# Status of UAM Proprotor Design Validation Campaign: Available Data and Computational Tools

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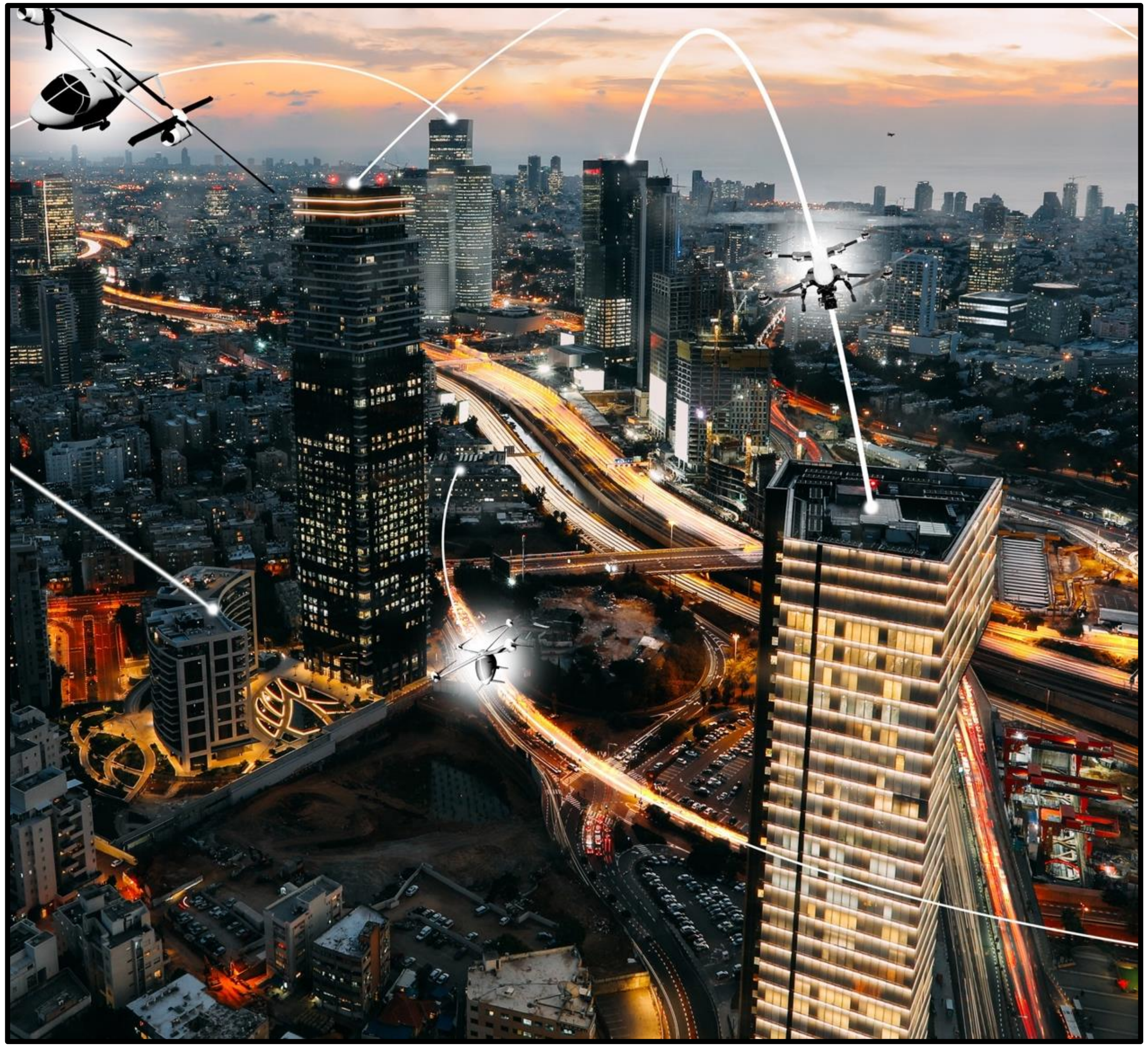
# Advanced Air Mobility (AAM) Challenge

- Opportunities of AAM vehicles are numerous
  - Large-sized vehicles for intraregional transportation
  - Medium-sized vehicles for urban and rural applications (UAM)
  - Small-sized vehicles for package deliveries and surveillance (sUAS)
- AAM challenges aeronautics community with unique challenges in performance and community impact
  - Safety
  - Reliability
  - Automation
  - Community impact (noise)



# AAM Challenge

- Traditional large transport vehicles limit design opportunities
  - Tube and wing
  - Not the case with hybrid wing or TTBW designs
- Large helicopters and multirotor vehicles do have design opportunities but are limited also
  - Traditional main/tail configurations
  - X-rotors, tandem, etc.
- AAM vehicles offer significantly more design opportunities
  - Rotor count, placement, blade count, rotation direction
  - Wing design and placement, installation effects
  - Blade shape and rotor sizing
- AAM vehicles also have significantly different flight mission requirements
- Offers opportunity to design from the ground up

➢ **What can our design tools predict?**

➢ **What do our design tools miss?**
  - Does validation data exist?
  - What about scale? Full vehicle vs component?

- Silva, C. and Johnson, W., "Practical Conceptual Design of Quieter Urban VTOL Aircraft," Vertical Flight Society’s 77th Annual Forum & Technology Display, Vertical Flight Society, Fairfax, VA, USA, 2021

# Outline

- **Validation of design optimization for AAM proprotors**
  - **Experimental validation process**
  - **Multidisciplinary design optimization procedure**
- **Update on available tools**

➢ **Isolated proprotor campaign**

➢ **Installed proprotor campaign**

- **Update on available UNWG SG1 Datasets**
  - **Previously 1, now 2, soon to be 4**
- **Conclusions**

Image credit: RVLT

# Experimental Design Validation Campaign

▬ Measured
▬ Background
◇ Predictions

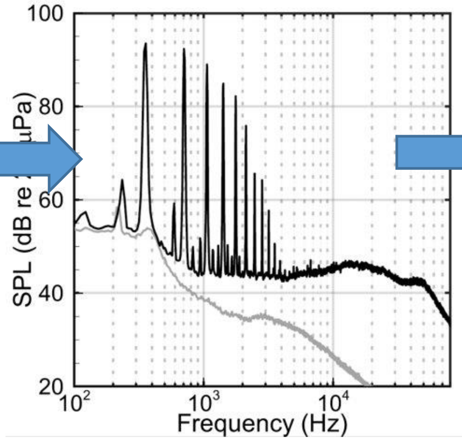
## Baseline Geometry

$$\phi = \mathrm{TAN}^{-1}\left(\frac{P}{\pi D}\,\frac{R}{r}\right)$$

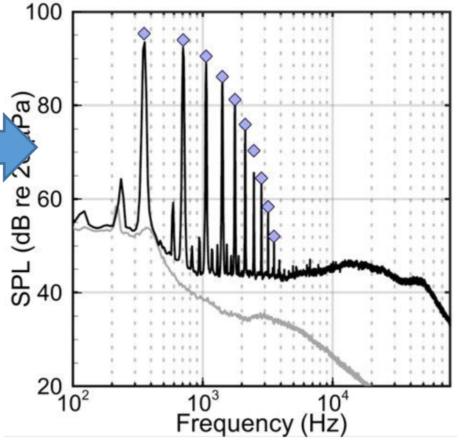
| Parameter | Value |
|---|---|
| $c$, in. (mm) | 1.5 (38.1) |
| $P$, in. (mm) | 16.0 (406.4) |
| $D_p$, in. (mm) | 24.0 (609.6) |

