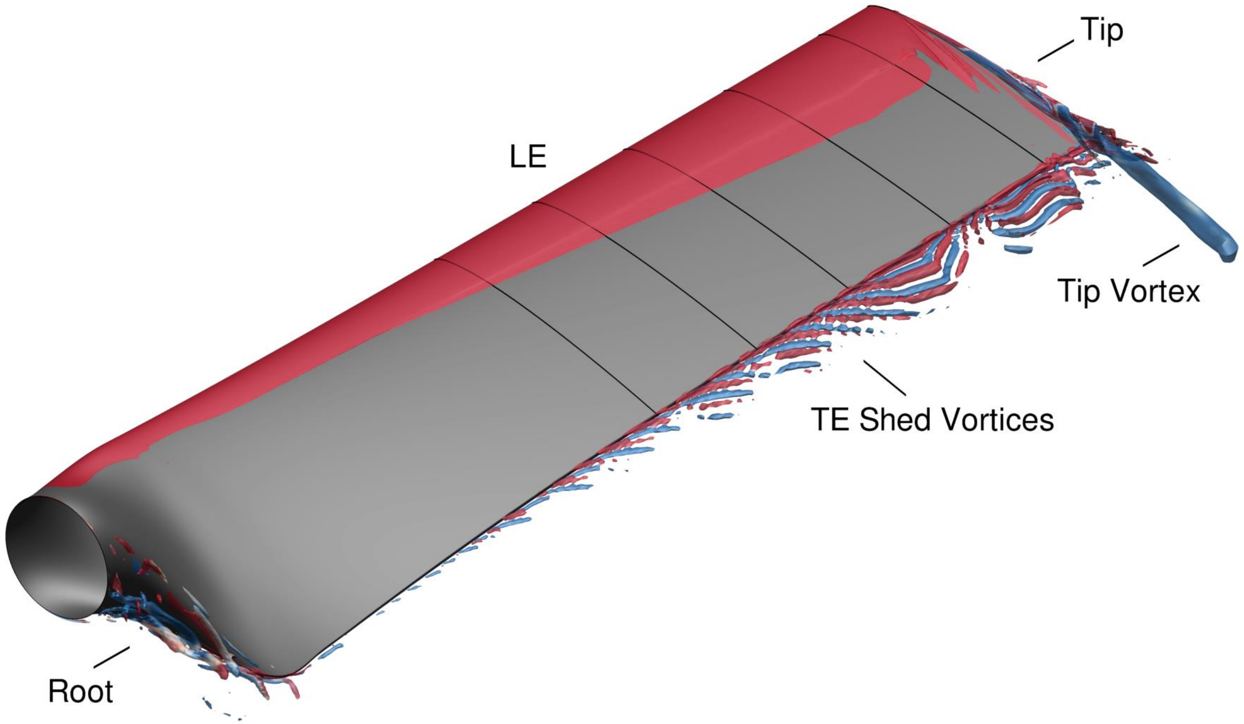
A Computational Study of Bluntness Vortex Shedding Noise Generated by a Small Canonical Rotor for UAM Applications



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Aeroacoustics Branch

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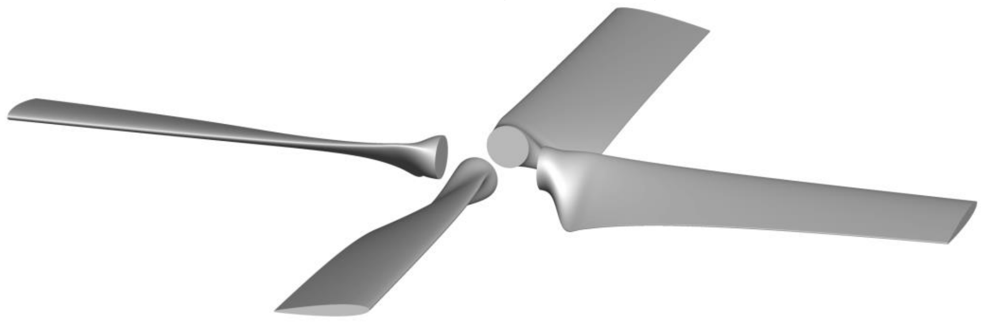
Acoustics III Session: Paper #112

Motivation

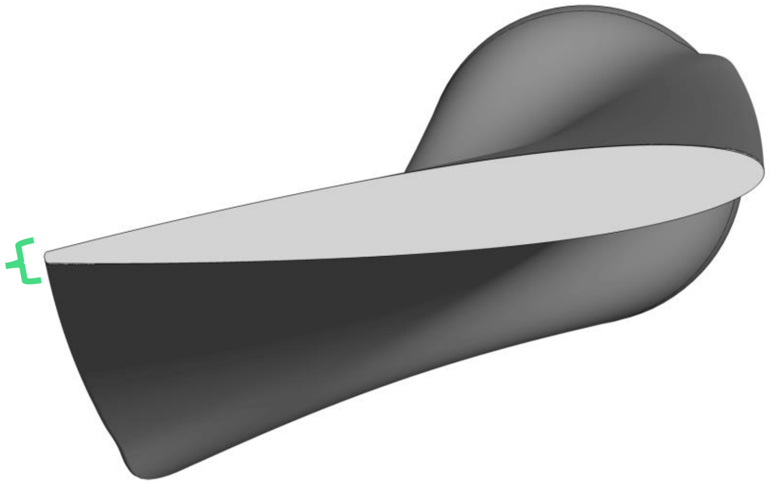
- Need to improve our broadband rotor noise models for UAM (Urban Air Mobility) vehicle noise predictions
- Sub-scale experiments help identify component noise sources and lead to better models
    - Tonal
    - Broadband
- ITR is a sub-scale canonical open geometry

ITR (Ideally Twisted Rotor)

D = 12.5 in (0.3175 m)



ITR's Blunt Trailing Edge



View looking down blade from tip

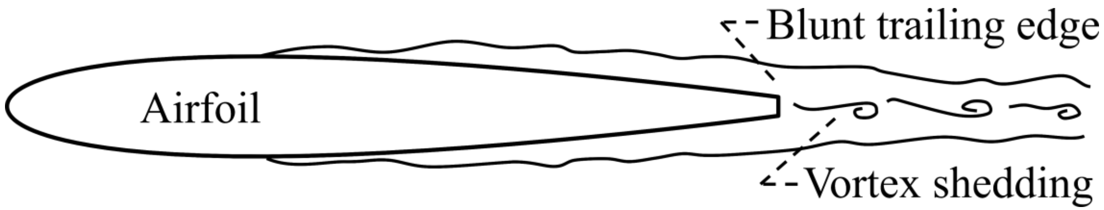
- ITR has a blunt trailing edge (1.54% h/c) due to manufacturing limitations
- BVS (Bluntness Vortex Shedding) observed in ITR experiments through low-fidelity predictions† and CFD simulations‡

† Pettingill, N. A., Zawodny, N. S., Thurman, C., and Lopes, L. V., "**Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover**," AIAA Paper 2021–1928.

‡Thurman, C., Zawodny, N. S., Pettingill, N. A., Lopes, L. V., and Baeder, J. D., "**Physics-informed Broadband Noise Source Identification and Prediction of an Ideally Twisted Rotor**," AIAA Paper 2021–1925.

BVS (Bluntness Vortex Shedding)

- Vortex shedding downstream of a blunt TE (trailing edge)
  - Kelvin-Helmholtz (K-H) instability grows in the shear layer
  - Leads to alternating vortex shedding
  - Quasi-2-D (high spanwise coherence)
- BVS is a type of airfoil TE self-noise (BPM)
  - Tonal (periodic) for an airfoil
  - Broadband (non-deterministic) for a rotor
- Low-fidelity model for BVS (BPM) often require tuning to predict correct trends [†*]
- Need to improve our models!



BVS Source Diagram
Adapted from Brooks, Pope, and Marcolini[**]

[**]Brooks, T. F., Pope, D. S., and Marcolini, M. A., "**Airfoil Self-Noise and Prediction**," NASA RP 1218, 1989.
[†]Pettingill, N. A., Zawodny, N. S., Thurman, C., and Lopes, L. V., "**Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover**," AIAA Paper 2021–1928.
[*]Blake, J. D., Thurman, C. S., Zawodny, N. S., and Lopes, L. V., "**Broadband Predictions of Optimized Proprotors in Axial Forward Flight**," AIAA Paper 2023–4183

Research Objective

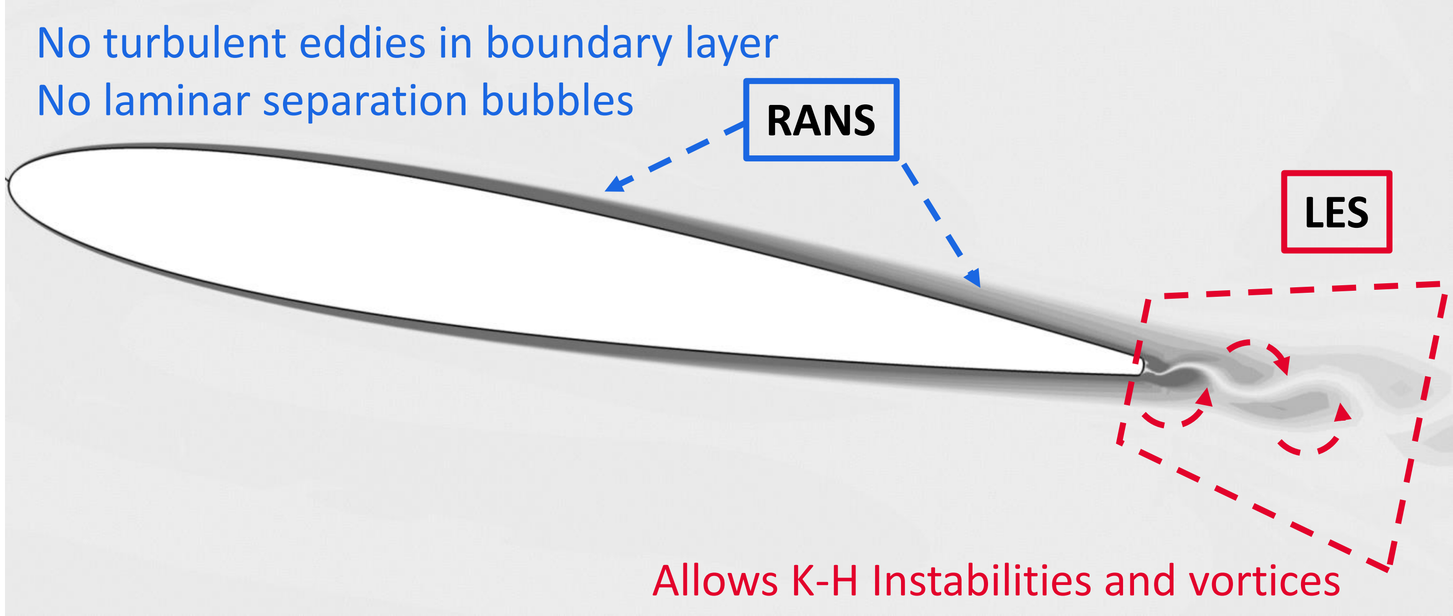
Research Objective:

Determine whether a 2-D hybrid RANS/LES airfoil simulation approach can be used to study BVS along the ITR

- Three research questions:
  1. How does BVS change along the ITR?
  2. Can we model spanwise BVS trends with representative airfoil simulations?
  3. Are 3-D flow effects significant enough to invalidate predictions made with 2-D airfoil simulations?

Methodology: Hybrid RANS/LES

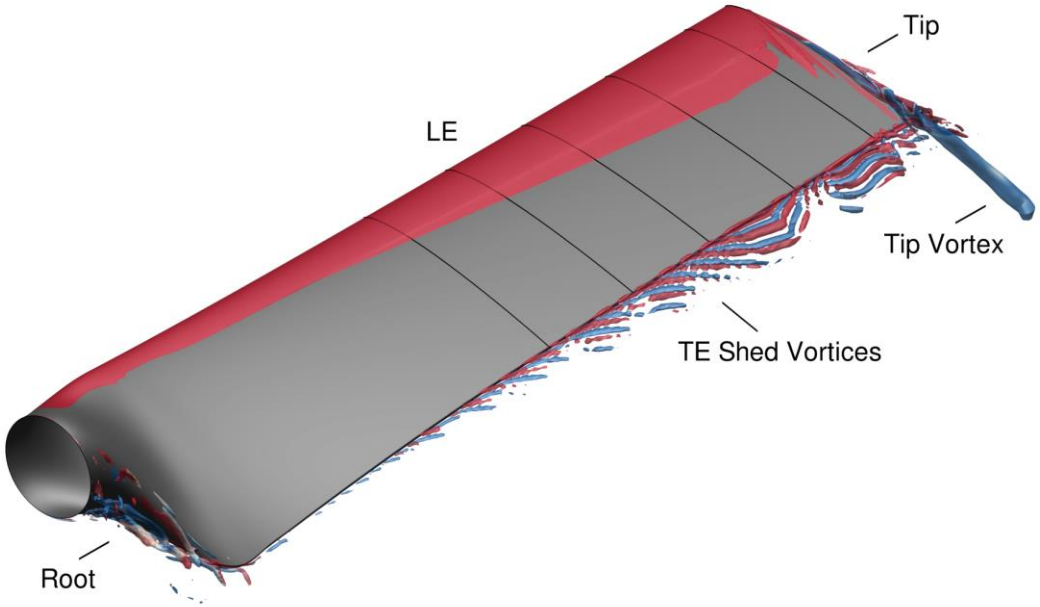
- Thurman et. al 2024‡ simulated the ITR in hover with hybrid RANS/LES
  - Identified BVS at r = 0.75R
  - Discovered BWBS (blade-wake back-scatter)
- **Key Insight:** Hybrid RANS/LES isolates BVS from other noise sources



ITR, Slice at r = 0.75R (Adapted from Thurman et al. 2024 ‡)

