Broadband Predictions of Optimized Proprotors in Axial Forward Flight

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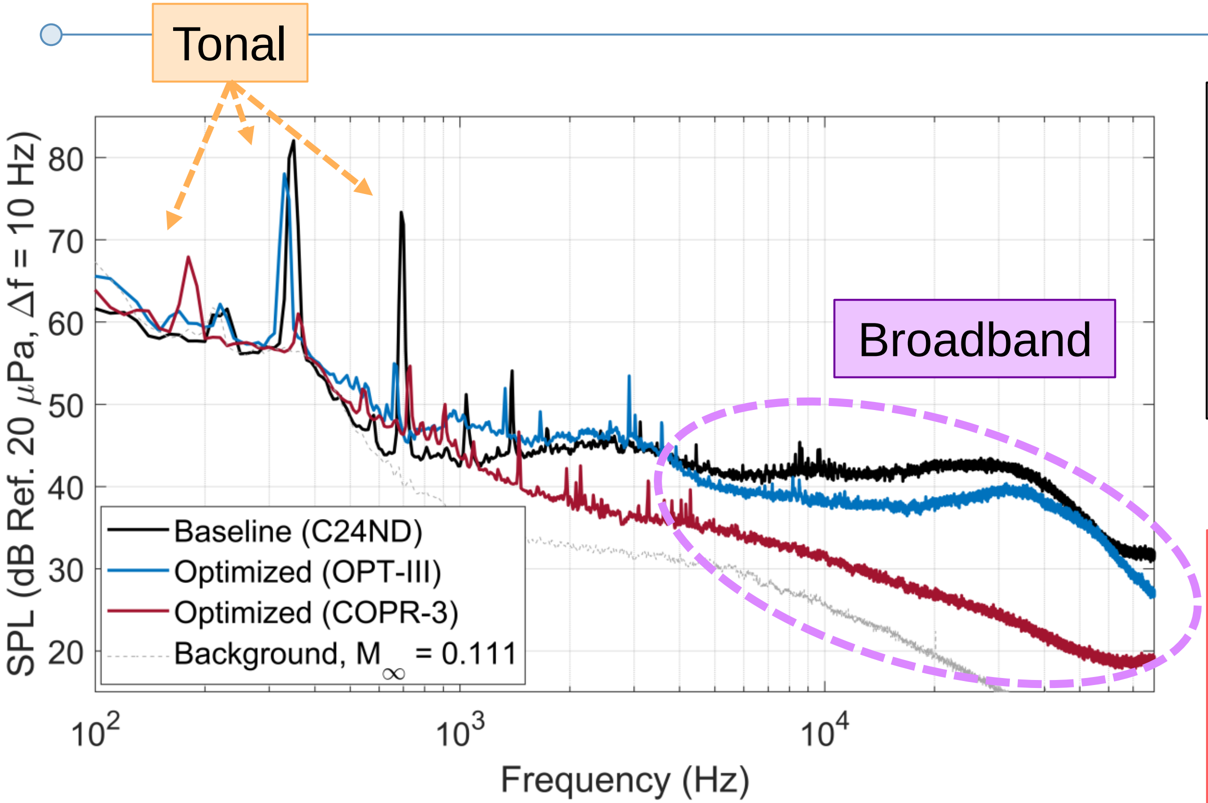
June 15, 2023: AA-43, Propeller, Rotorcraft and V/STOL Noise VII - Simulation and Prediction

Motivation



Tonal

Broadband

Model Scale Proprotors (D = 2 ft.)
LSAWT Experiments, 45° below rotor plane

Expect tonal noise to dominate
in axial flight

Broadband noise is *potentially* significant for multirotor UAM vehicles (e.g., Joby[†‡])

[†] Bain, J.; Goetchius, G. and Josephson, D.
Flyover Noise Comparison Between Joby Aircraft and Similar Aircraft, VFS, 2022

[‡] Pascioni, K. A.; Watts, M. E.; Houston, M.; Lind, A.; Stephenson, J. H. and Bain, J., *Acoustic Flight Test of the Joby Aviation Advanced Air Mobility Prototype Vehicle*, AIAA 2022-3036, 2022

When might broadband noise dominate?