## Baseline Tunnel Entry

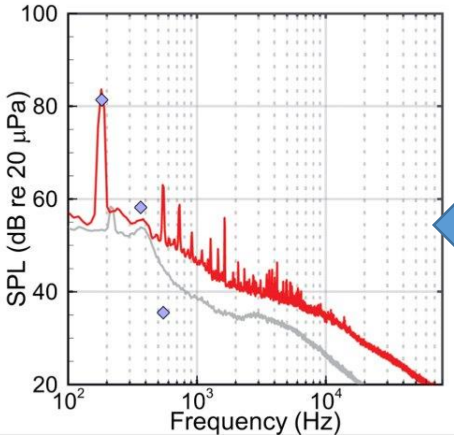
## Baseline Data



## Analysis Using Optimization Tools

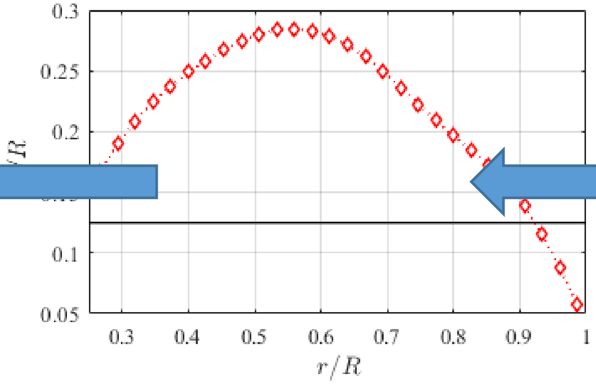


## Validation Data

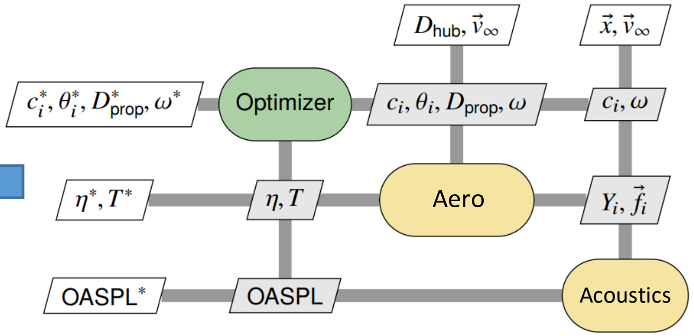


## Optimization Tunnel Entry

## Optimized Geometry

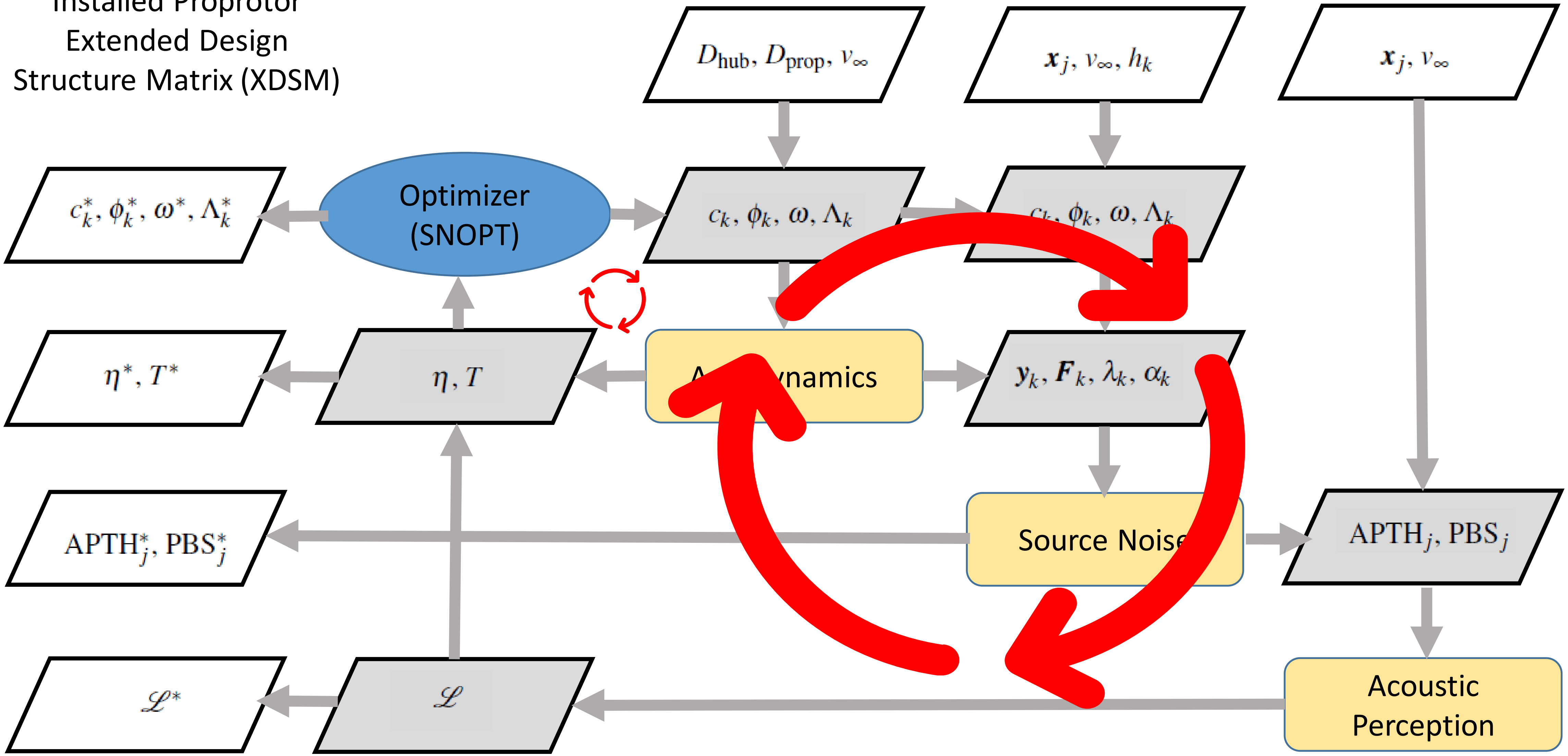


## Design Optimization



# Multidisciplinary Design Optimization

Installed Proprotor
Extended Design
Structure Matrix (XDSM)



$D_{\text{hub}}, D_{\text{prop}}, v_\infty$

$\boldsymbol{x}_j, v_\infty, h_k$

$\boldsymbol{x}_j, v_\infty$

$c_k^*, \phi_k^*, \omega^*, \Lambda_k^*$

Optimizer (SNOPT)

