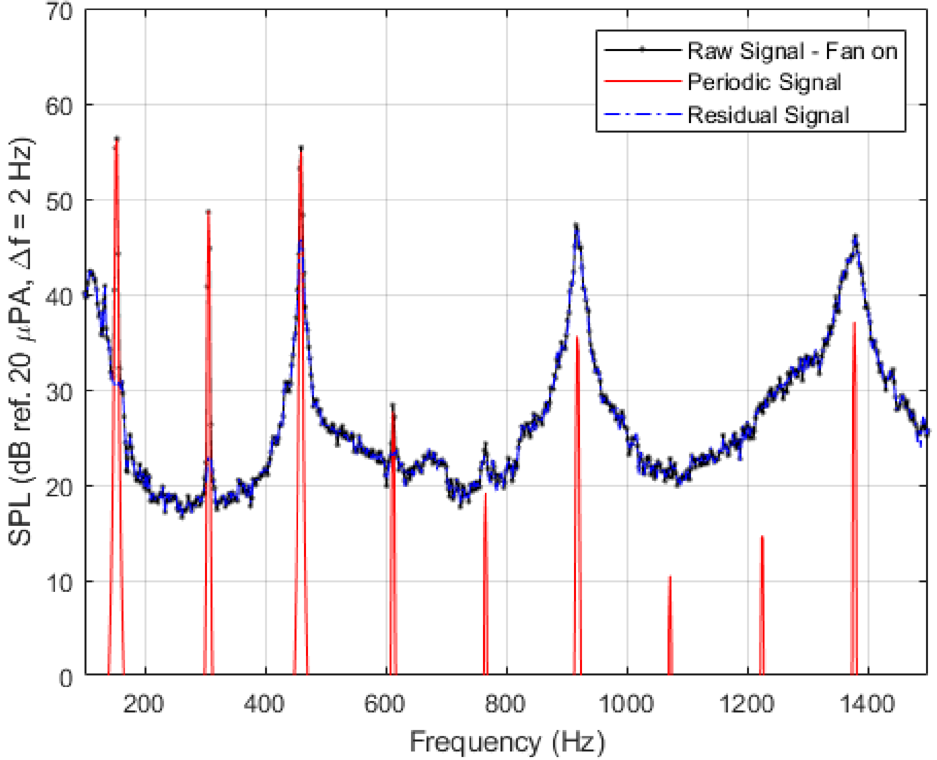


Why have the background free stream flow on?