Tonal noise is shifted to lower frequencies by a slower rotation rate

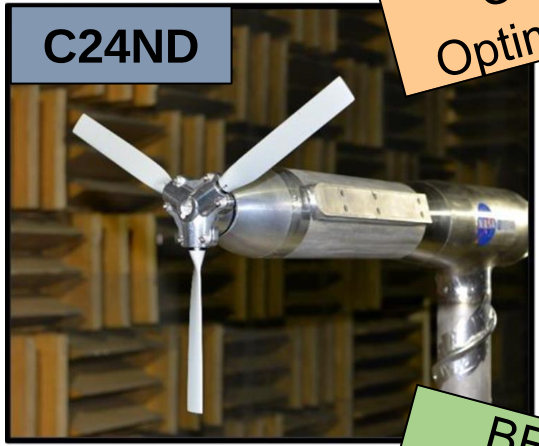
We might ***perceive*** high frequency broadband noise to be ***louder*** than low frequency tonal noise (A-weighting)

Research question:

Can our tools predict broadband noise trends correctly for axial flight?

Experimental Data

Baseline Design:
Helically Twisted

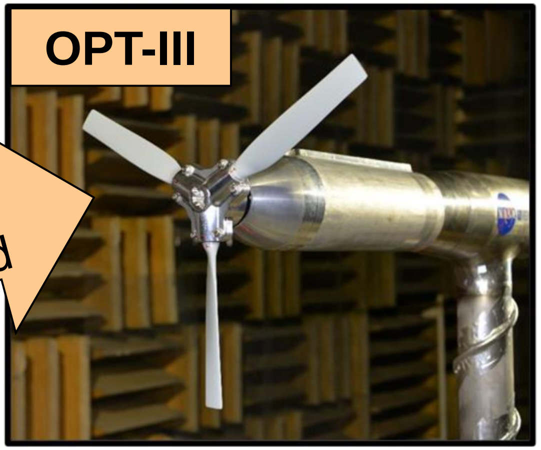


Source: NASA

D = 0.6096m (2 ft.)

Optimized Designs

CFD Optimized



Source: NASA

BEMT Optimized

Source: NASA

- Proprotor design validation campaign
  - ⇒ Minimize tonal noise from a baseline design using OpenMDAO
  - ⇒ Study low-noise designs
  - ⇒ Evaluate our prediction tools
- Low Speed Aeroacoustic Wind Tunnel (LSAWT) tests
  - ⇒ Hover and forward flight
  - ⇒ Several M_{tip} and M_{∞}
- TM is available **(NASA/TM-20220015637)**
  - ⇒ Documents tunnel entry
  - ⇒ Performance and acoustic data
  - ⇒ Data and geometry released: **2022 Optimized Rotor Data Set**

Low-Fidelity Prediction Methods

Aerodynamics

- ANOPP-PAS (Propeller Analysis System)
  - BEMT with radially varying inflow
  - Local α, M, and Re at each blade station
- Thrust at the design condition was matched by adjusting blade collective
- Blade stations from r/R = 0.2 to 0.99

Noise Predictions

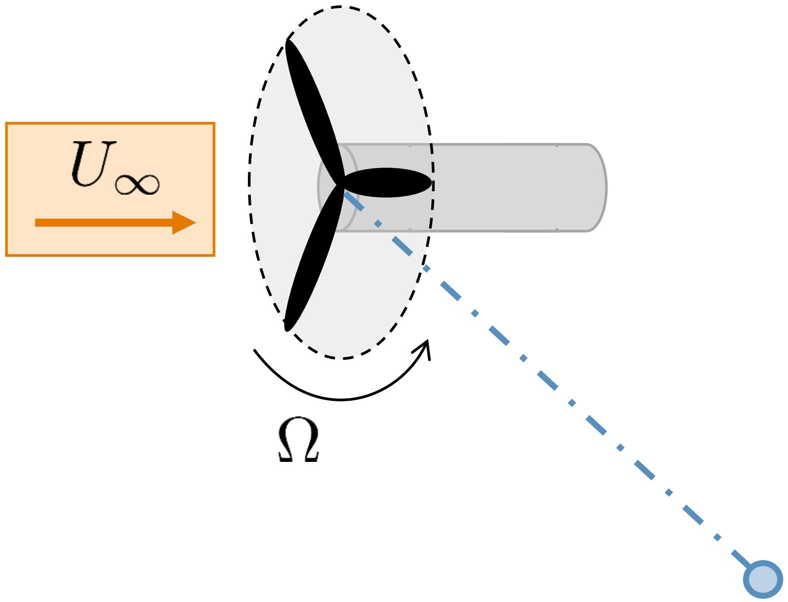
- Broadband Self-Noise: ANOPP2 (ASNIFM)[*]
  - Brooks, Pope, and Marcolini (BPM)
  - Implemented for rotors
- Tested in hover and edgewise flight[†‡^]
- **Not often applied to axial flight**