$c_k, \phi_k, \omega, \Lambda_k$

$c_k, \phi_k, \omega, \Lambda_k$

$\eta^*, T^*$

$\eta, T$

A ynamics

$\boldsymbol{y}_k, \boldsymbol{F}_k, \lambda_k, \alpha_k$

$\text{APTH}_j^*, \text{PBS}_j^*$

Source Noise

$\text{APTH}_j, \text{PBS}_j$

$\mathscr{L}^*$

$\mathscr{L}$

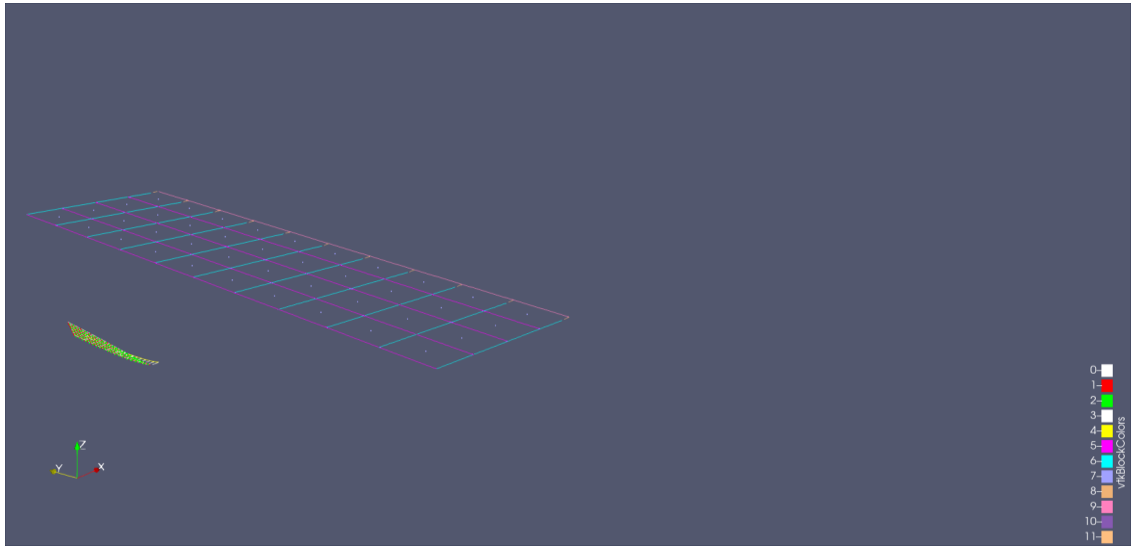
Acoustic Perception

# Aerodynamics

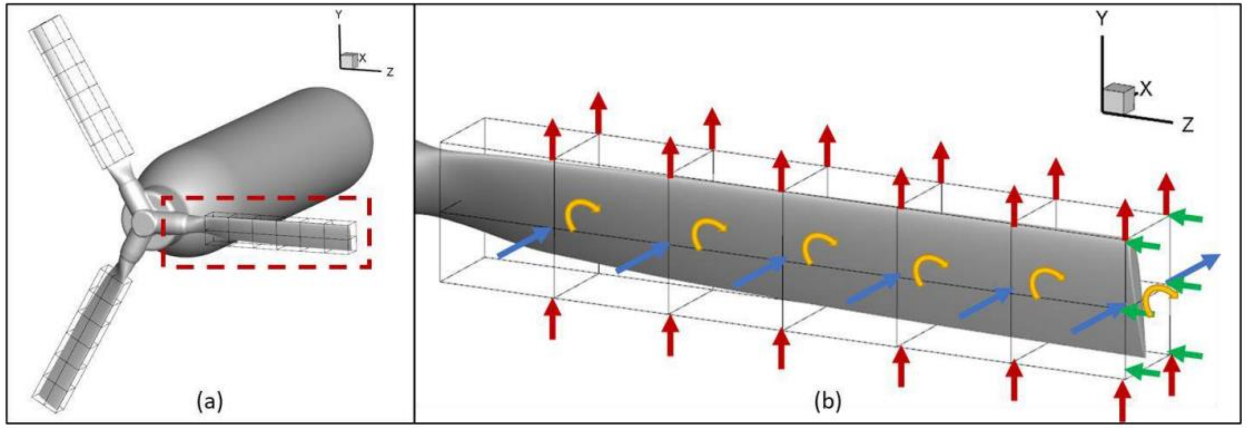
Available codes highlighted in red

Increasing Fidelity

- Blade element momentum theory (BEMT)
  - Implementation:
    - CCBlade.jl from A. Ning, BYU.
  - Advantages:
    - Robust (important for multi-disciplinary optimization)
    - Accurate (for simple configurations single rotor, on-axis flow)
    - Derivatives available via automatic differentiation (AD)
    - Very easy to use
  - Disadvantages:
    - Can't do multiple rotors, installation effects
- Unsteady Vortex Lattice Method (UVLM)
  - Implementations:
    - VortexLattice.jl from T. McDonnell, A. Ning, BYU
    - VSPAERO, part of OpenVSP, D. Kinney, NASA ARC
  - Advantages:
    - Naturally incorporate more complex configurations
    - Reasonably computationally efficient
      - Slower than BEMT, but much faster than CFD
      - Much easier workflow than CFD
  - Disadvantages:
    - Stability of derivatives may be a problem (but there's hope).
- Unsteady Reynolds-averaged Navier-Stokes (URANS)
  - Implementations:
    - Open-source multi-physics suite SU2 from Stanford University
  - Advantages:
    - Blade shape deformations
    - Frequency weighting
    - Multiple observer positions
  - Disadvantage
    - Could not reduce tip chord length significantly
    - Difficult to converge
    - Slow



- Ingraham, D. J., "Low-Noise Propeller Design with the Vortex Lattice Method," April 2022, NASA Acoustics Technical Working Group



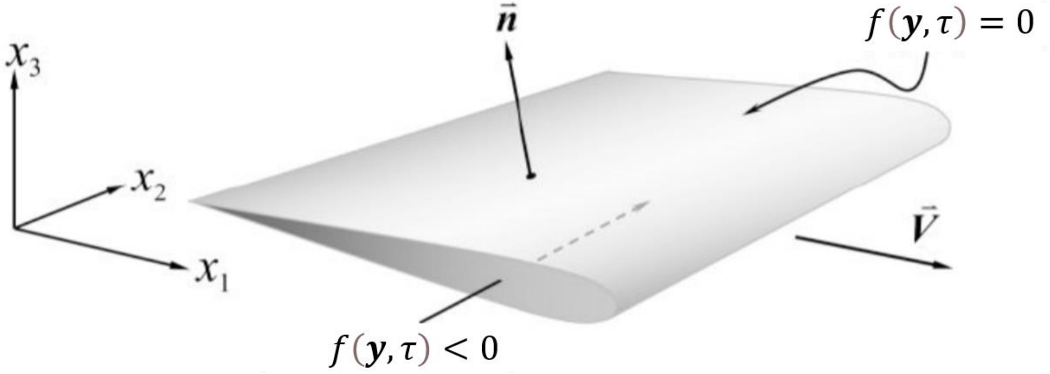
- Icke, R. O., Baysal, O., Lopes, L. V., Diskin, B., "Optimizing Proprotor Blades Using Coupled Aeroacoustic and Aerodynamic Sensitivities," August 2–6 2021, AIAA Paper No. 2021-3037, presented at AIAA AVIATION 2021 Forum. doi:10.2514/6.2021-3037

# Source Noise

Available codes highlighted in red

## Tonal Noise

- **ANOPP2 Formulation 1A IFM (AF1AIFM):**



Farassat's Formulation 1A (F1A)
Compact and Nondeforming Blade

$$\frac{4\pi}{\rho_\infty} p'_m(\mathbf{x},t) = \int_{F=0} \left[\Psi \mathscr{C}_{1A} K\right]_{\text{ret}} \mathrm{d}u$$

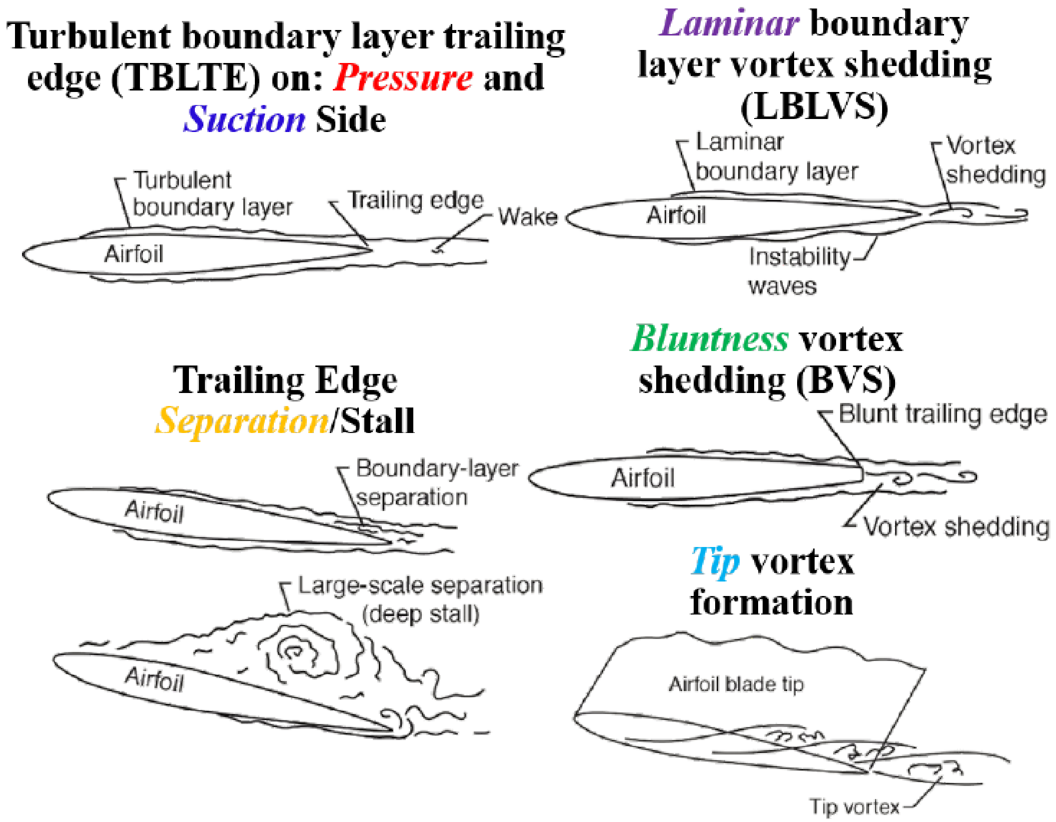
$$4\pi c_\infty p'_d(\mathbf{x},t) = \int_{F=0} \left[\dot{\mathbf{F}} \mathscr{D}_{1A} K\right]_{\text{ret}} \mathrm{d}u + \int_{F=0} \left[\mathbf{F} \mathscr{E}_{1A} K\right]_{\text{ret}} \mathrm{d}u$$