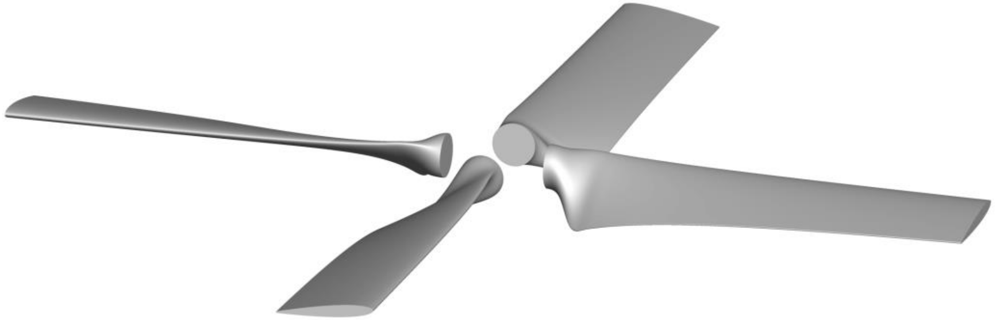
Self-Noise Sources Predicted by CFD	Turbulence Model	TBL-TE Noise Turbulent Boundary Layer Trailing Edge	LBL-VS Noise Laminar boundary layer vortex shedding	BVS
	RANS	No	No	No
	Hybrid RANS/LES	**No**	**No**	**Yes**
	LES	Yes	Yes	Yes

Identifying BVS on the ITR



Rotor Simulation Setup

- Hover at Ω = 5500 RPM (M_{tip} = 0.269)‡
- OVERFLOW2 Setup
  - Dual-time approach (angular step of 0.25°)
  - Second-order in time (BDF2OPT)
  - Fifth-order in space (HLLE++)
  - Improved implicit SSOR
  - Turbulence model: SA-DDES (Spalart-Allmaras Delayed Detached Eddy Simulation)
  - *See paper for more details*
- Reprocessed 15 revs of simulation data

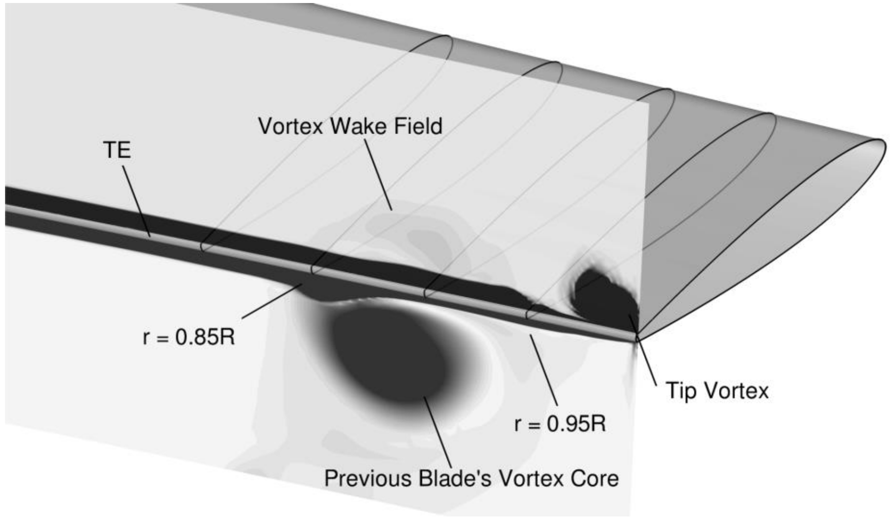


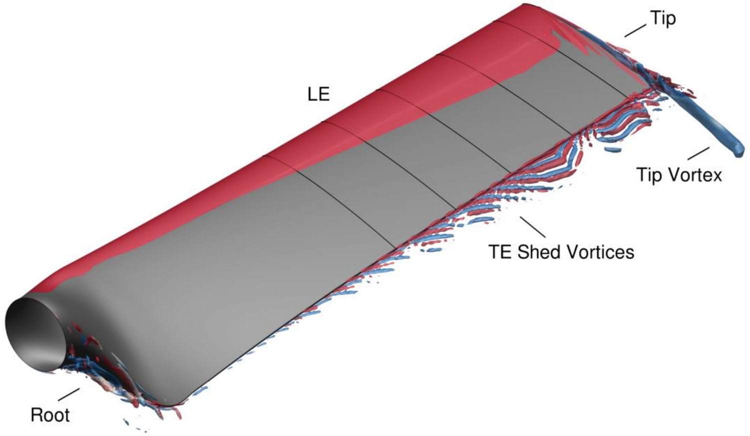
‡Thurman, C., Zawodny, N. S., Pettingill, N. A., Lopes, L. V., and Baeder, J. D., "**Physics-informed Broadband Noise Source Identification and Prediction of an Ideally Twisted Rotor**," AIAA Paper 2021–1925.

Rotor Flowfield Features

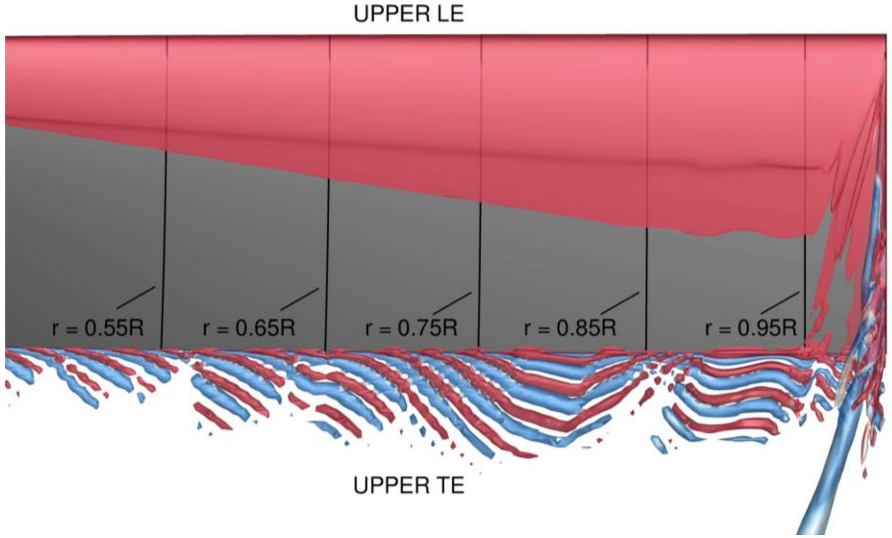
- Previous blade's wake interacts with blade outboard of r = 0.85R
- BVS is disrupted due to BWI (blade-wake interaction)
- Blade-wake effects appear minimal inboard of r = 0.75R

Vorticity magnitude
white = low, black = high

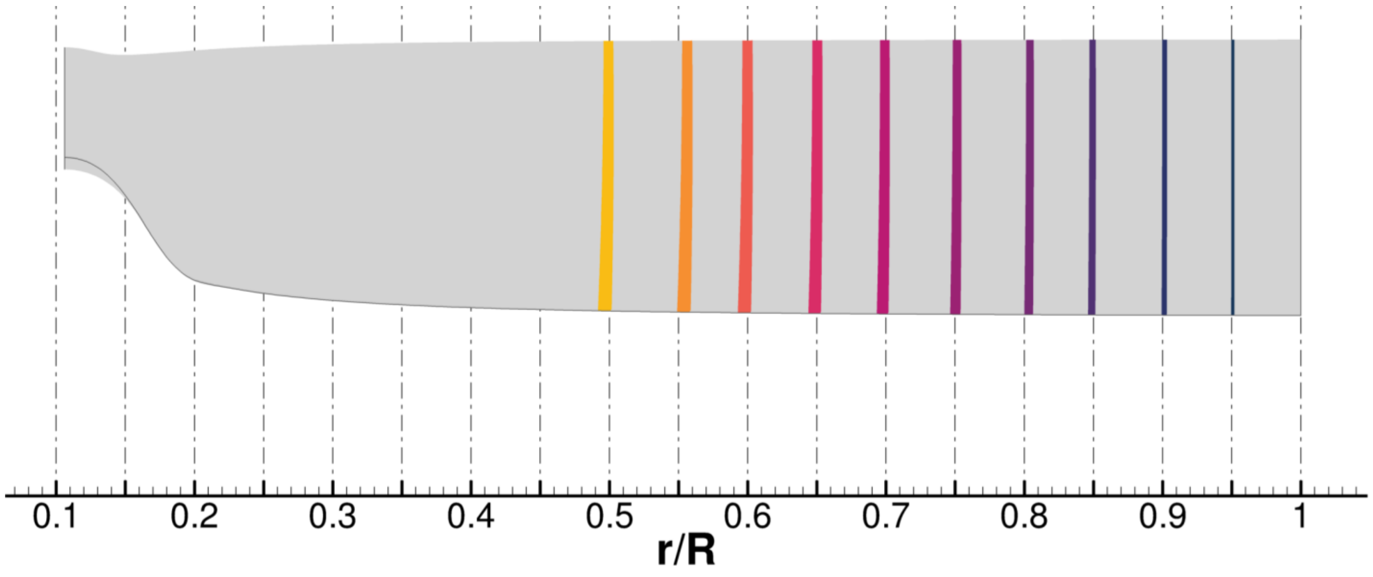


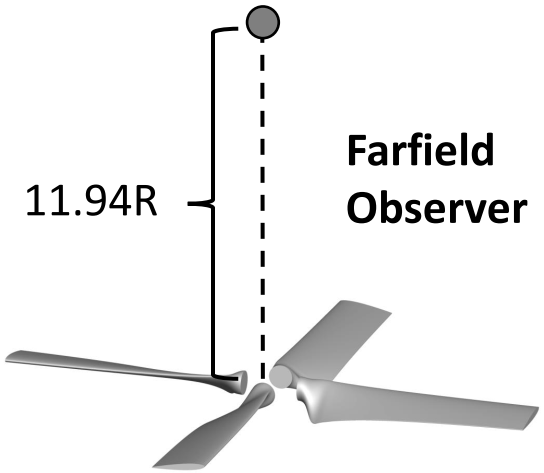


Q-Criterion isosurface colored by streamwise vorticity
red = rotation into page
blue = rotation out of page