[*] Lopes, L. V., and Burley, C. L., "ANOPP2 User's Manual," NASA TM 2016-219342, National Aeronautics and Space Administration, October 2016.

[†] Zawodny, N., Boyd, D., and Burley, C., *Acoustic Characterization and Prediction of Representative, Small-Scale Rotary-Wing Unmanned Aircraft System Components*, AHS, 2016.

[‡] Pettingill, N., Zawodny, N., Thurman, C., and Lopes, L., *Acoustic and Performance Characteristics of an Ideally Twisted Rotor in Hover*, AIAA SciTech, 2021.

[^] Pettingill, N. and Zawodny, N. S., *Identification and Prediction of Broadband Noise for a Small Quadcopter,* VFS, 2019.



Single Microphone

45° below rotor plane, 12R

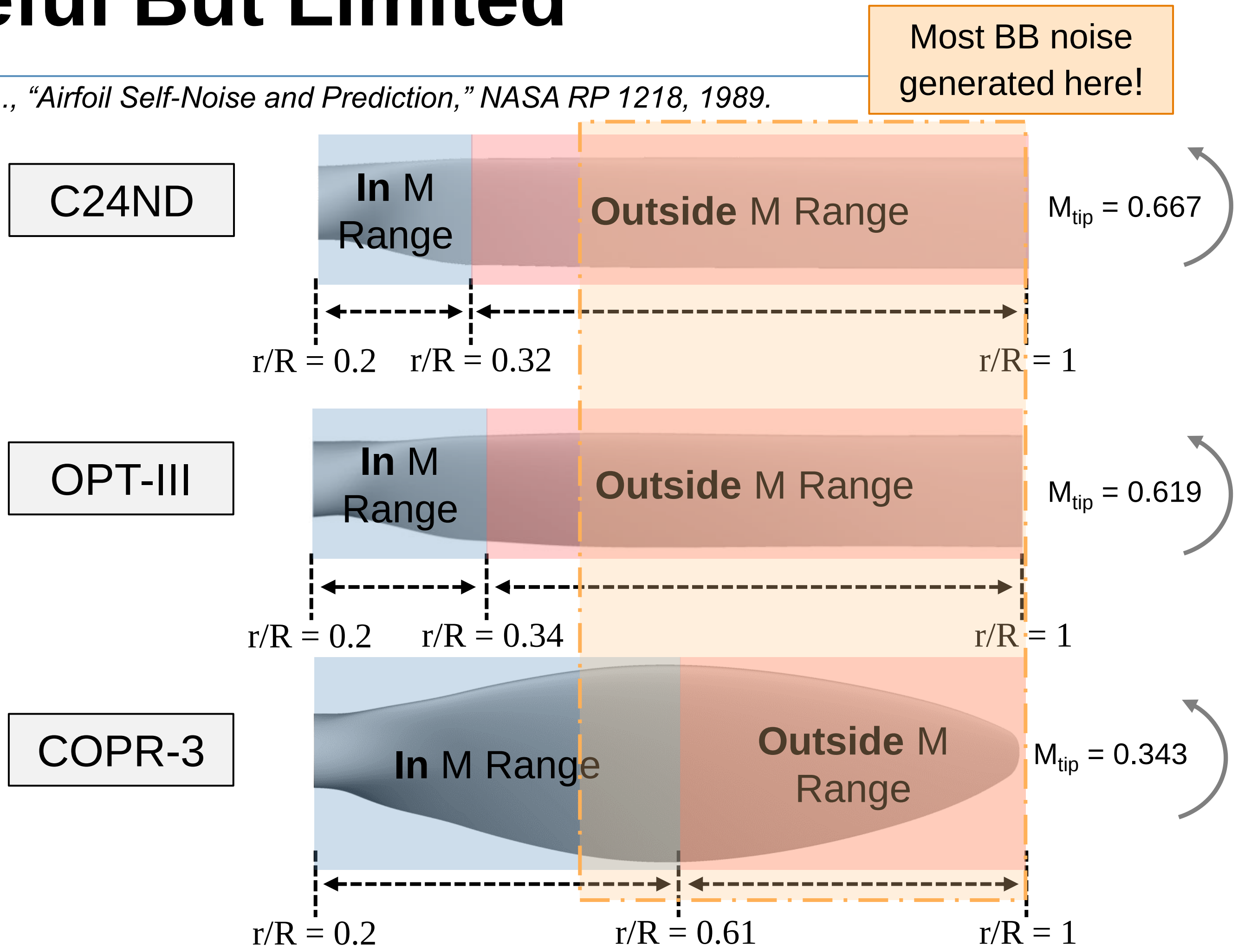
BPM**: Useful But Limited

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

- BPM Method
  - ⇒ Semiempirical
  - ⇒ Six self-noise sources for 2D and 3D airfoils