Where $\mathscr{C}_{1A}$, $\mathscr{D}_{1A}$, and $\mathscr{E}_{1A}$ are functions of $\hat{\boldsymbol{r}}_j$ and $\boldsymbol{M}_i$ and their source time derivatives

- Lopes, L. V., "ANOPP2 Farassat Formulations Internal Functional Modules (AFFIFMs) Reference Manual," NASA TM 2021-0021111, National Aeronautics and Space Administration, December 2021.
- Lopes, L. V., "Compact Assumption Applied to the Monopole Term of Farassat's Formulations," Journal of Aircraft, Vol. 54, No. 5, September 2017, pp. 1649–1663, doi:10.2514/1.C034048.

## Broadband Self Noise

- **ANOPP2 Self Noise IFM (ASNIFM):**



**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)**

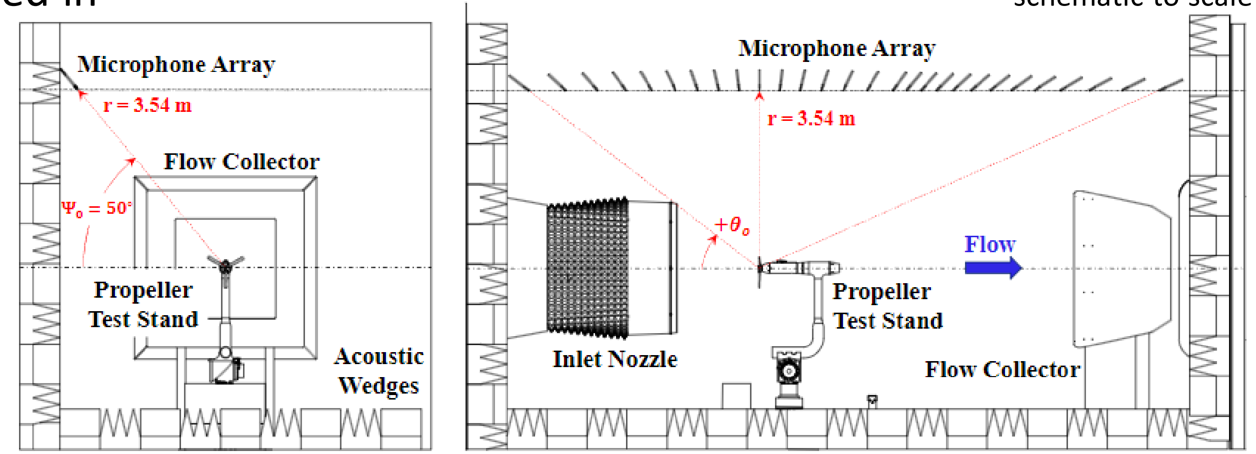
***Tip* vortex formation**

- Brooks, T. F., Pope, S. D., and Marcolini, M. A., "Airfoil Self-Noise and Prediction," NASA RP 1218, National Aeronautics and Space Administration, July 1989.
- Pettingill, N. A., Zawodny, N. S., Thurman, C. S., and Lopes, L. V., "Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover," January 11–12 & 19–21 2021, AIAA Paper No. 2021-1928, presented at AIAA Scitech 2021 Forum. doi:10.2514/6.2021-1928.

# Acoustic Perception

Available codes highlighted in red

- Several different acoustic constraints that can be utilized in this approach
- Current campaign
  - Tonal noise only
  - Low-fidelity
    - Inplane observer
    - One forward flight condition
    - Unweighted OASPL
  - High-fidelity
    - Spatially integrated acoustic power
    - Hover and one forward flight condition
    - A-weighted OASPL
- Future campaigns will expand capabilities
  - With and without broadband self noise
  - Single microphone vs spatially integrated acoustic power
  - Hover and/or one or more forward flight condition
  - Several different weighing metrics
- ANOPP2 Acoustic Analysis Utility (AAAU)

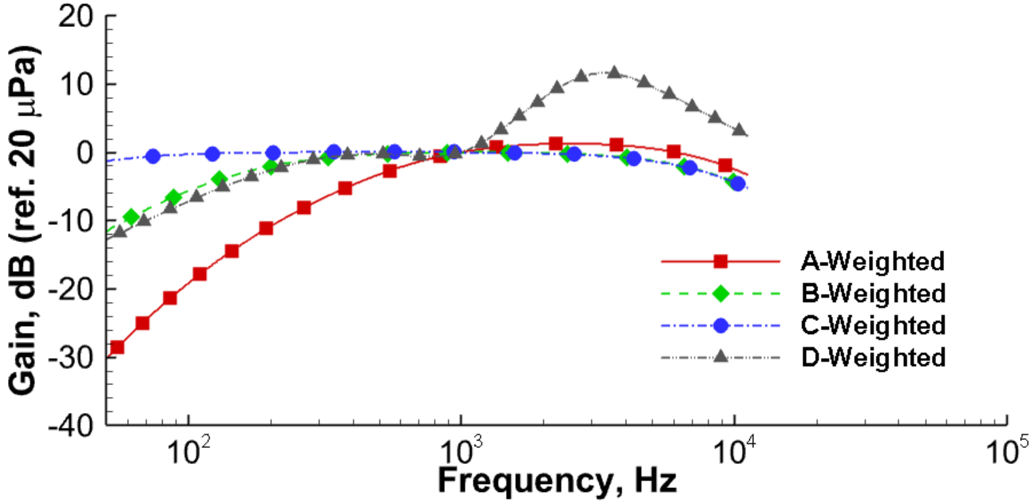


schematic to scale

a) Downstream view.

b) Side view.

- Litherland, B. L., Borer, N. K., and Zawodny, N. S., “X-57 ‘Maxwell’ High-Lift Propeller Testing and Model Development,” August 2-6 2021, AIAA Paper No. 2021-3193, presented at AIAA AVIATION 2021 Forum. doi:10.2514/6.2021-3193



- Lopes, L. V. and Burley, C. L., “ANOPP2’s User’s Manual,” NASA TM 2016-219342, National Aeronautics and Space Administration, October 2016.