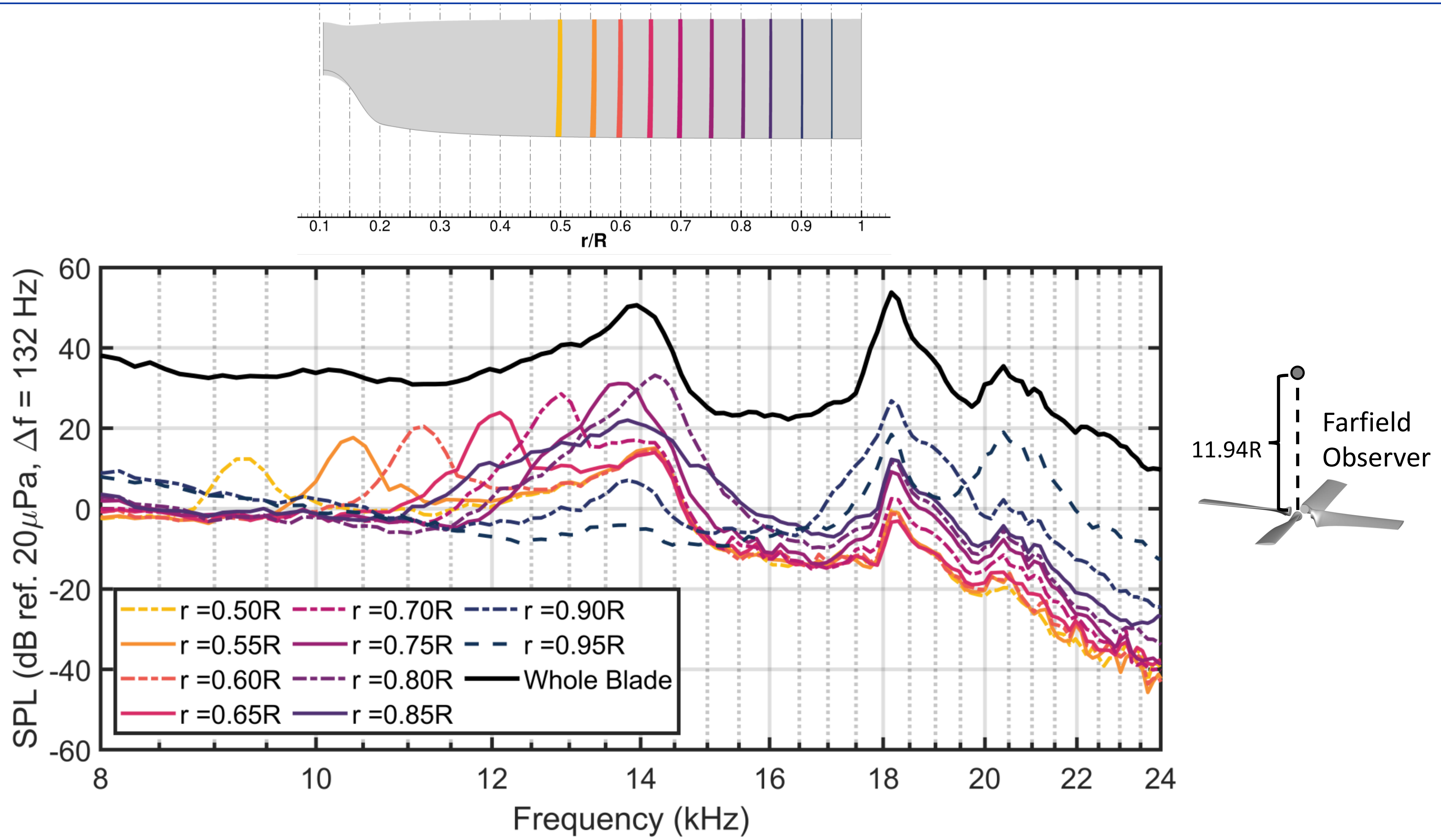
Rotor Noise Sources





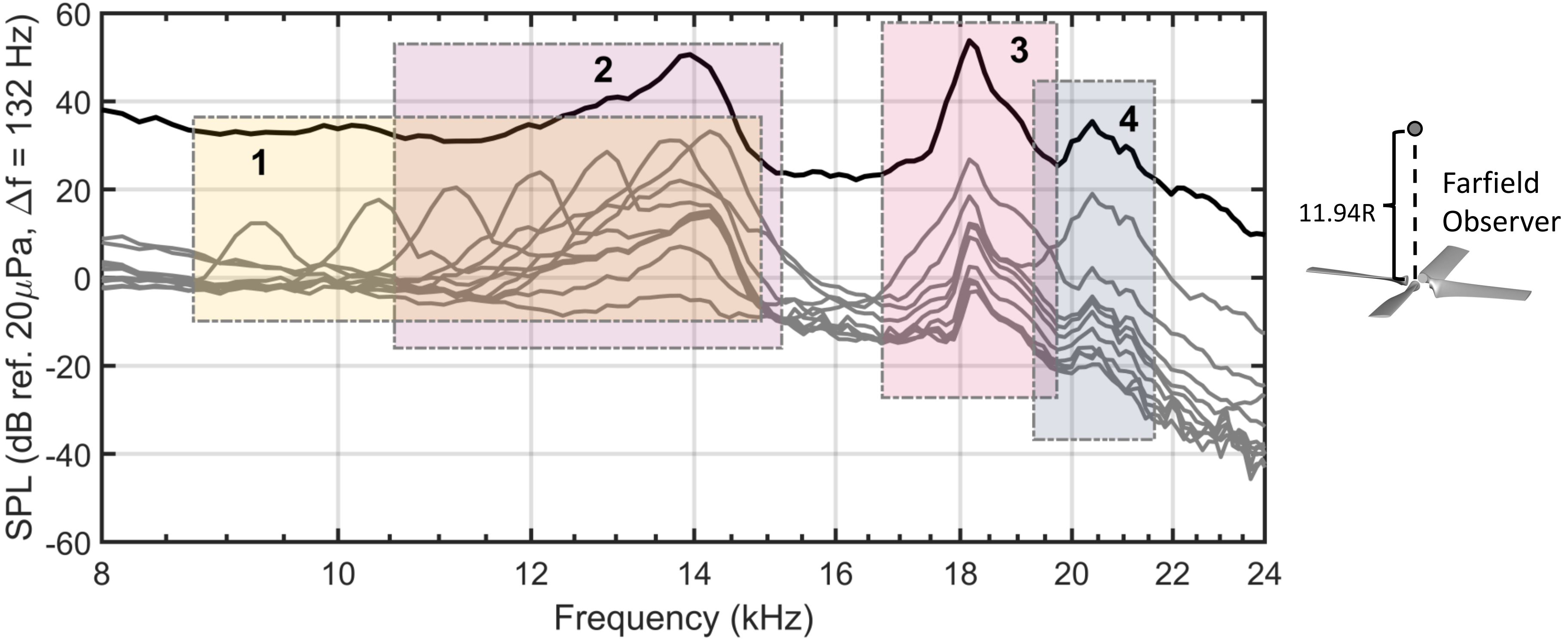
- Short spanwise sections extracted from the blade at every 0.05R
- Noise from each spanwise section was computed using ANOPP2's Formulation 1A solver (F1A)
- Farfield observer placed on rotor axis to eliminate Doppler shift and tonal contributions

Rotor Noise Sources



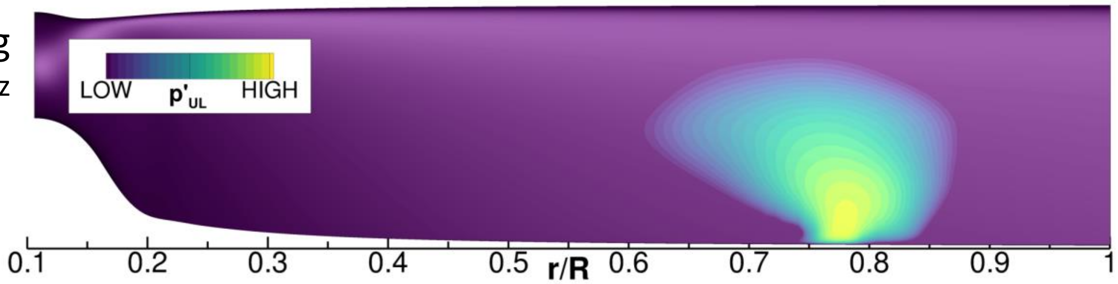
Rotor Noise Sources

Four Regions

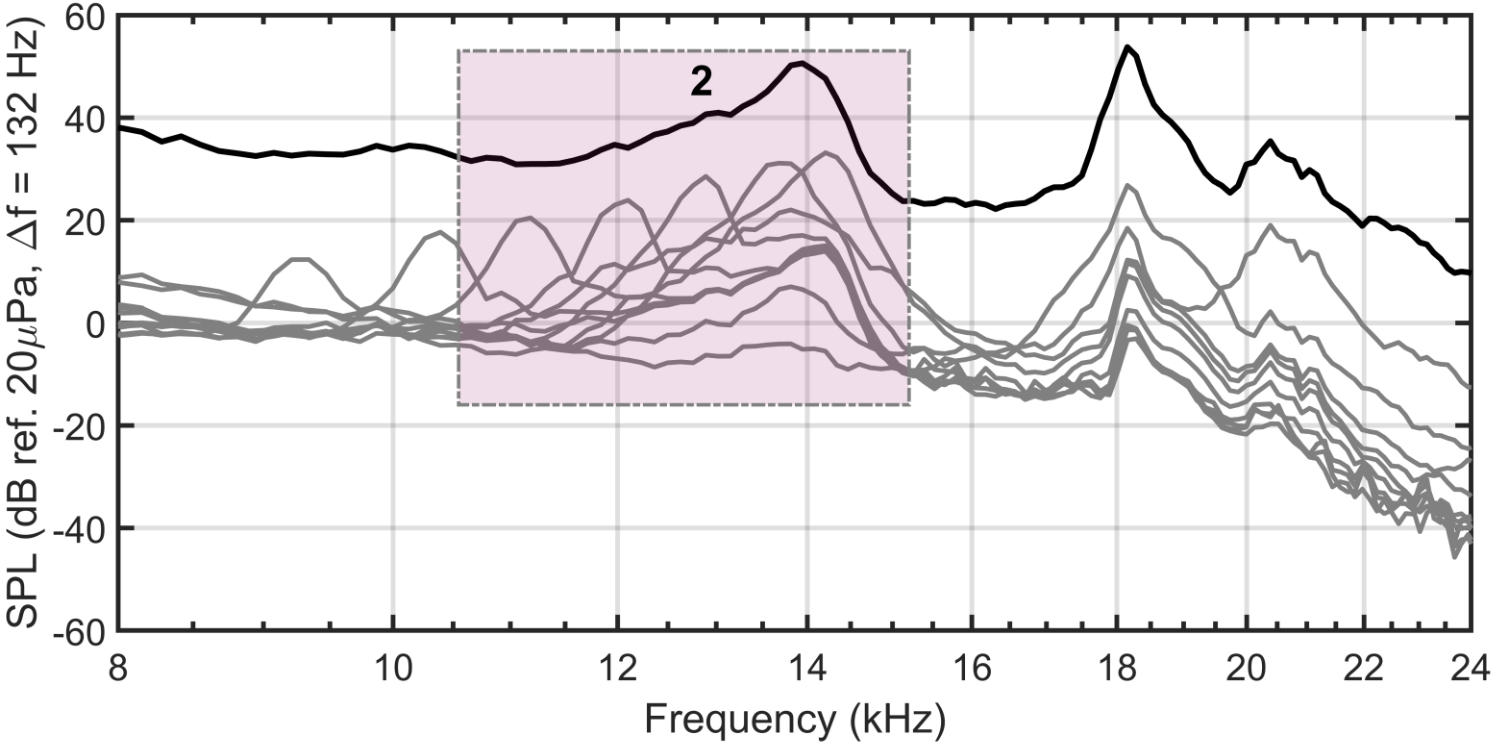


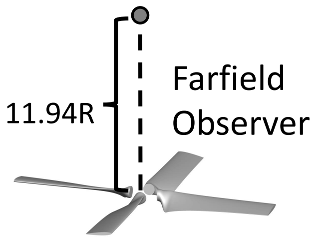
Rotor Noise Sources

F1A unsteady loading
f = 13.885 kHz



BWBS
(outboard)

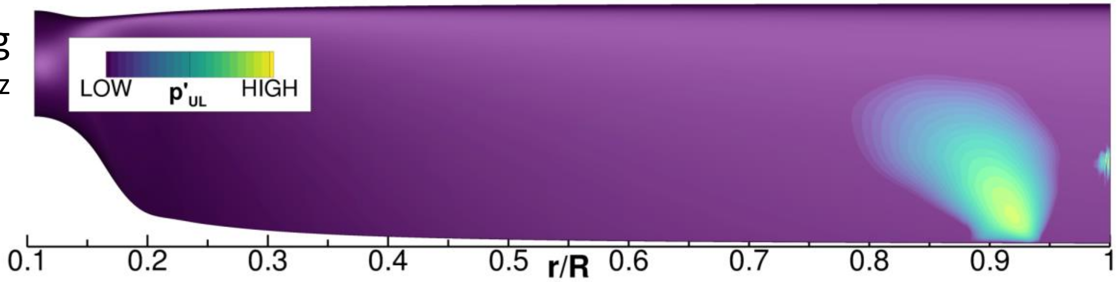




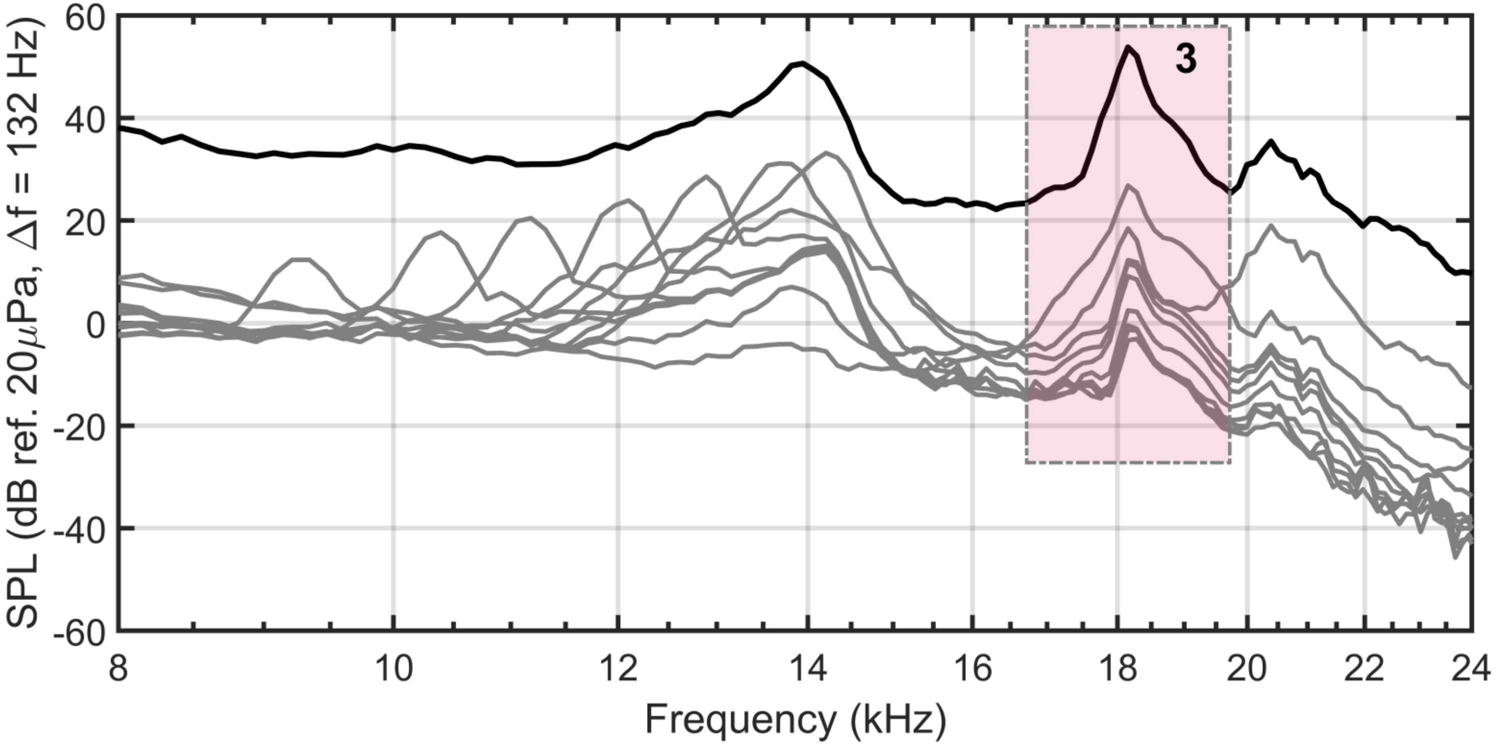
BWBS (Blade-wake back-scatter)

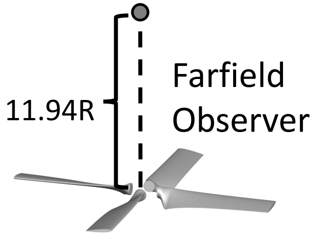
Rotor Noise Sources

F1A unsteady loading
f = 18.205 kHz



BWBS
(outboard)