  - ⇒ Widely used in low- and mid-fidelity analysis
- Built on limited data set
  - ⇒ Only for an NACA 0012
  - ⇒ Only two modeled BL trips
    - Untripped/naturally transitional
    - Heavily tripped
  - ⇒ Reynolds number up to $1.5\text{x}10^6$
  - ⇒ **Mach number up to 0.208**

Blade station **Mach numbers*** are **greater than the BPM limit**!

**Reynolds numbers are in range*



Research question:

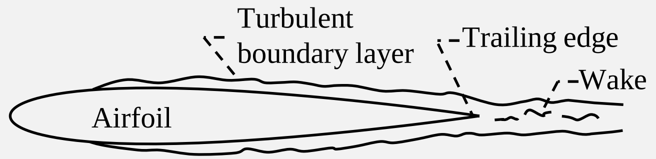
Can our tools predict broadband noise trends correctly for axial flight?

Two[†] Main Self-Noise Mechanisms**

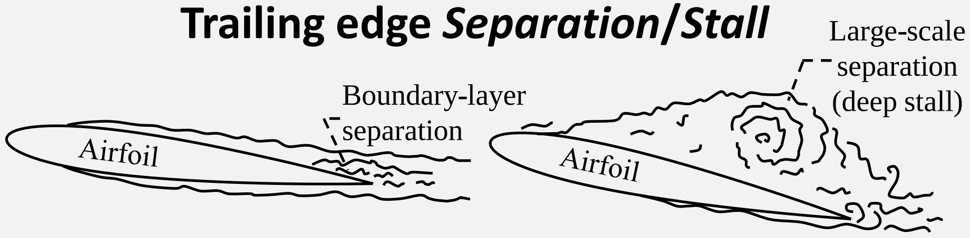
***Adapted from: Brooks, T. F., Pope, D. S., and Marcolini, M. A., "Airfoil Self-Noise and Prediction," NASA RP 1218, 1989.*

Total TBL-TE

Turbulent boundary layer trailing edge (TBL-TE) noise on *Suction and Pressure* Side