# Outline

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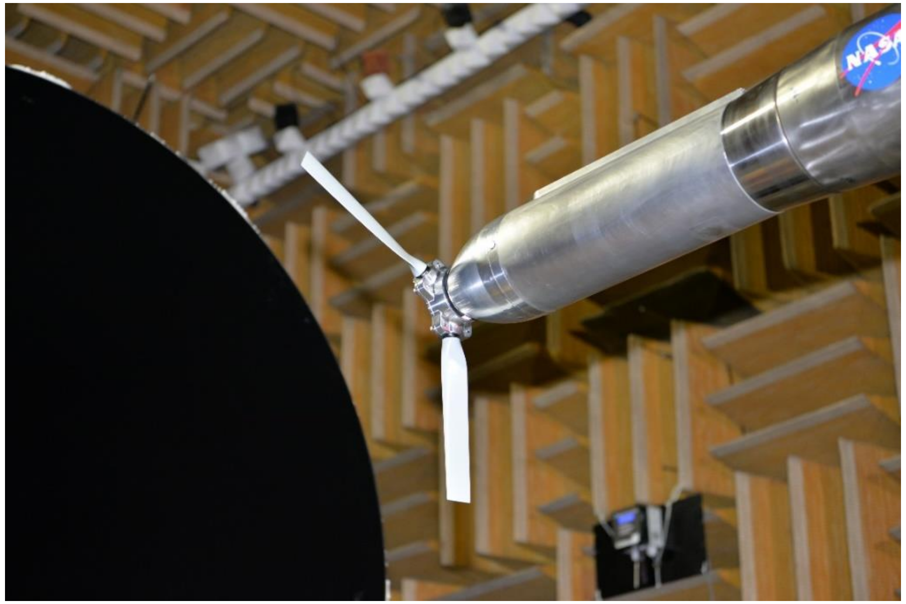
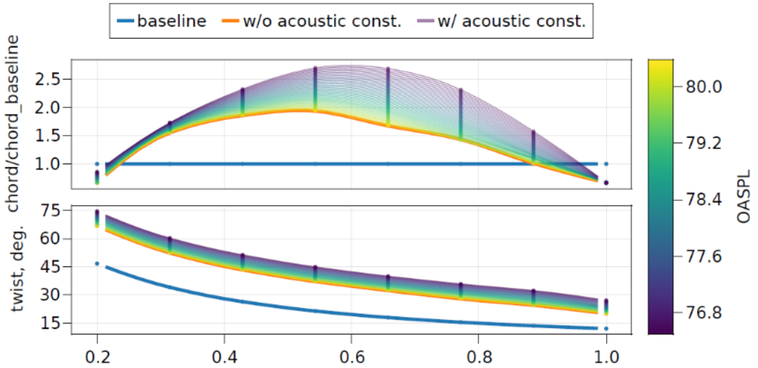
  - Experimental validation process
  - Multidisciplinary design optimization procedure
- Update on available tools
- **Isolated proprotor campaign**
- **Installed proprotor campaign**
- **Update on available UNWG SG1 Datasets**
  - **Previously 1, now 2, soon to be 4**
- **Conclusions**

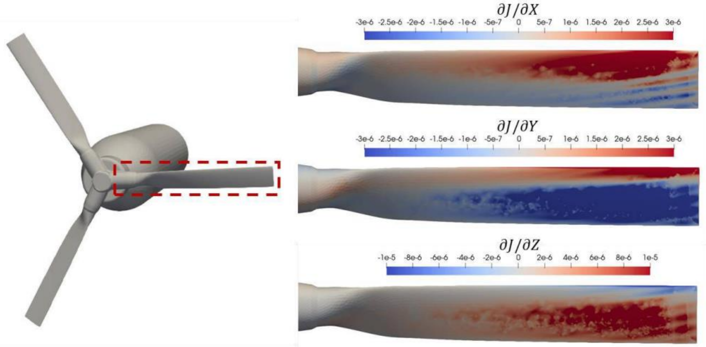
Image credit: RVLT

# Isolated Proprotor Design Optimization Campaign

- Helically Twisted Rotor (HTR) aka C24ND
  - Used for checkout of Propeller Test Stand (PTS)
  - $\phi\left(\frac{r}{R}\right) = \operatorname{atan}\frac{P}{\pi D * \frac{r}{R}}$
  - D = 24” (propeller diameter)
  - P = 16” (propeller pitch)
  - C = 1.5” (constant chord length)
  - NACA 0012 airfoils
  - Measurement data for multiple flight conditions
- This is a very noisy rotor
- Two optimization efforts
  - ccblade.jl: BEMT, OASPL at single in plane observer, no frequency weighting, one forward flight condition
  - SU2: URANS, multiple observer positions, a-weighted integrated OASPL, one forward flight and one hover condition







- Ingraham, D. J., Gray, J. S., and Lopes, L. V., “Gradient- Based Propeller Optimization with Acoustic Constraints,” January 8–12 2019, AIAA Paper No. 2019-1219, presented at AIAA Scitech 2019 Forum. doi:10.2514/6.2019-1219
- Icke, R. O., Baysal, O., Lopes, L. V., Diskin, B., “Optimizing Proprotor Blades Using Coupled Aeroacoustic and Aerodynamic Sensitivities,” August 2–6 2021, AIAA Paper No. 2021-3037, presented at AIAA AVIATION 2021 Forum. doi:10.2514/6.2021-3037