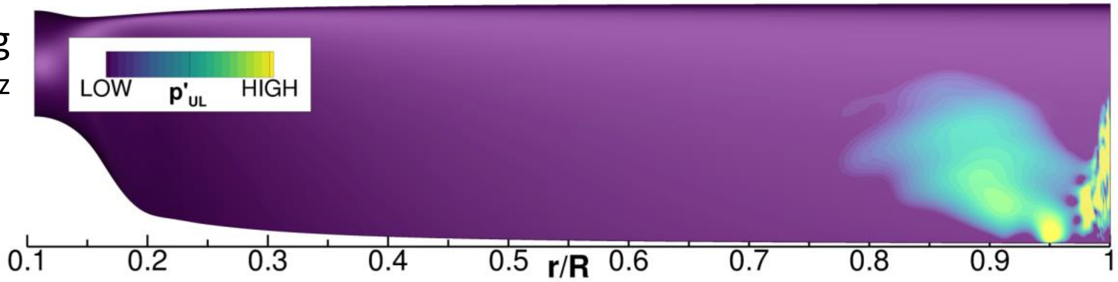




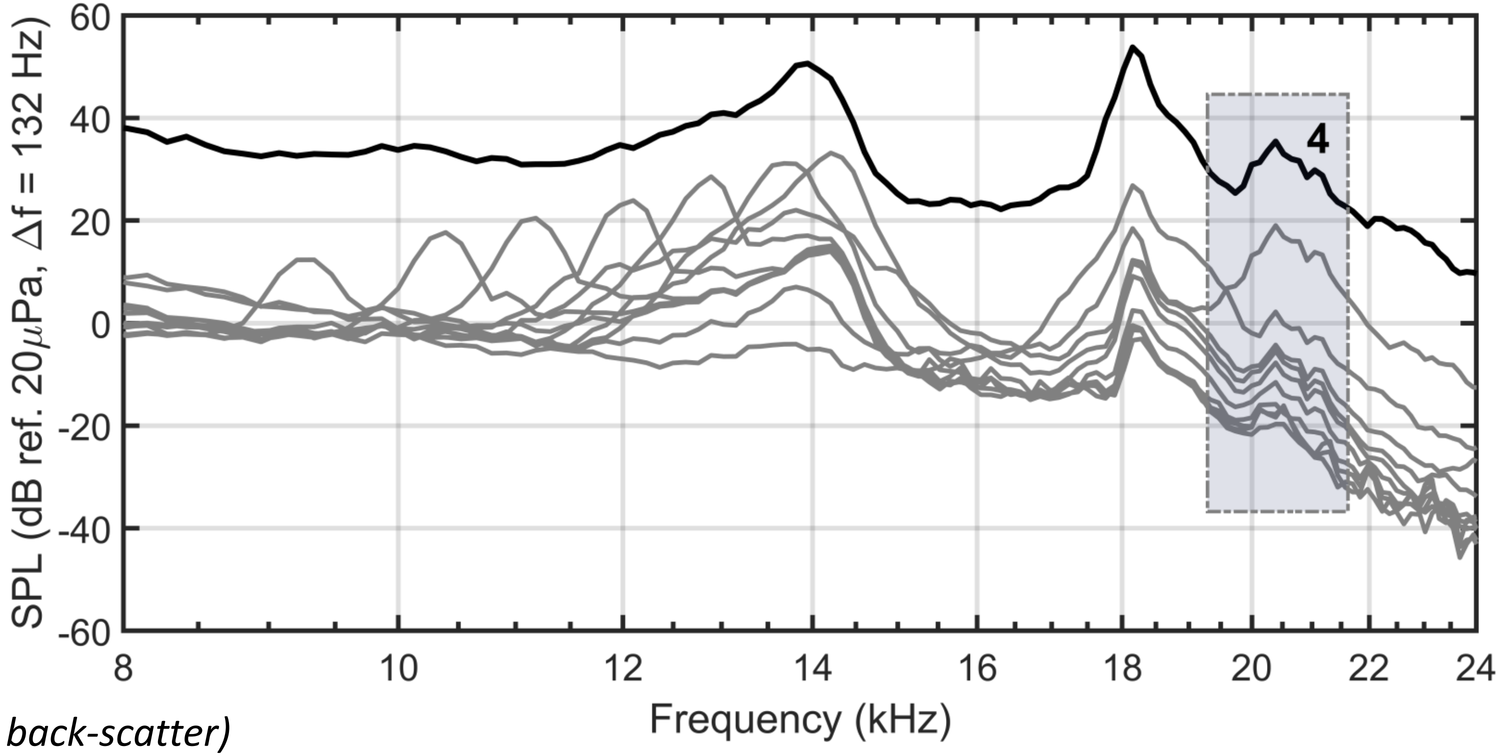
BWBS (Blade-wake back-scatter)

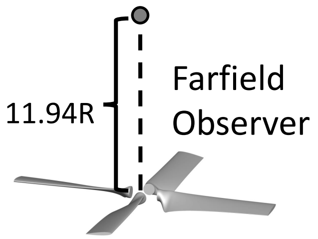
Rotor Noise Sources

F1A unsteady loading
f = 20.412 kHz



BWBS/TVF
(outboard)

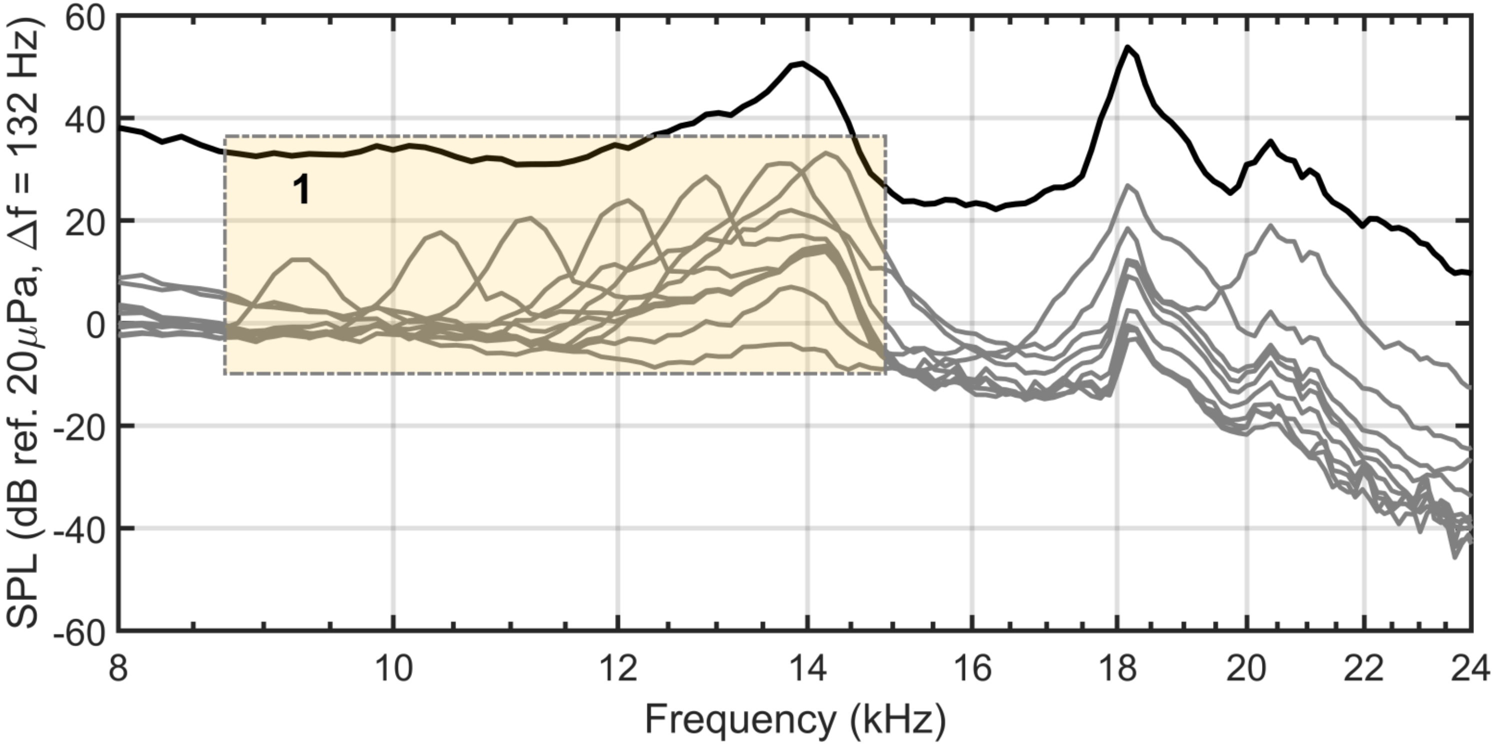


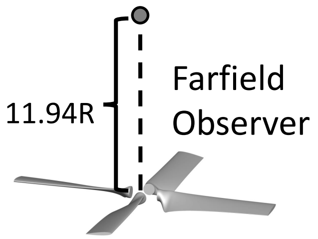


BWBS (Blade-wake back-scatter)
TVF (Tip vortex formation)

Rotor Noise Sources

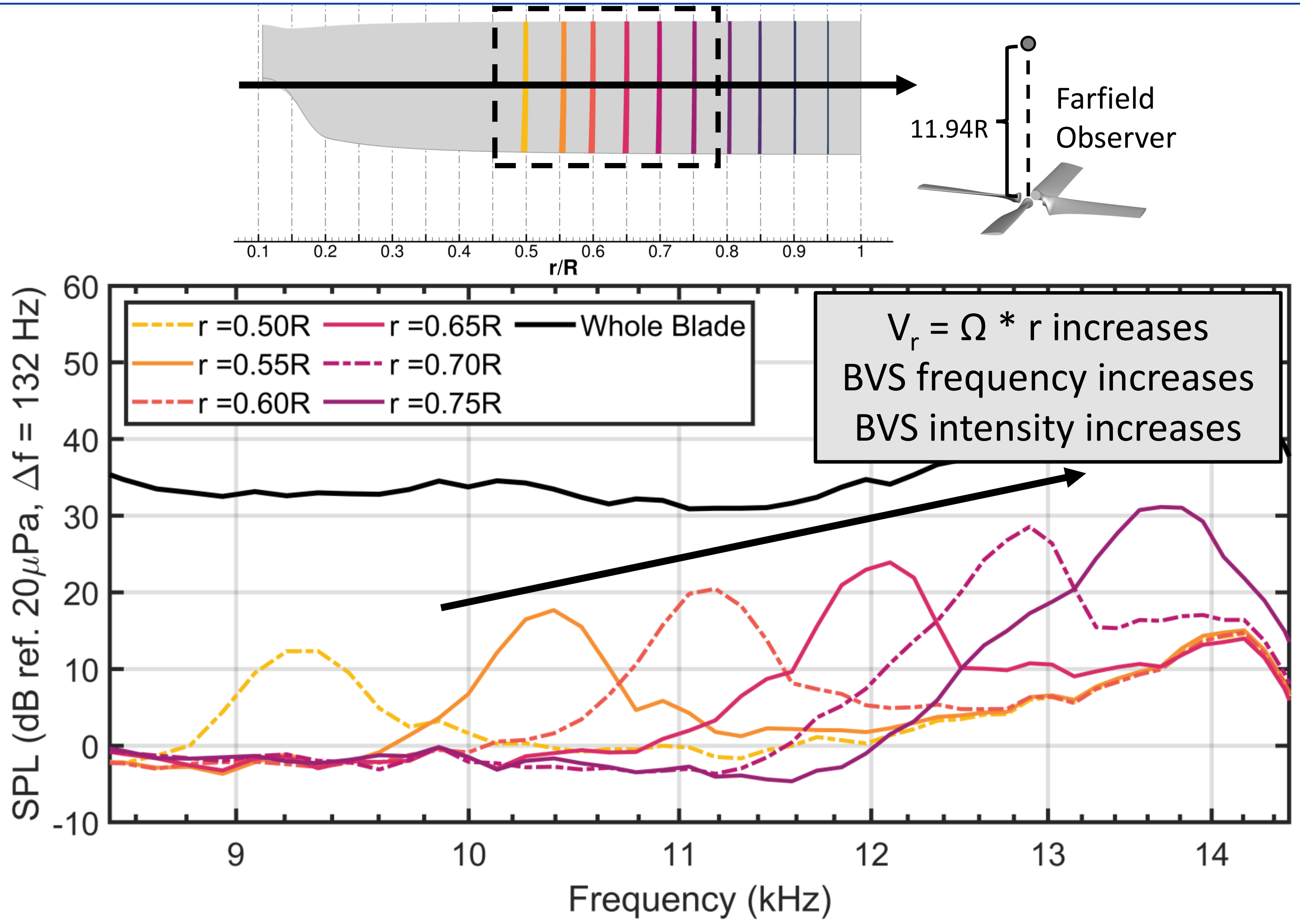
BVS
(along the blade)