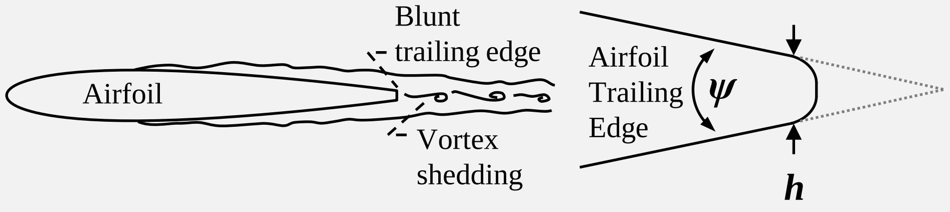


Trailing edge *Separation/Stall*



BVS

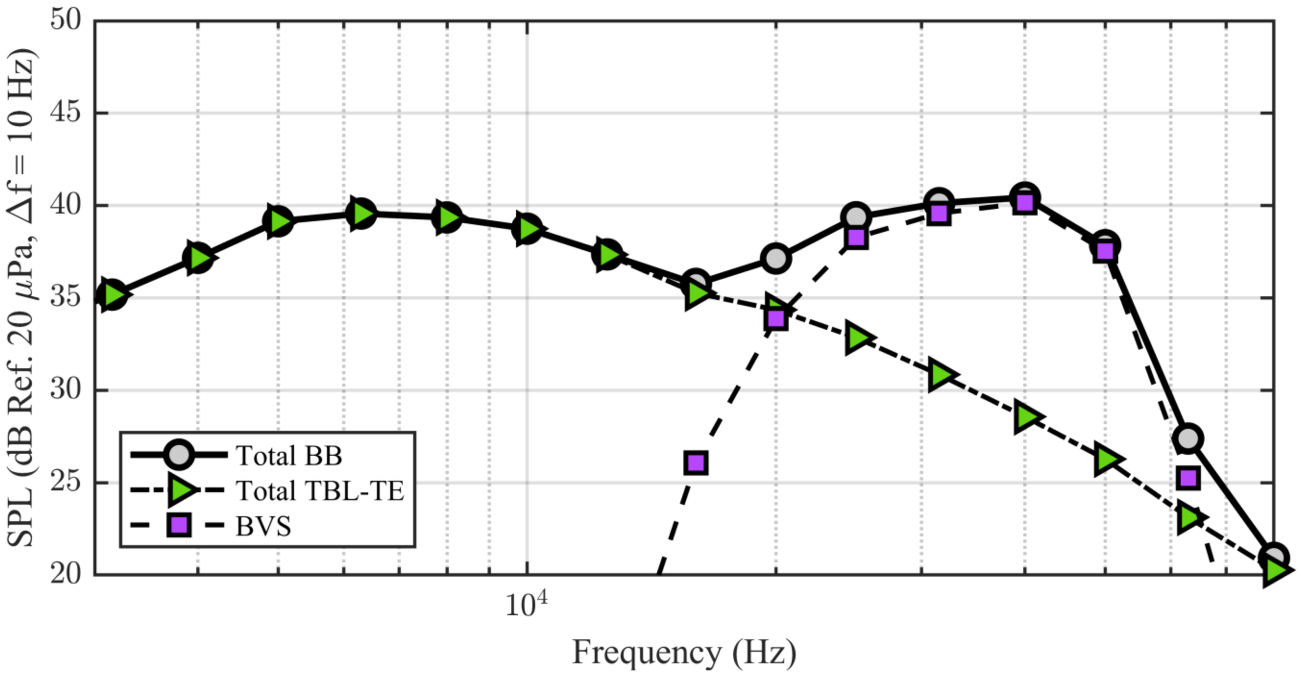
***Bluntness* vortex shedding noise**



[†] *LBL-VS and tip vortex noise are not considered here.*

OPT-III: $M_{tip} = 0.619$, $M_\infty = 0.111$

θ_{mic} = 45° below rotor plane



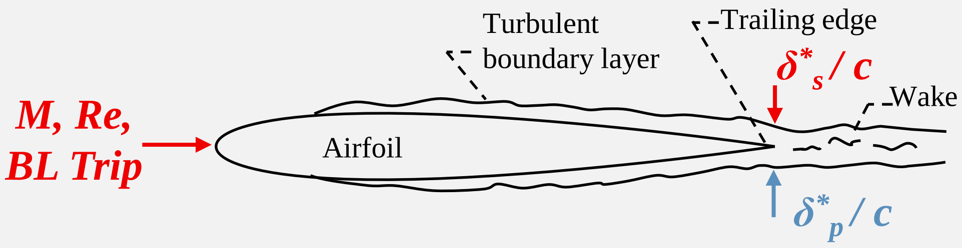
(Third-Octave converted to 10 Hz Narrowband)