Hardwall Duct US

Static, 9198 RPM, $\theta_{mic} = 0^\circ$



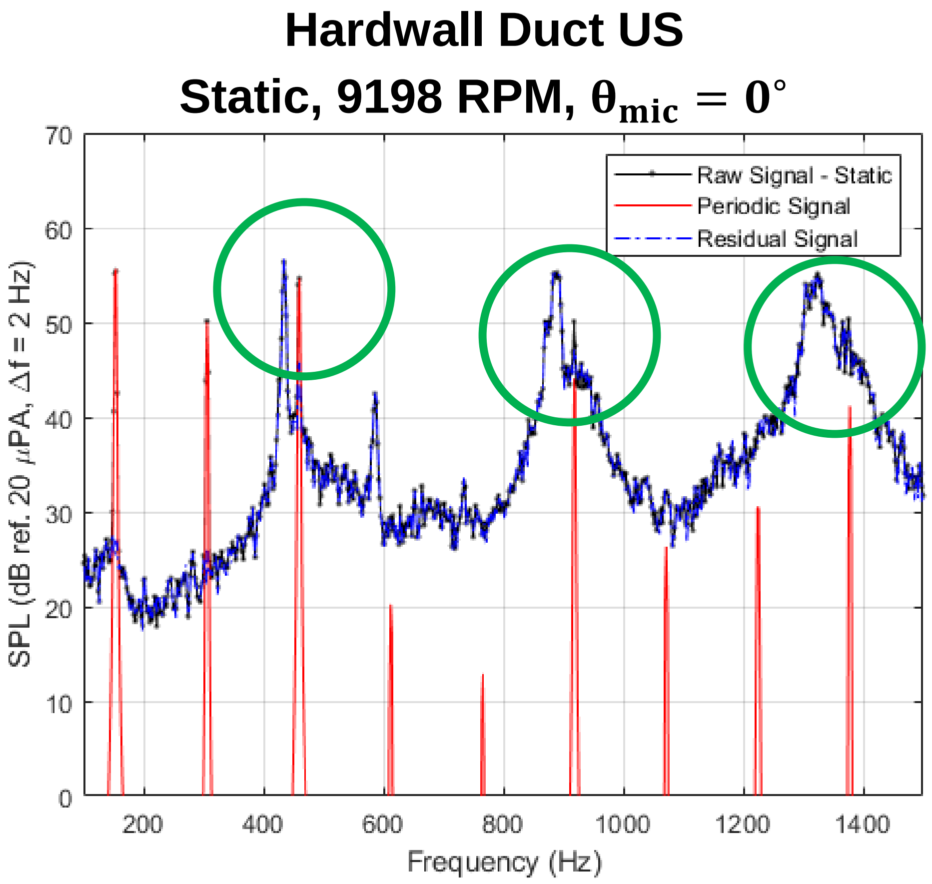
Hardwall Duct US

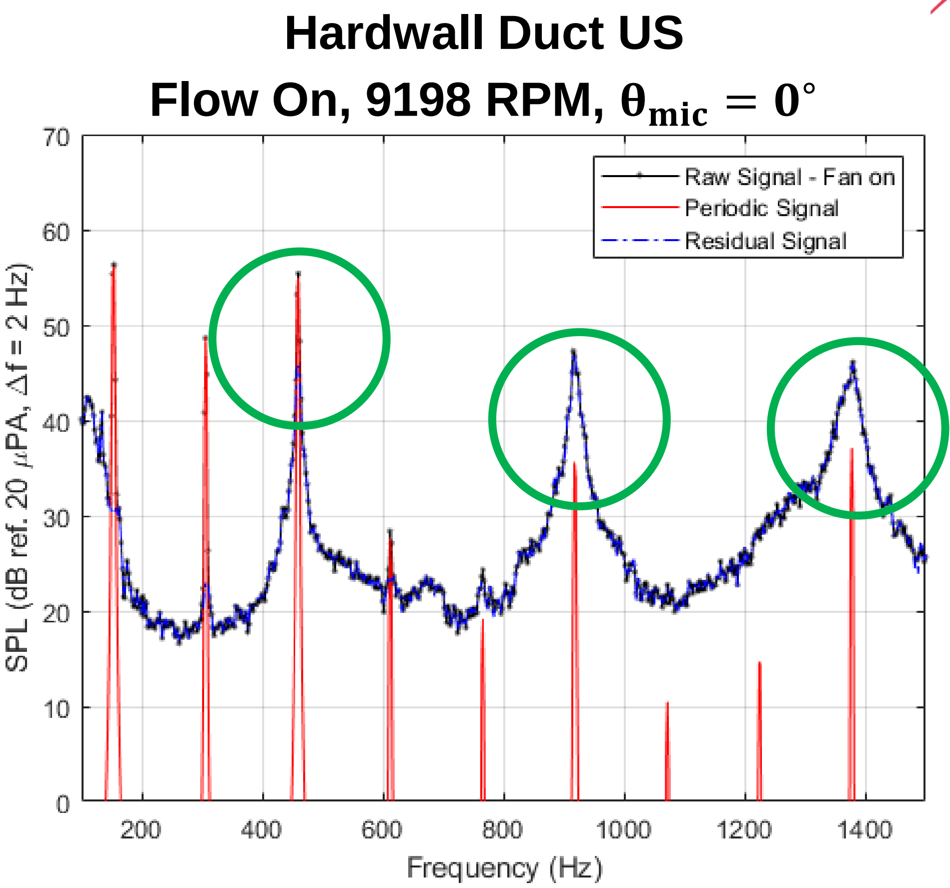
Flow On, 9198 RPM, $\theta_{mic} = 0^\circ$

- With no background flow on (static), the spectrum shows additional tonal content below the low harmonic BPFs.
- This is consistent at multiple rotation rates and could be due to inlet separation.