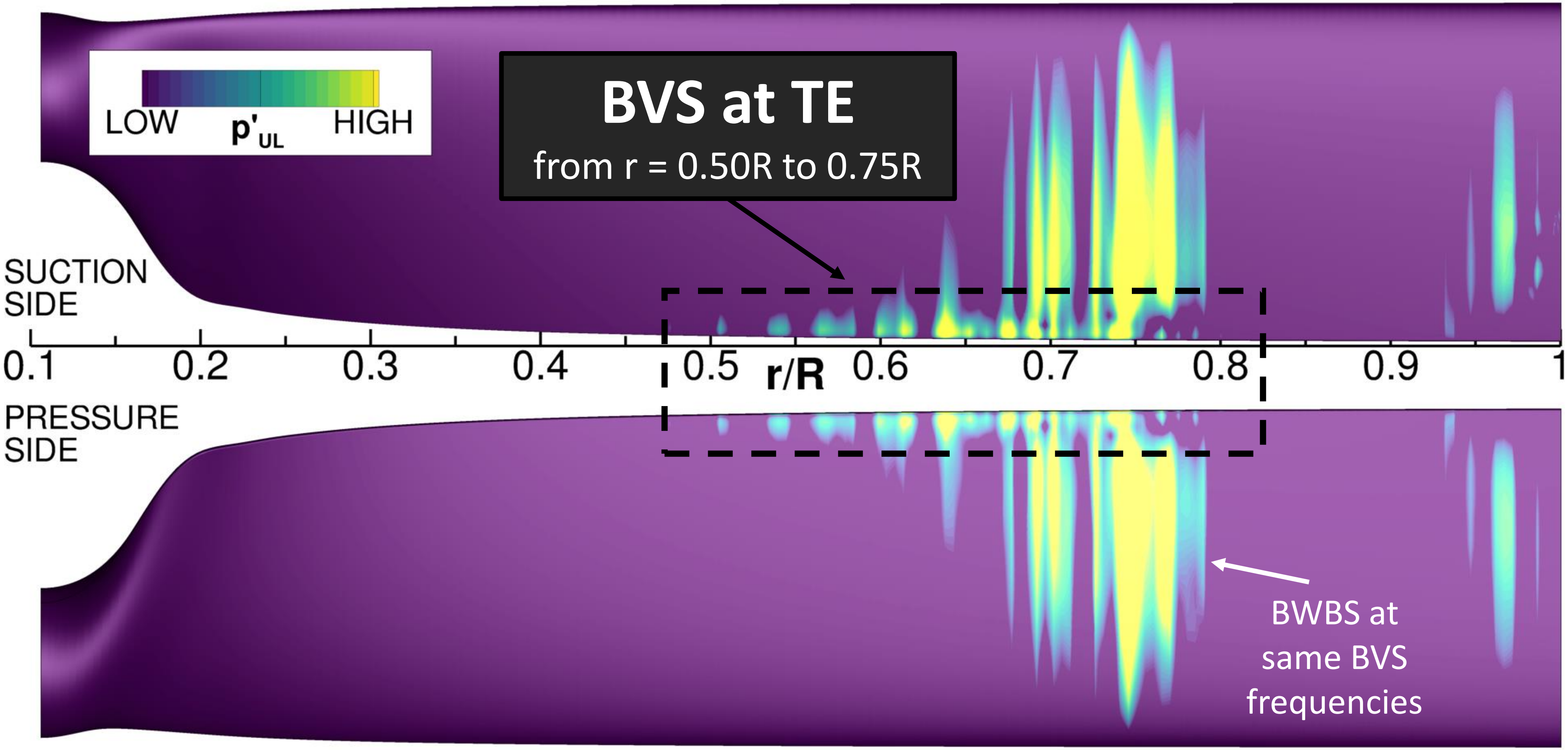
BVS Along the Blade

- Exclude sections outboard of r = 0.75R that are influenced by blade-wake
- BVS frequency should scale to Strouhal number ≈ 0.1**
- $St_{BVS} = f * h / (V_r)$
  - $V_r = \Omega * r$ increases along blade
  - h is constant
  - *f should increase!*



Brooks, T., and Hodgson, T., "Trailing Edge Noise Prediction from Measured Surface Pressures**," Journal of Sound and Vibration, Vol. 78, (1), 1981, pp. 69–117.

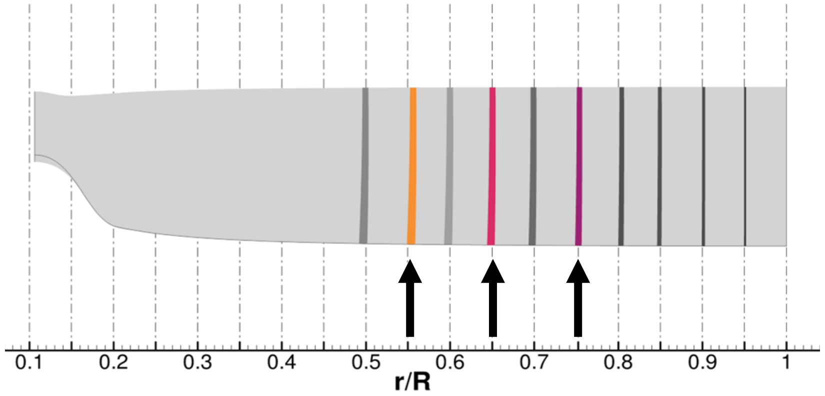
Strouhal Scaling

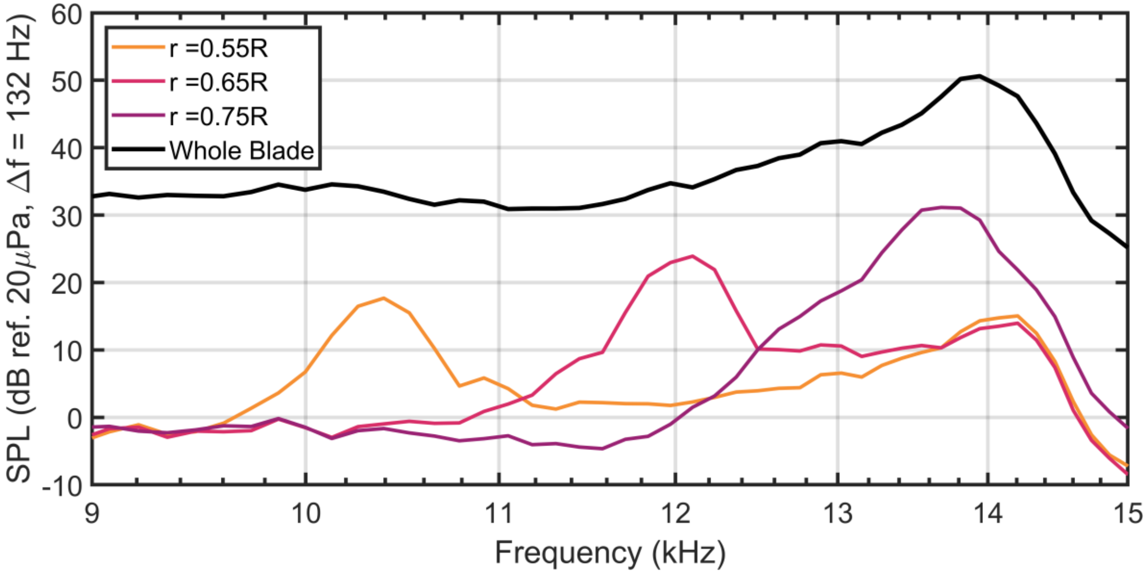


F1A unsteady loading term (in observer time) at St = 0.1

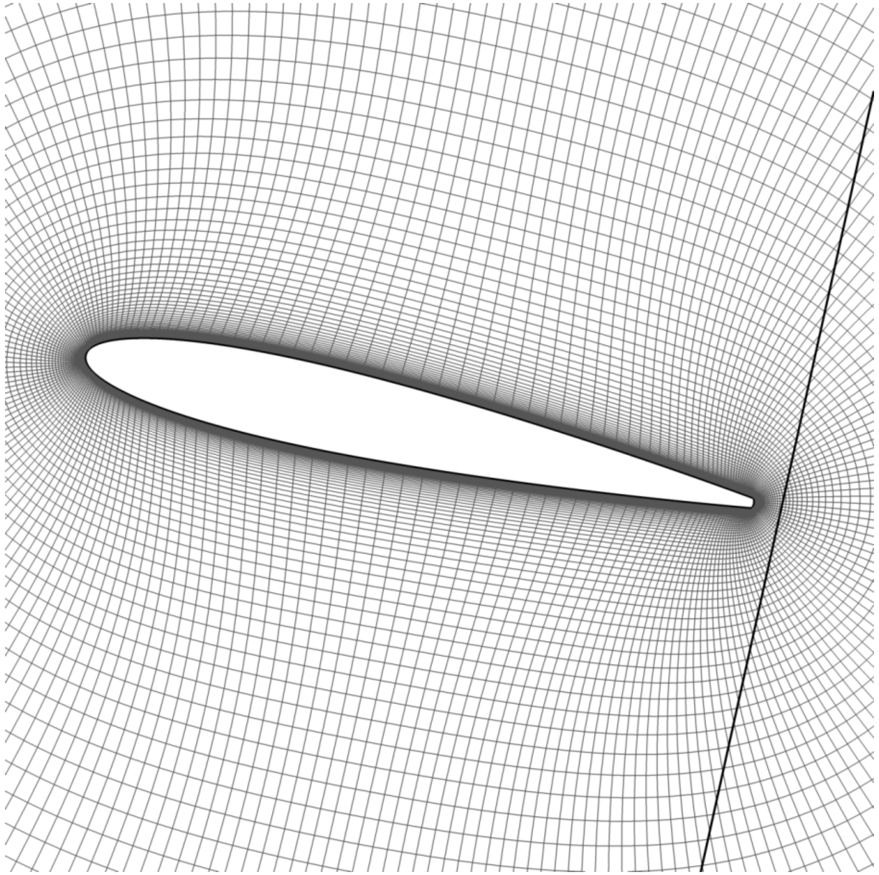
Three Selected Blade Stations

- Confirmed that Region 1 is BVS
  - Strong TE pressure fluctuations
  - Frequencies scale to St ≈ 0.1 along the blade
  - Coherence and phase (*see paper*)
- Stay inboard of r = 0.75R to study BVS to minimize blade-wake effects
- Focus on 0.55R, 0.65R, 0.75R





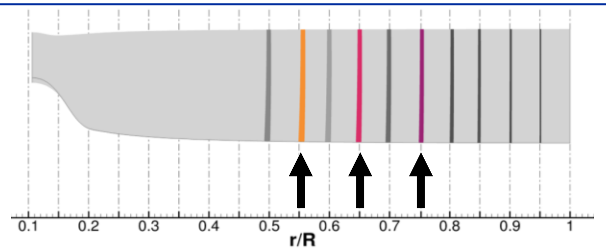
Airfoil Simulations of BVS

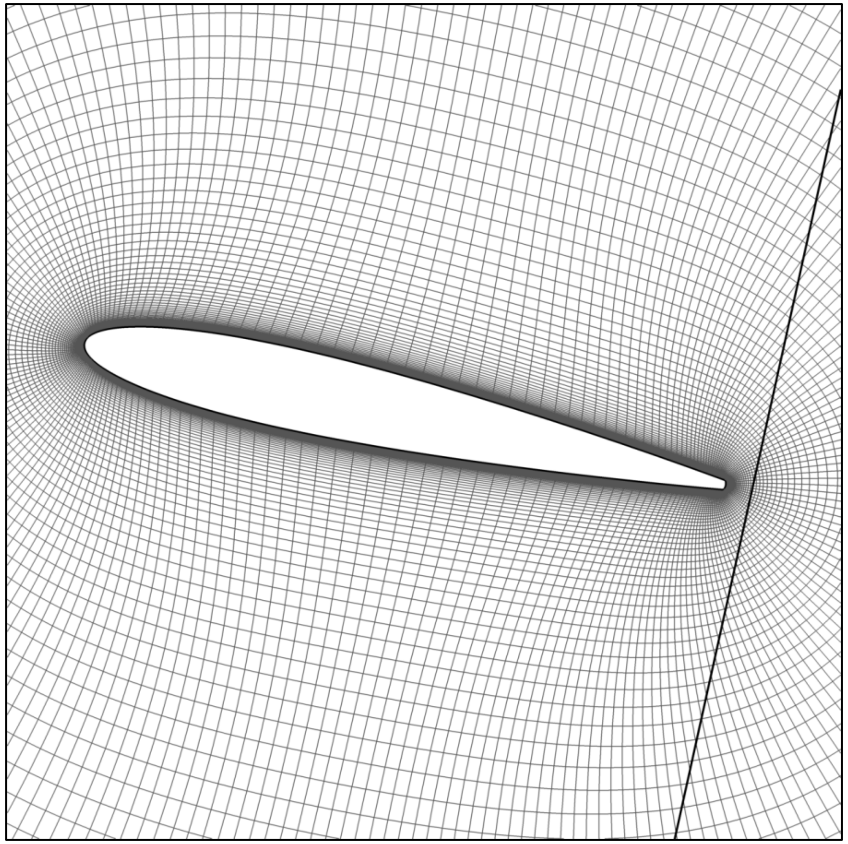


2-D Airfoil Simulation Conditions

- NACA 0012 airfoil sections
  - Chord, c = 1.25 in (31.75 mm)
  - TE bluntness, h = 0.019 in (0.49 mm)
  - h/c = 1.54%
- Duplicate rotor simulation
  - Same surface grid, extracted from rotor (225 points)
  - Same wall-normal spacing for volume grid, extended to 100*c (151 points)
  - Same numerical schemes
  - Same timestep size
  - α_{eff} obtained by matching Cp peak at the three rotor stations
- **Main difference: modeling BVS as a 2-D vortex (2-D vs. 3-D)**
  - No crossflow or blade wake effects