TBL-TE Noise Mechanism**

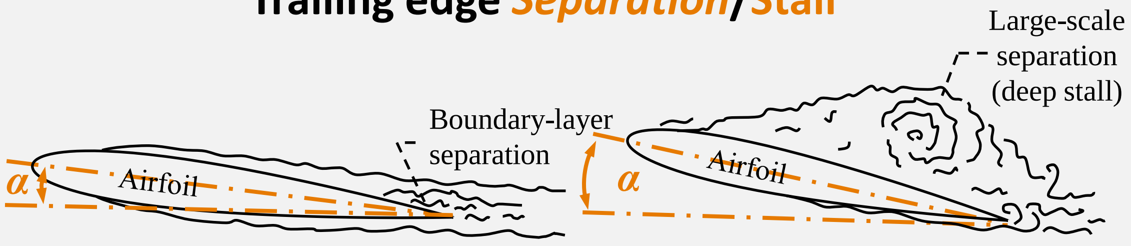
***Adapted from: Brooks, T. F., Pope, D. S., and Marcolini, M. A., "Airfoil Self-Noise and Prediction," NASA RP 1218, 1989.*

Total TBL-TE

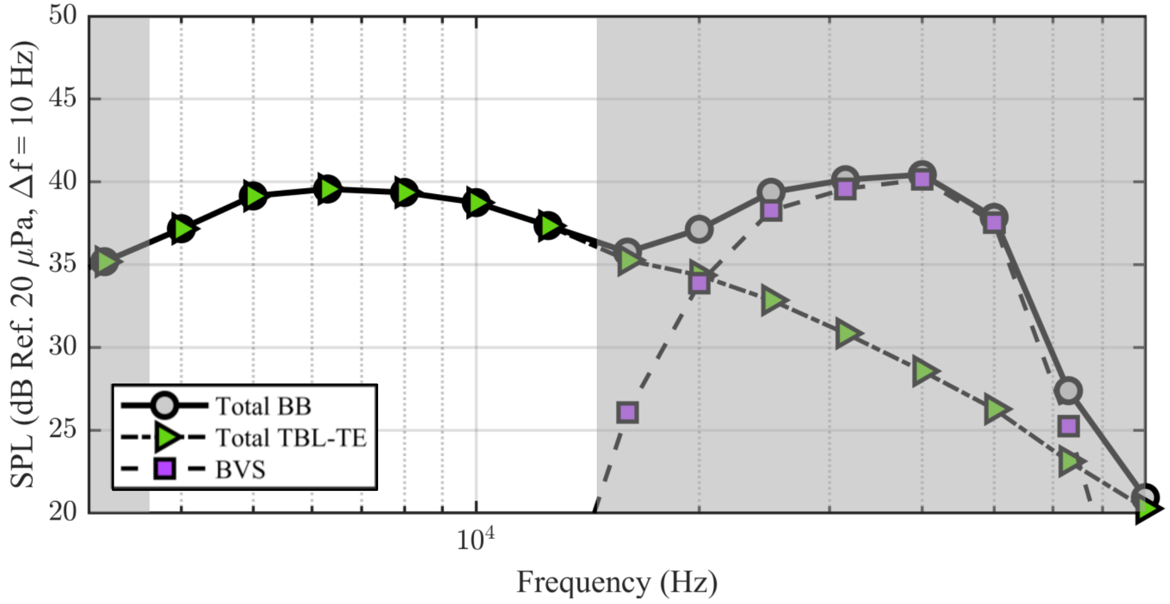
Turbulent boundary layer trailing edge (TBL-TE) on: *Suction* and *Pressure* Side