- A background flow of approximately 5 m/s was turned on in the SHAC.
- This removed the additional low frequency tones, as well as “splitting/spreading” behavior.
- The freestream may be helping reattach the flow

Why have the background free stream flow on?





- With no background flow on (static), the spectrum shows additional tonal content below the low harmonic BPFs.
- This is consistent at multiple rotation rates and could be due to inlet separation.

- A background flow of approximately 5 m/s was turned on in the SHAC.
- This removed the additional low frequency tones, as well as “splitting/spreading” behavior.
- The freestream may be helping reattach the flow

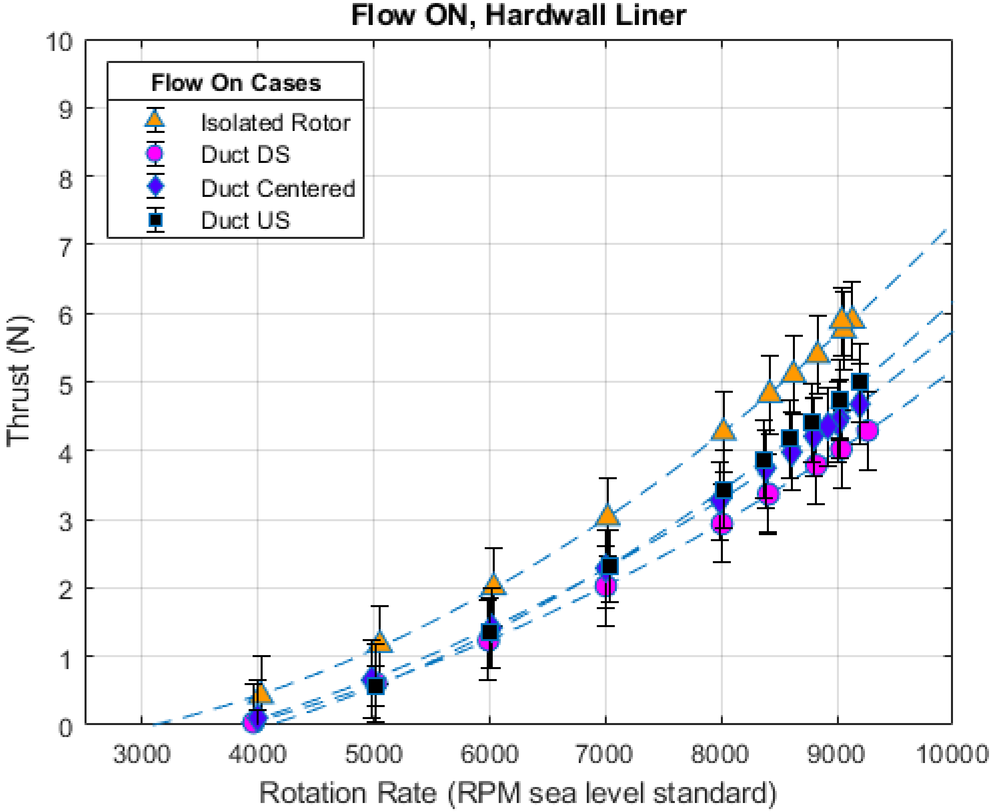
Performance Results

Flow off, 9000 RPM sea level standard

- The **isolated propeller** produces **1.7 lbs** of thrust
- The **ducted propellers** produce **~1.5 lbs** of thrust with the ducts center installed, with **~0.55 lbs** of that being generated by the ducts

Flow on, 9000 RPM sea level standard

- The **isolated propellers** produces **1.3 lbs** of thrust
- The **ducted propellers** produce **~0.97 lbs** of thrust with the ducts center installed, with **~0.1 lbs** of that being generated by the ducts
- The **net thrust** and **torque** **increase** when moving the ducts **upstream** for the **flow ON** cases.



Note: duct is not aerodynamically designed and may not be the most optimized configuration.