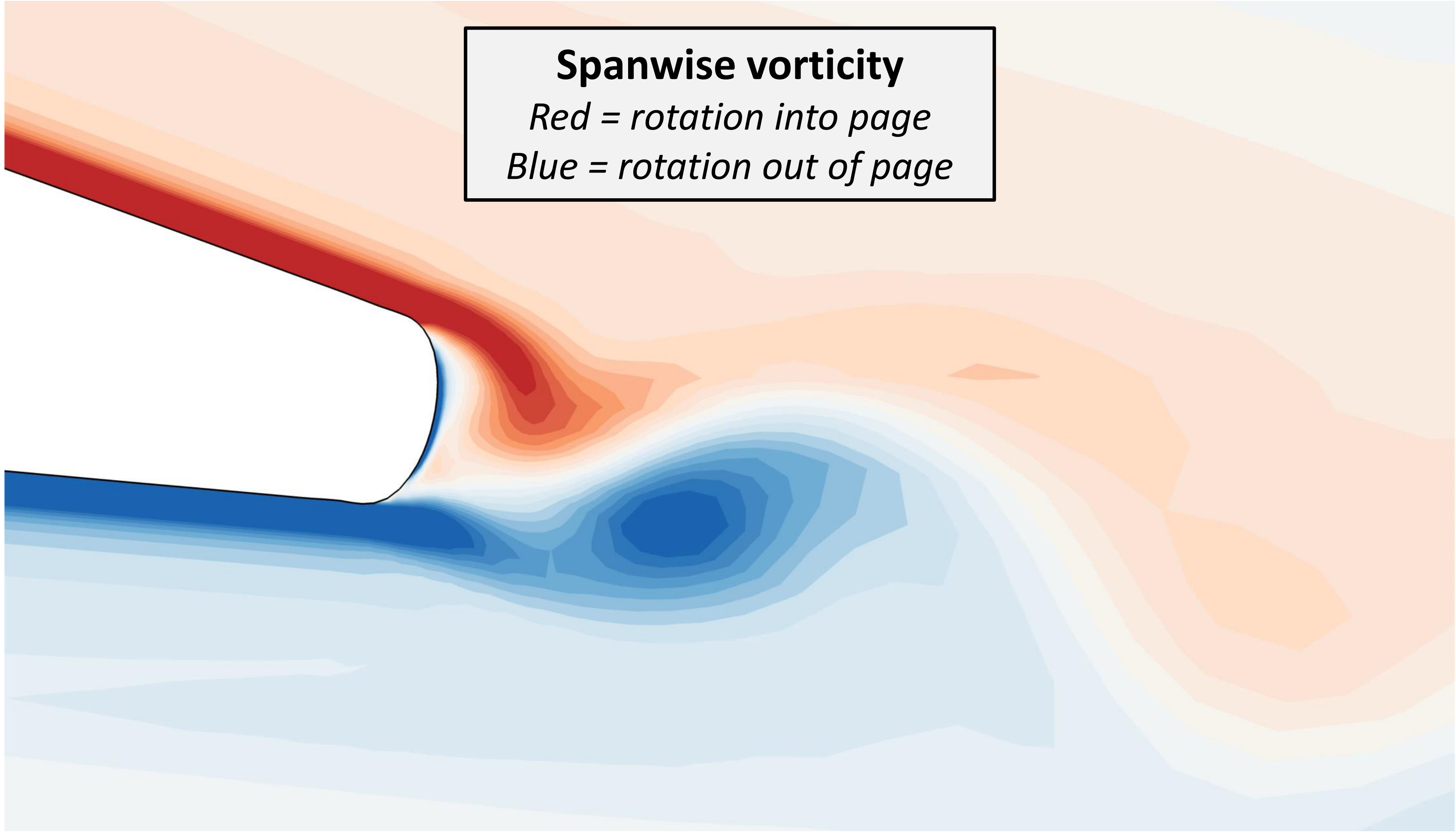
Nominal r/R	Reynolds (nearest 100)	Mach	α_{eff} (deg.)	Δt / BVS Period
0.55	109,800	0.149	2.765	12.85
0.65	129,600	0.175	2.402	10.89
0.75	148,700	0.201	2.070	9.49





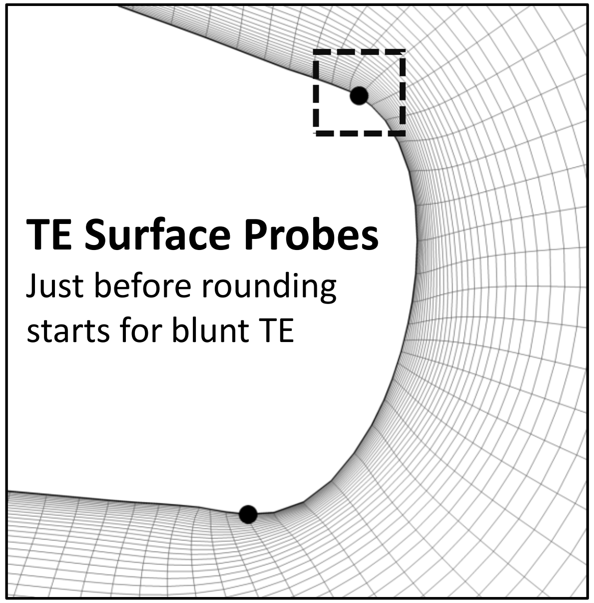
BVS in Near-Wake at r = 0.55R

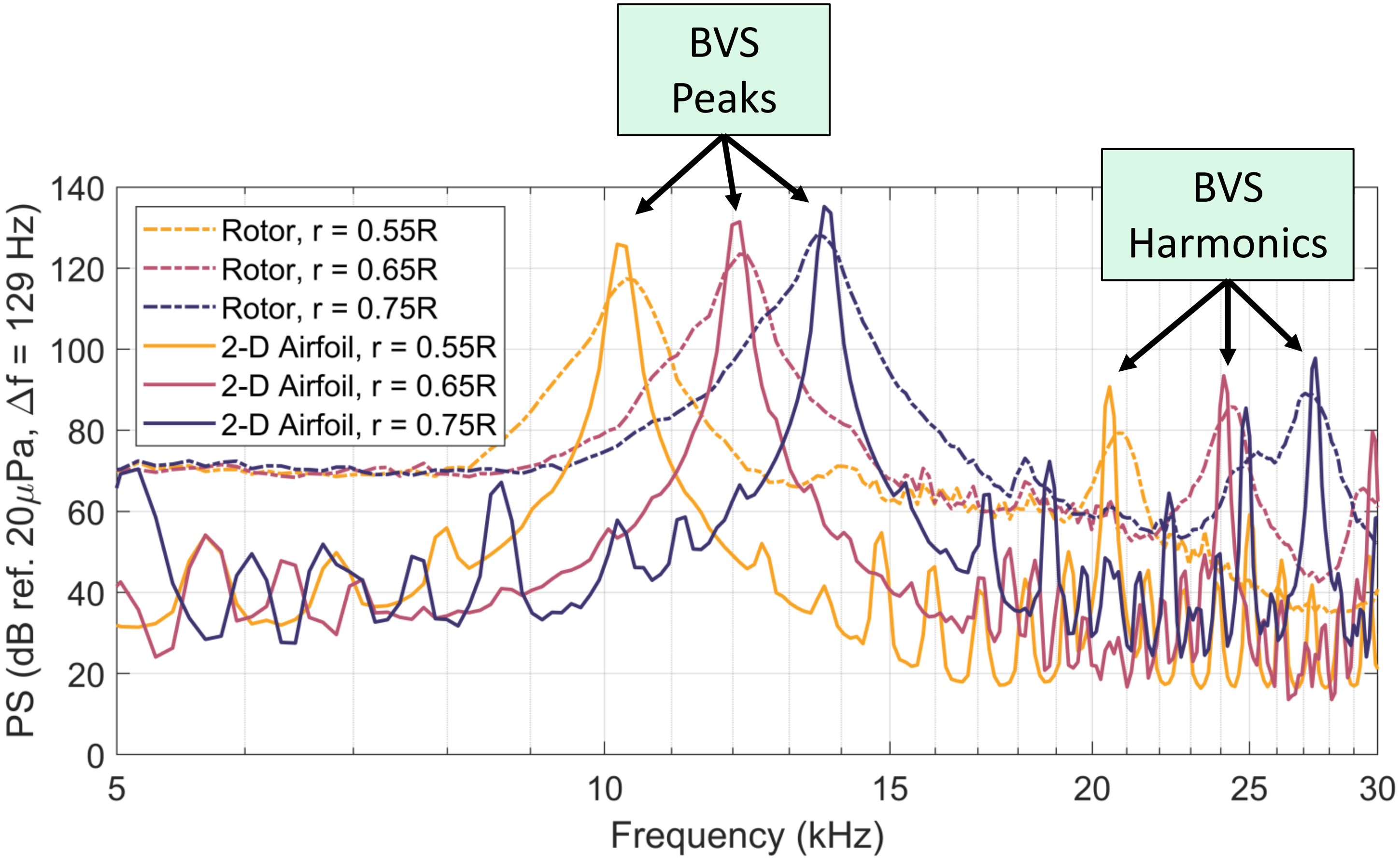
- Vortex shedding from suction and pressure side
- K-H roll-up observed
- Pressure side vortex appears stronger due to $\alpha_{eff} = 2.765°$



TE Wall Pressure Spectra (WPS)

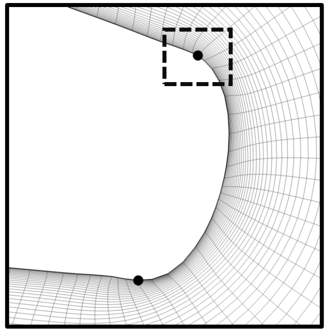
- BVS should generate strong pressure fluctuations at the TE

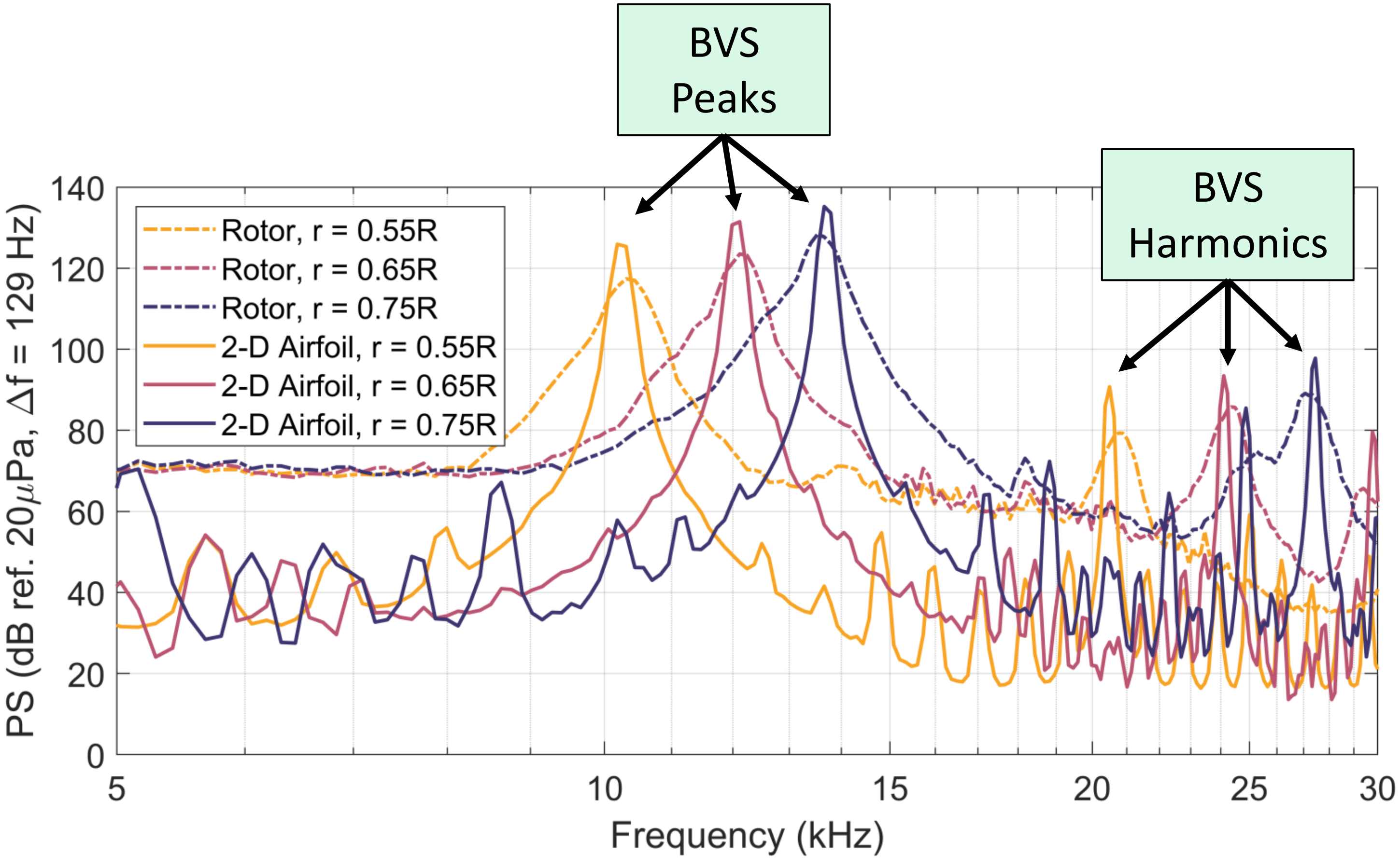




TE Wall Pressure Spectra (WPS)

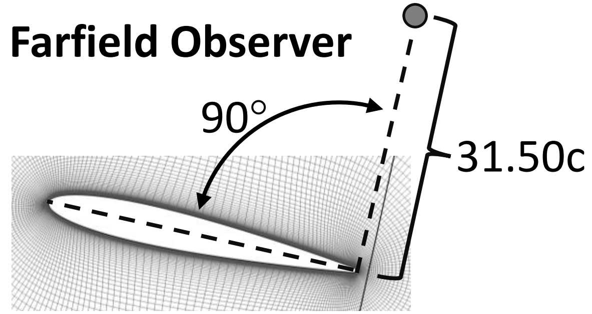
- Peak BVS frequencies predicted within 100-200 Hz of the rotor simulation
  - <2% difference
- 2-D sims overpredict peak BVS WPS amplitudes by 5-10 dB
  - No spanwise vorticity term?
  - Crossflow effect?
- Rotor peaks are wider
  - Influence of BVS inboard/outboard "felt" at the station of interest