# Isolated Proprotor Design Optimization Campaign

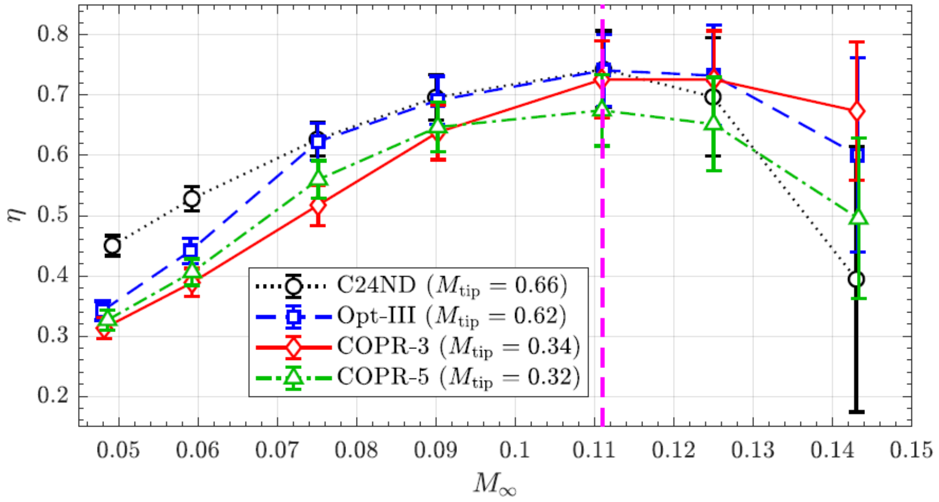
Baseline

SU2

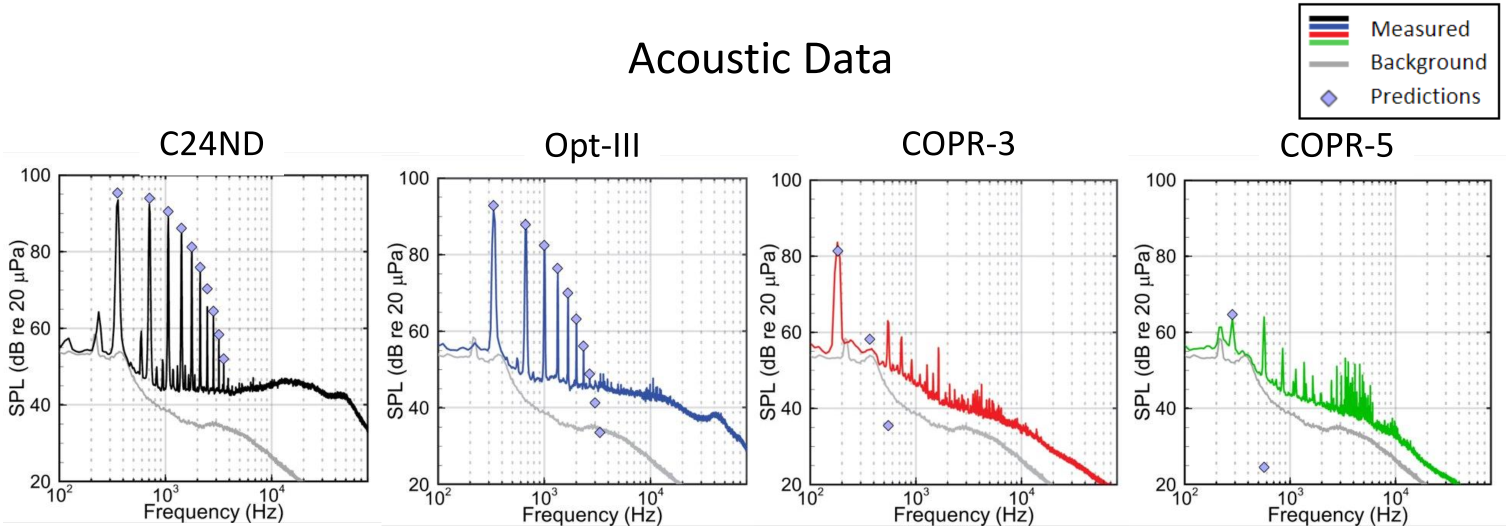
ccblade.jl

ccblade.jl blade design x5

## Performance Data



## Acoustic Data

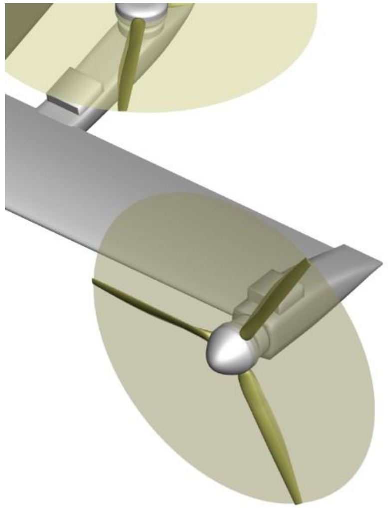


Preliminary predictions using ANOPP-PAS, will use AF1AIFM in future

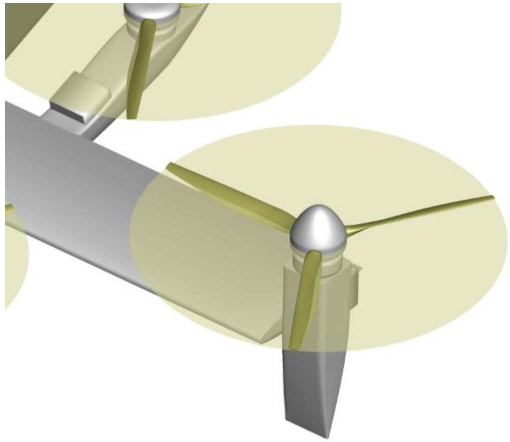
# Installed Proprotor Design Optimization Campaign

- Focus on low-fidelity aerodynamics for quicker turnaround time (also more capability)
- Tackle new physics in the optimization cycle
  - Broadband noise via ASNIFM
  - Aerodynamic installation effects via VortexLattice.jl and/or VSPAERO (tiltprop)
  - Add more dynamic and community-representative acoustic constraints
- Baseline geometry will be COPR-3 (optimized isolated proprotor)
- Computational effort for installed proprotor will wrap up in early spring
- Tunnel entry in late spring or summer conditional on LSAWT upgrades

Forward Flight Proprotor



Hover Proprotor



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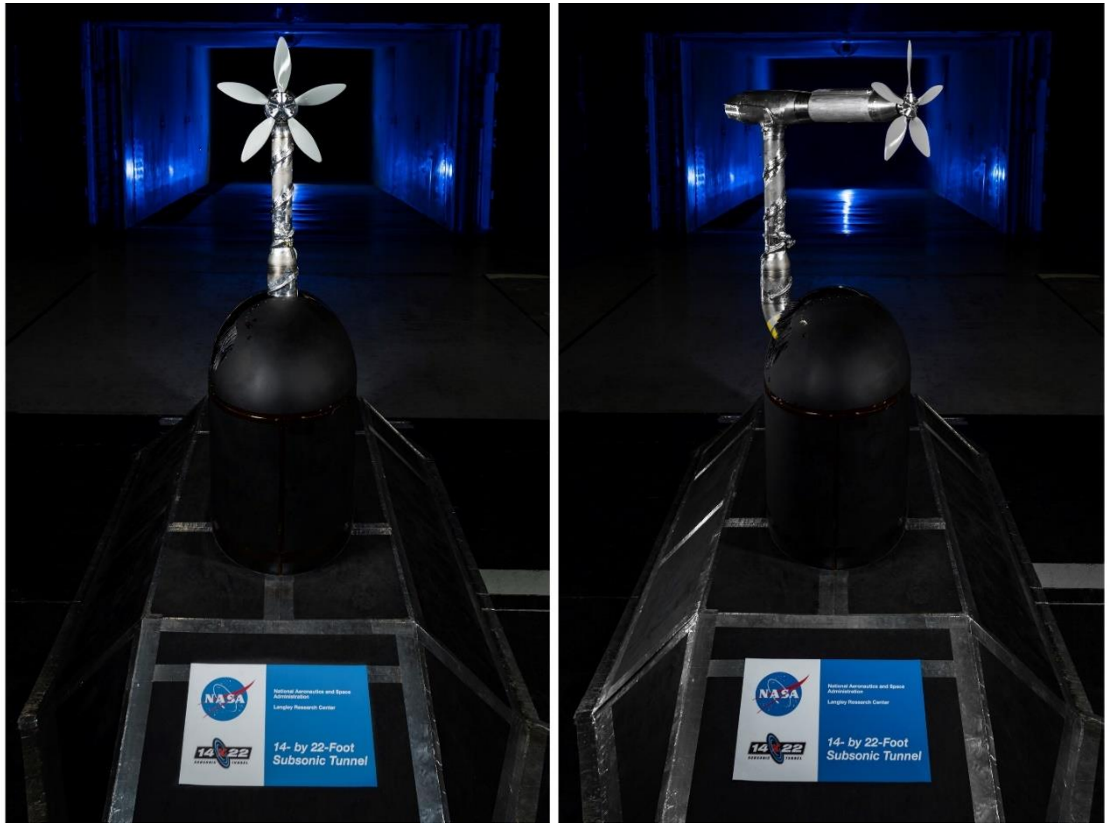


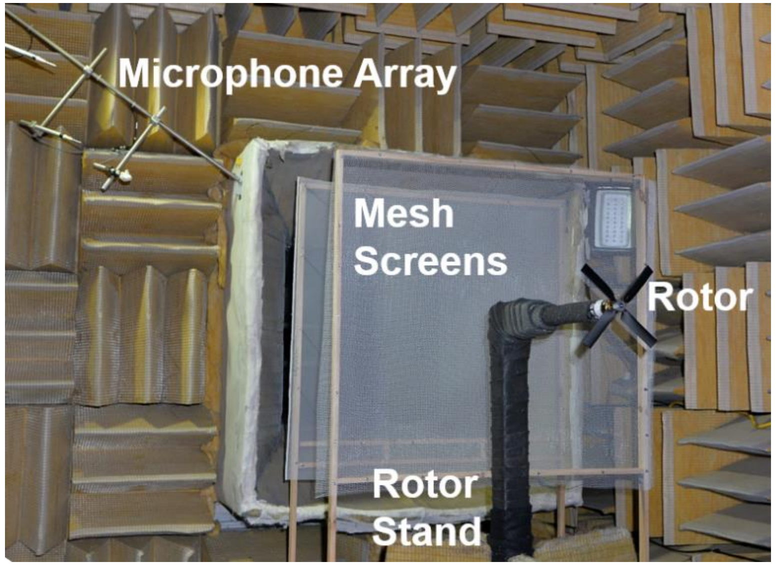
Image credit: RVLT

# 1) Ideally Twisted Rotor Dataset (2021)

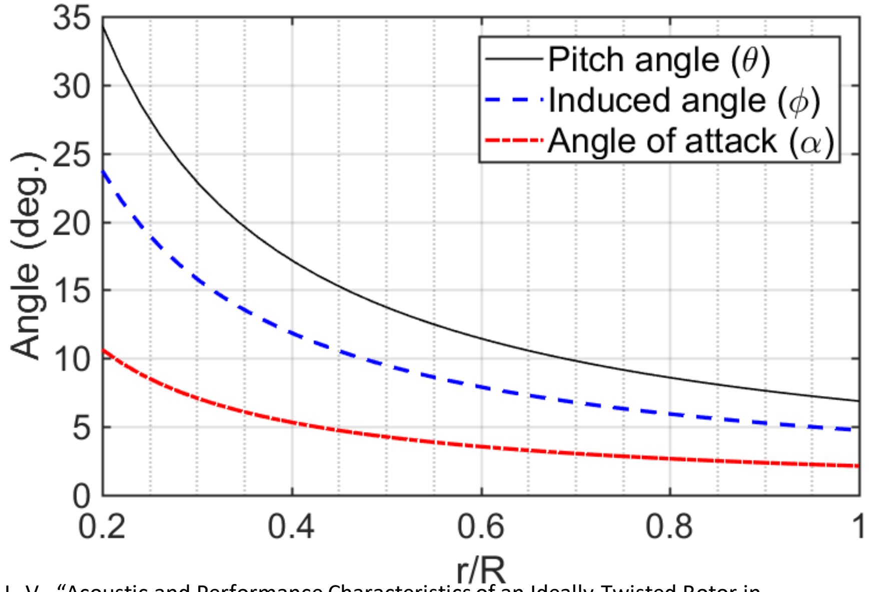
- Ideally, radially constant induced inflow to minimize induced power.
- From blade element momentum theory (BEMT) in hover:

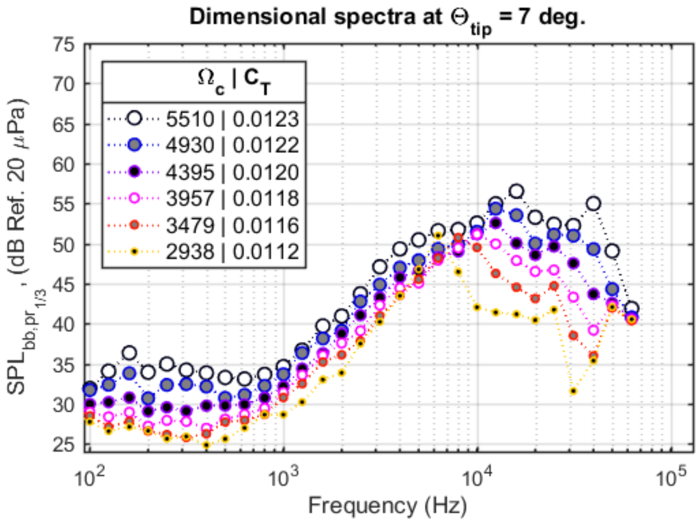
$$\lambda(r) = \frac{\sigma C_{l_\alpha}}{16}\left(\left(1 + \frac{32}{\sigma C_{l_\alpha}}\theta r\right)^{1/2} - 1\right) \qquad \theta = \frac{Constant}{r}$$

- Small Hover Anechoic Chamber (SHAC)
- Hover condition only
- Multiple surface materials (influence of roughness on broadband noise)



| | Parameter | Value |
|---|---|---|
| Geometry | $R$ (m) | 0.1588 |
| | $c/R$ | 0.20 |
| | $\Theta_{tip}$ (°) | 6.9 |
| | $N_b$ | 4 |
| | $\sigma$ | 0.255 |
| Operating Condition | $C_T$ | 0.0137 |
| | $M_{tip}$ | 0.27 |
| | $\Omega_c$ (RPM) | 5500 |

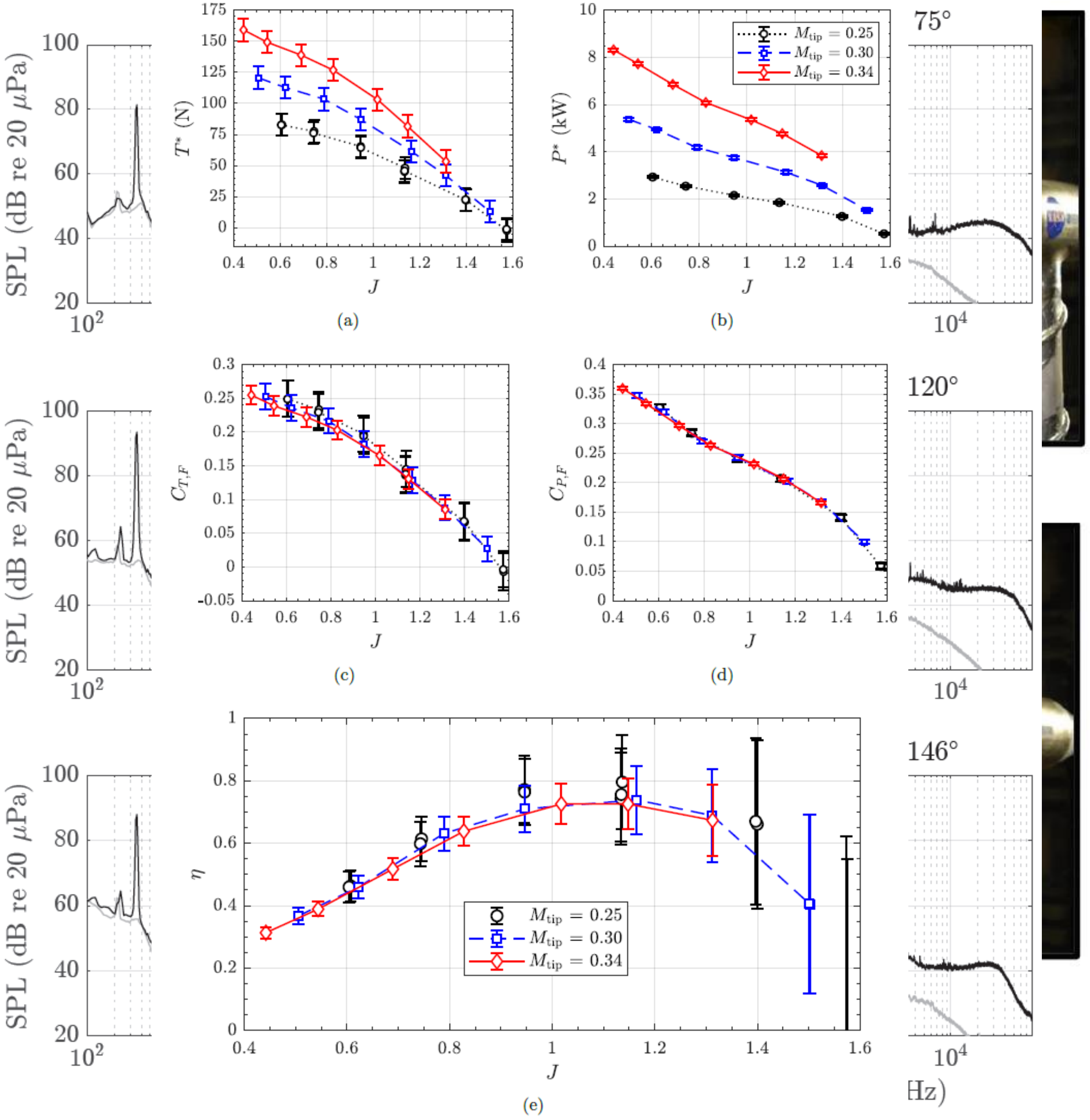




- Pettingill, N. A., Zawodny, N. S., Thurman, C. S., and Lopes, L. V., "Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover," January 11–12 & 19–21 2021, AIAA Paper No. 2021-1928, presented at AIAA Scitech 2021 Forum. doi:10.2514/6.2021-1928.