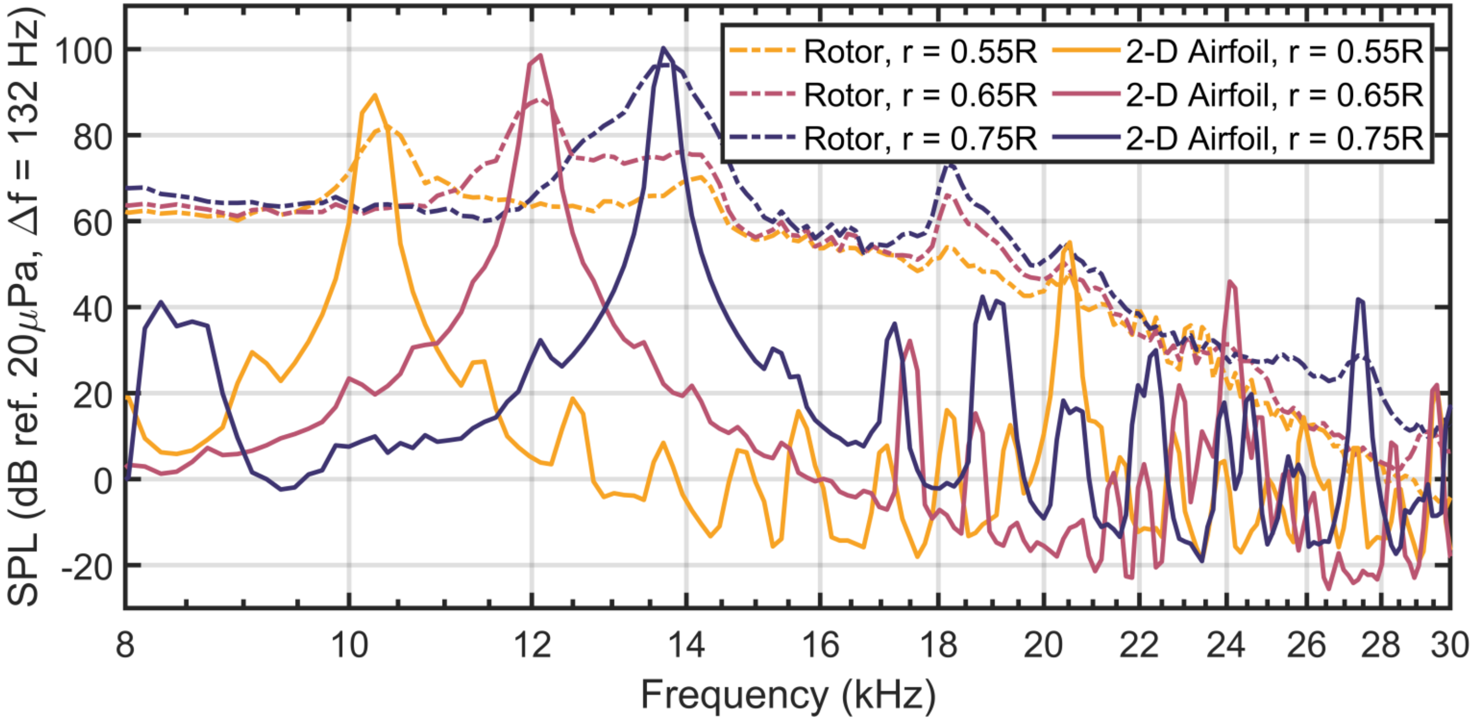




Farfield Noise

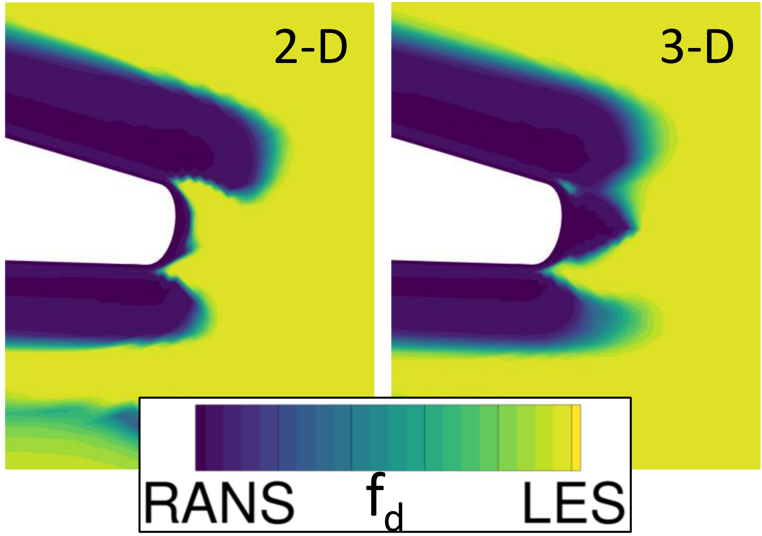
- Farfield noise computed from unsteady pressures on the whole airfoil surface
- SPL scaled to a common span of 3.28 ft (1 m) span
- Frequency trends predicted correctly (< 2% difference)
- 2-D airfoil overpredicted peak amplitude by 5-10 dB
- Possible effect of blade-wake at r = 0.75R

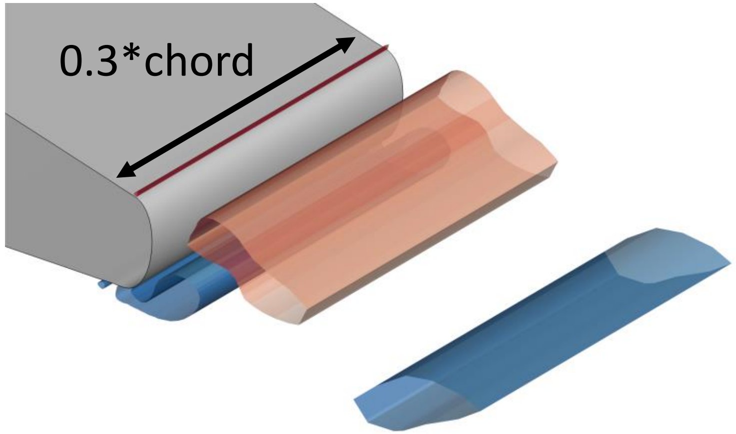




3-D Airfoil Simulation

- 3-D airfoil simulation at r = 0.75R
- Delayed switch from RANS to LES influenced BVS (*see paper*)
  - Likely an issue with the DDES shielding function (f_d)
  - Shedding frequency underpredicted by 387 Hz
- High density of spanwise points required to predict BVS
  - Almost LES-level
  - 65 points (195 points /chord)
- Infinitely coherent 2-D vortex
  - Nothing to break up the spanwise coherence





Q-criteria Isosurface colored by *spanwise vorticity*
red = rotation into page
blue = rotation out of page

Research Objective (Revisited)

Research Objective:

Determine whether a 2-D hybrid RANS/LES airfoil simulation approach can be used to study BVS along the ITR

- Three research questions:
  1. How does BVS change along the ITR?
  2. Can we model spanwise BVS trends with representative airfoil simulations?
  3. Are 3-D flow effects significant enough to invalidate predictions made with 2-D airfoil simulations?

Conclusions

1. How does BVS change along the ITR?
   BVS frequency and amplitude increase along the span of the ITR

2. Can we model spanwise BVS trends with representative airfoil simulations?
   2-D hybrid RANS/LES simulations can be used to investigate BVS
   - Replicated spanwise BVS trends for three rotor stations
   - Shedding frequency predicted within 2% of rotor simulations
   - Overpredicted wall pressures and farfield noise (~10 dB)
   - Approximately 100x decrease in computational cost compared to rotor

3. Are 3-D flow effects significant enough to invalidate predictions made with 2-D airfoil simulations?
   Crossflow effects on ITR appear to be minimal

Future application:

Predict BVS noise trends to improve low-fidelity self-noise models (BPM) for UAM rotors where broadband noise is going to be important

Acknowledgments

- Supported by the NASA Revolutionary Vertical Lift Technology (RVLT) project
- Midrange HPC K-cluster for computational resources
- Len Lopes for assistance with ANOPP2 frequency metadata
- Doug Boyd with OVERFLOW2 help

Thank you

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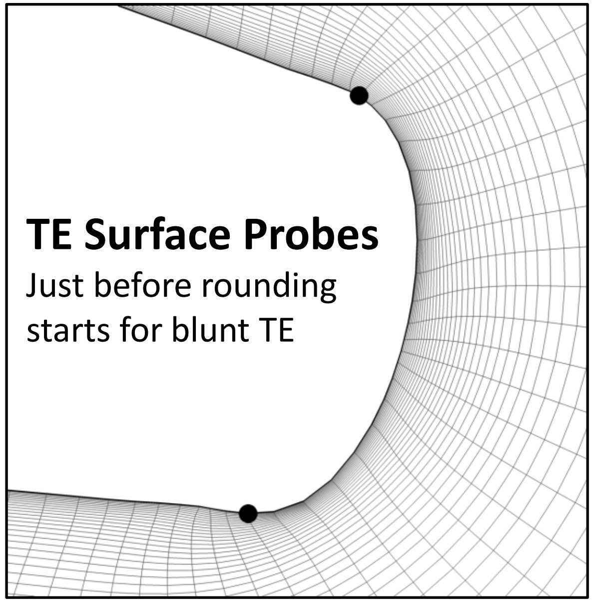
Aeroacoustics Branch

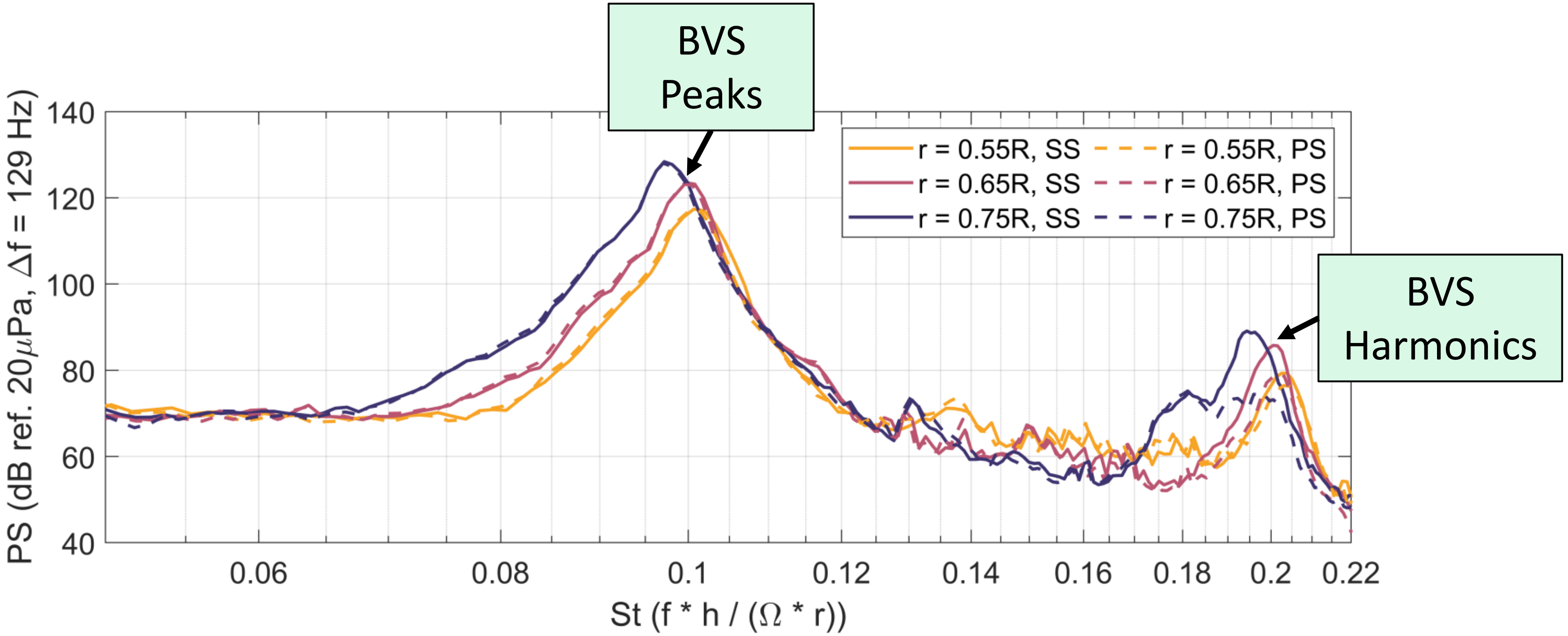
NASA Langley Research Center

Backup Slides

TE Wall Pressure Spectra

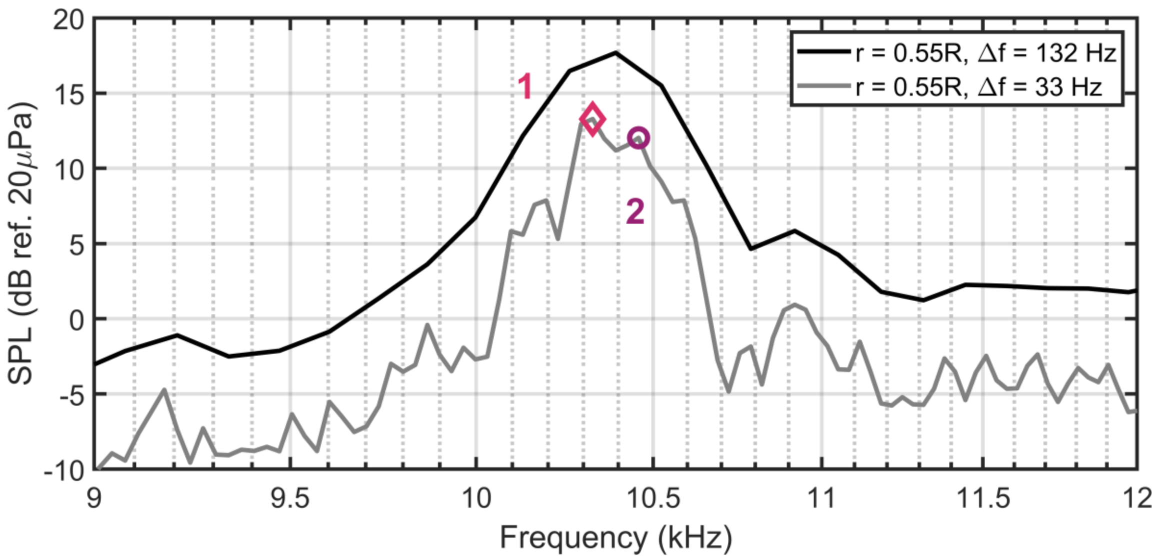
- BVS should generate strong pressure fluctuations at the TE
- On both suction side (SS) and pressure side (PS) surface pressure probes
- Largest-amplitude peaks (BVS) approximately collapse to St ≈ 0.1



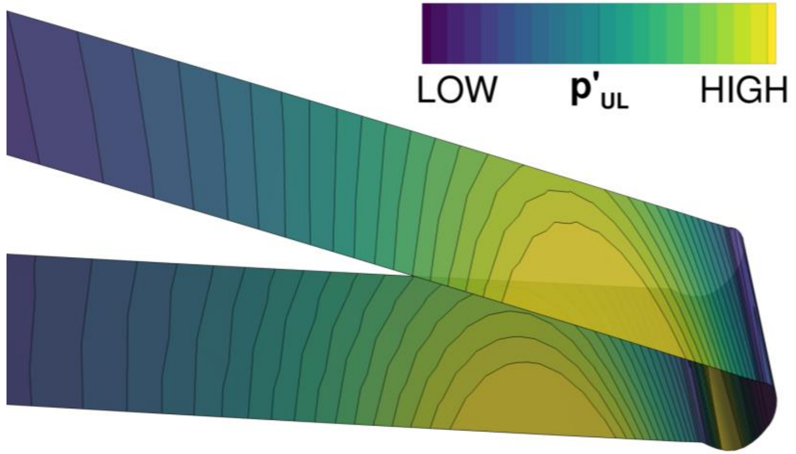


Spectral Width of BVS Peaks

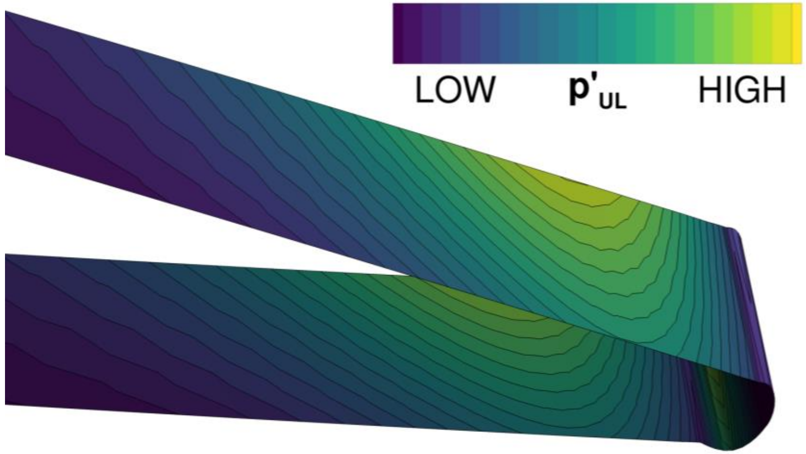
- Why are the peaks so wide?
- Frequency increases along blade due to $V_r = \Omega * r$
- BVS slightly inboard/outboard is "felt" in wall pressure at the station of interest
- r = 0.55R station



Peak 1

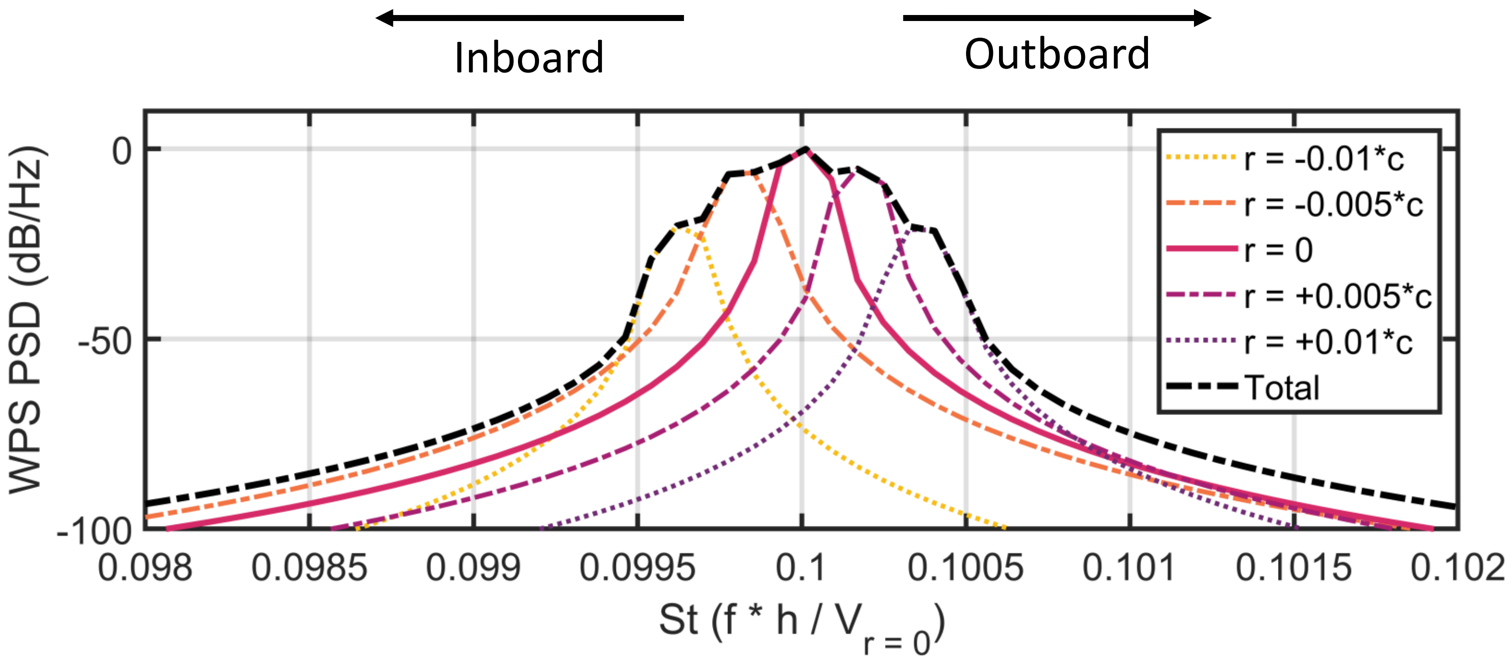


Peak 2

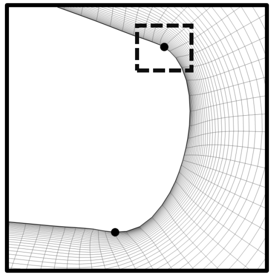


Example WPS

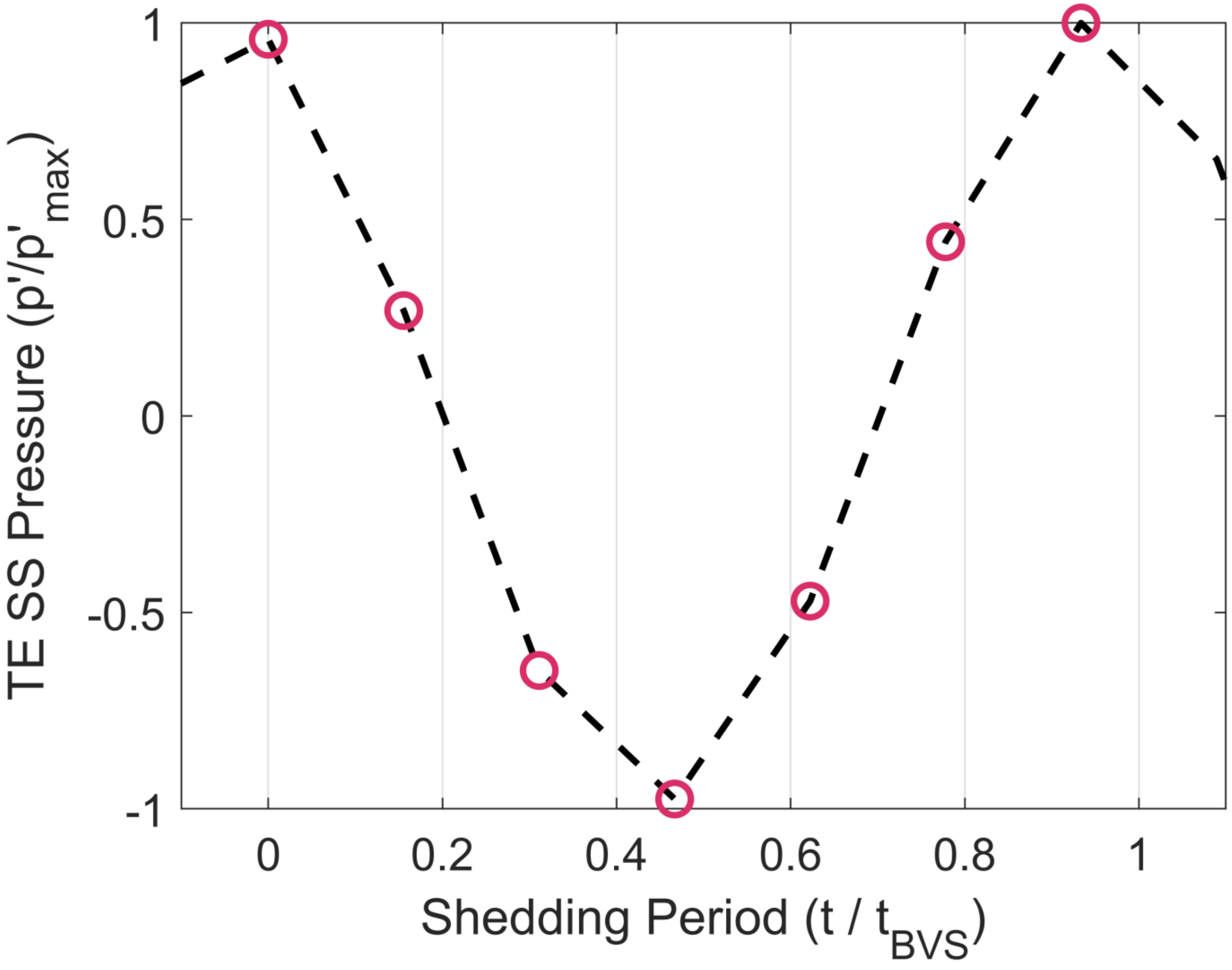
- Example WPS from adjacent blade stations
- Influence of BVS inboard/outboard "felt" at r = 0
- St scaled by V at r = 0
- Superposition of peaks leads to a wider frequency hump



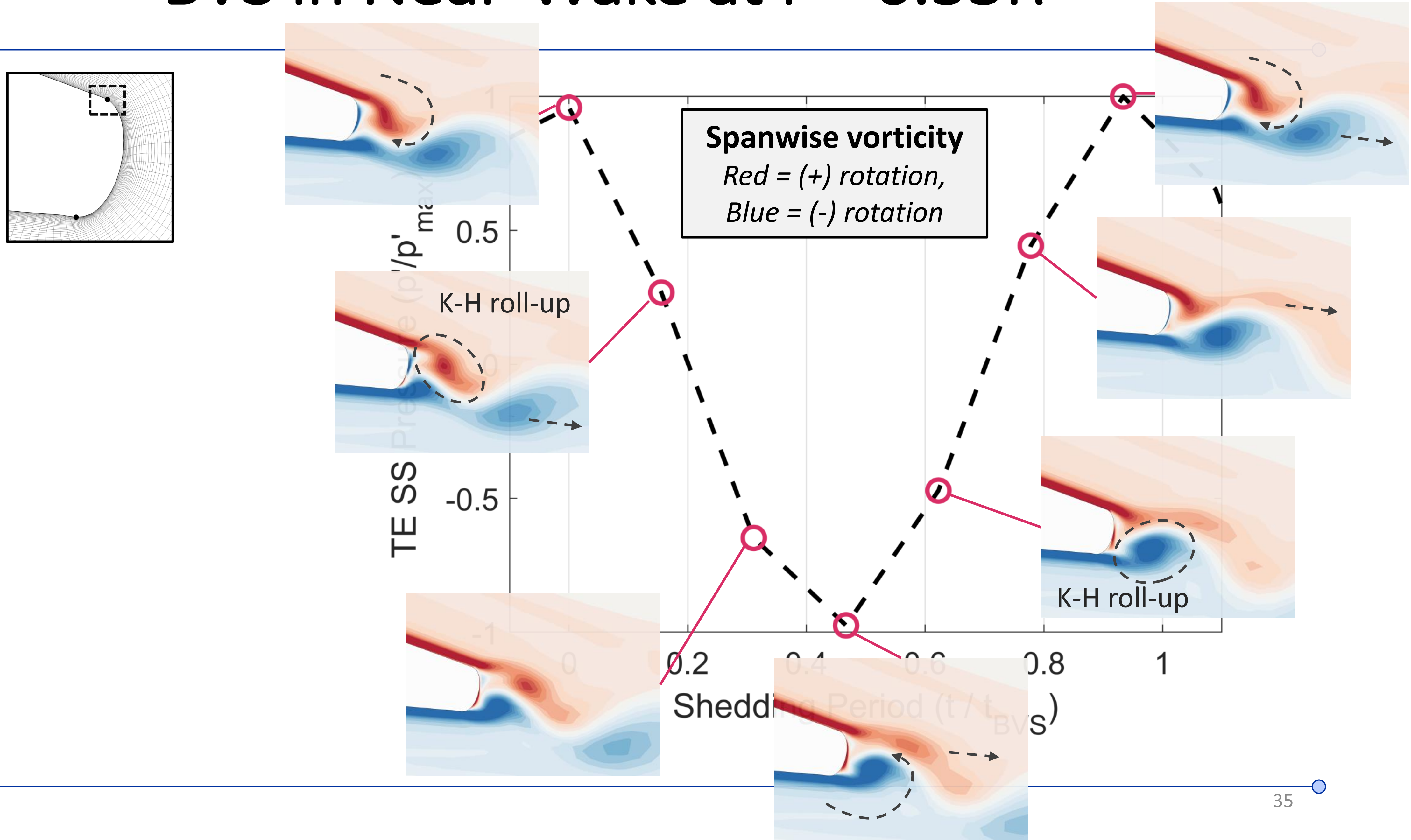
BVS in Near-Wake at r = 0.55R



- Unsteady suction side pressures taken at TE
- Every other timestep (to match rotor sim)



BVS in Near-Wake at r = 0.55R



Application of the 2-D Method

- **How to apply the 2-D method when the angle of attack (α_{eff}) from the rotor simulation is not known?**
- BEMT (blade element momentum theory) can predict α_{eff}
- Slight change in shedding frequency for a 1 deg. change in α_{eff} from BEMT
  - 10.130 kHz (α_{eff} from BEMT)
  - 10.262 kHz (α_{eff} from rotor sim)