# 2) Helically Twisted Rotor Design Optimization (2022)

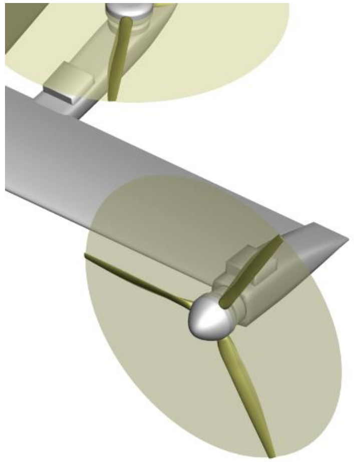
- Started with very noisy helically twisted rotor (a.k.a. C24ND)
- Low-fidelity and high-fidelity optimization efforts resulted in Opt-III and COPR-3 and COPR-5 designs
- Low Speed Aeroacoustic Wind Tunnel (LSAWT)
- A first TM is near publication documenting tunnel entry and measurement data
  - Performance data
  - Acoustic data
- A second TM early next year comparing predictions to measurements and will draw conclusions on acoustic trends



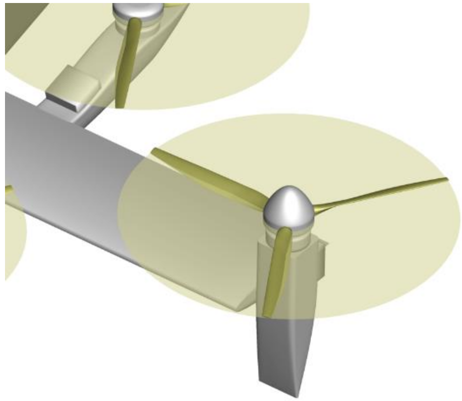
# 3) Installed COPR-3 Proprotor (Available Late 2023)

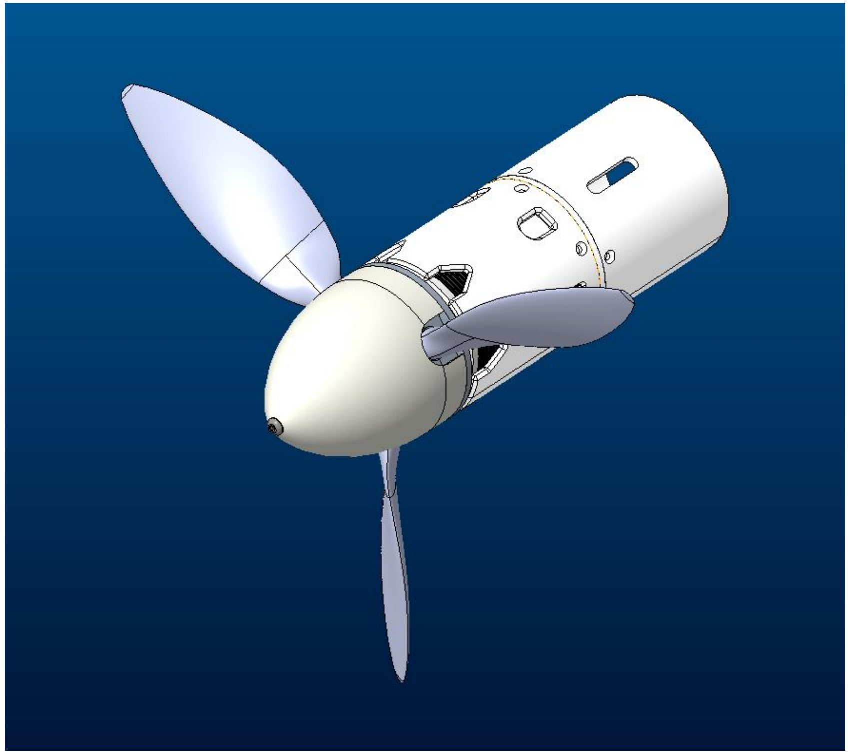
- Installed proprotor test data will be made available via UNWG SG1
- Will include geometry of baseline, wing, and multiple optimized geometries
  - Different aerodynamic, source noise, and perception constraints lead to different designs
- Wing/prop configurations based on RAVEN vehicle
  - Ratio of wing to proprotor radius ~ 1
  - Due to tunnel limitations, proprotor will have 1 ft diameter
    - COPR-3 has 2 ft diameter, allows for proprotor scaling study

Forward Flight Proprotor



Hover Proprotor





# 4) Optimum Hovering Rotor (Available Early 2023)

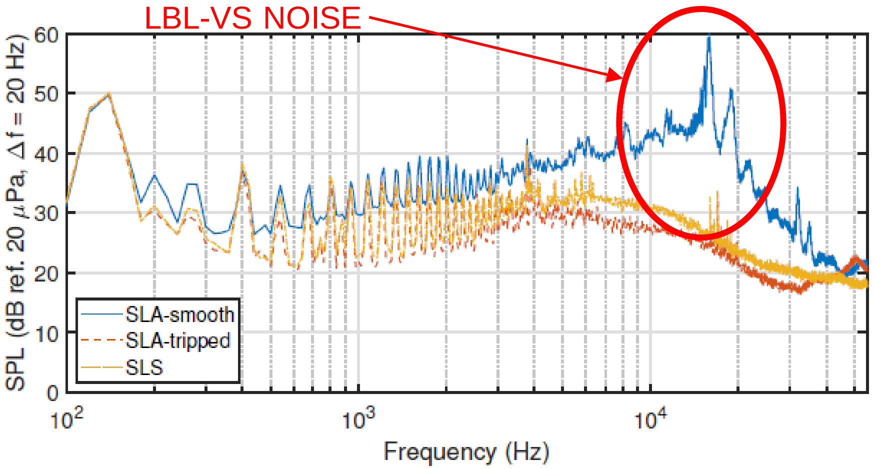
- Minimum induced power requirement
- Minimum profile power requirement

$$\theta_{tw}(r) = \frac{1}{r}\left(\frac{4C_{T_{design}}}{5.73\sigma(r)} + \sqrt{\frac{C_{T_{design}}}{2}}\right) - \alpha_0$$

- Focusing on LBL-VS noise and how to mitigate
  - Dependent on surface materials

➢ SLA-smooth (Protolabs – Accura Xtreme)
➢ SLA-tripped (Protolabs – Accura Xtreme with boundary layer trip)
➢ SLS (Protolabs – PA12 Mineral-filled)

- Planned dataset release spring UNWG meeting



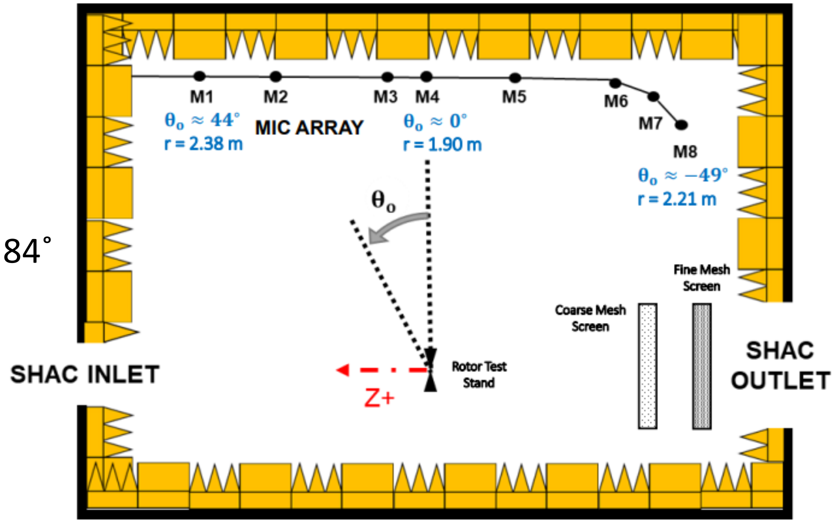
**SLS**

**SLA-tripped**

## Design conditions

- R = 7.5 in
- Ω = 2500 - 5000 RPM
- $T_{design}$ = 1.875 lb
- $c_{tip}$= 0.75 in
- TE bluntness = 0.03c(r)
- NACA 5408 airfoil: $\alpha_0$ = -4.84˚
- Taper = 2.25 to 1

not to scale



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- Pettingill, N. A., Zawodny, N.S., Thurman, C.S., “Aeroacoustic Testing of UAS-Scale Rotors for a Quadcopter in Hover and Forward Flight,” June 14–17 2022, AIAA Paper No. 2022-3110, presented at AIAA Aeroacoustics Conference. doi:10.2514/6.2022-3110.

# Conclusions

1. Presented two campaigns on the validation of tools used in proprotor design optimization including an acoustic constraint
2. Presented the aerodynamic and acoustic tools being used in those campaigns, all of which are available outside NASA
3. Presented four experimental datasets that are or will be shortly available to the community via UNWG SG1