Trailing edge *Separation*/*Stall*



TBL-TE largely depends on δ^*/c

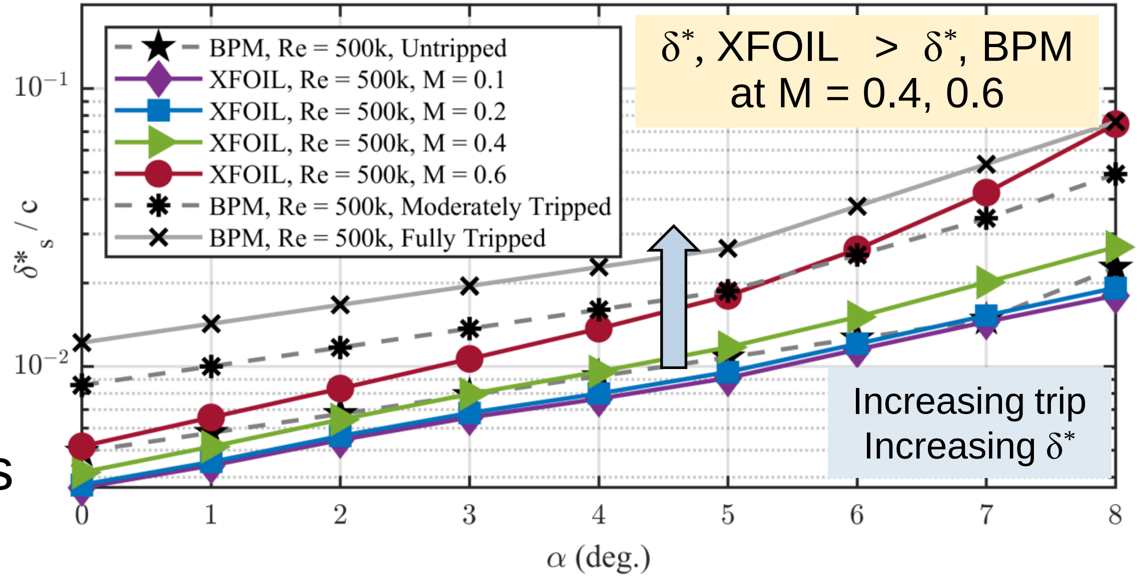


Only TBL-TE noise is highlighted
gray boxes cover frequencies not dominated by TBL-TE

Modeling δ^* for TBL-TE Noise

- δ^* model depends on boundary layer trip
  - ⇒ Untripped / natural transition
  - ⇒ Fully / aggressively tripped
  - ⇒ Moderately tripped (calculated average in ASNIFM)
- No physical trip in the proprotor tests!
  - ⇒ Underpredicted TBL-TE noise with untripped setting
  - ⇒ Calculated δ^* were possibly too small?
  - ⇒ Trip needed to model correct TBL-TE noise trends
- δ^* is assumed to *only* depend on Reynolds number in the BPM method
- **Could δ^* *also* depend on Mach number?**

<u>δ^* for a constant Reynolds number:</u>
BPM (untripped) vs. XFOIL (natural transition)

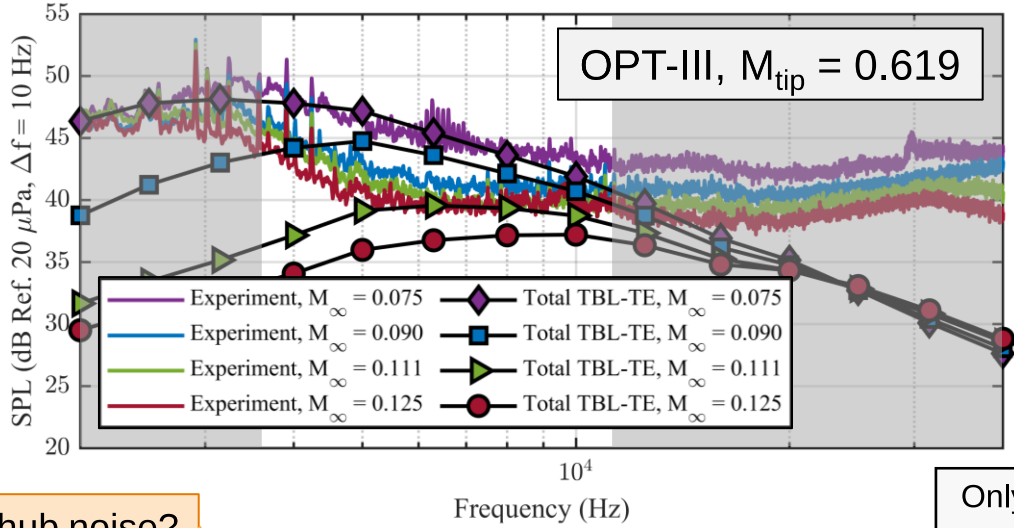


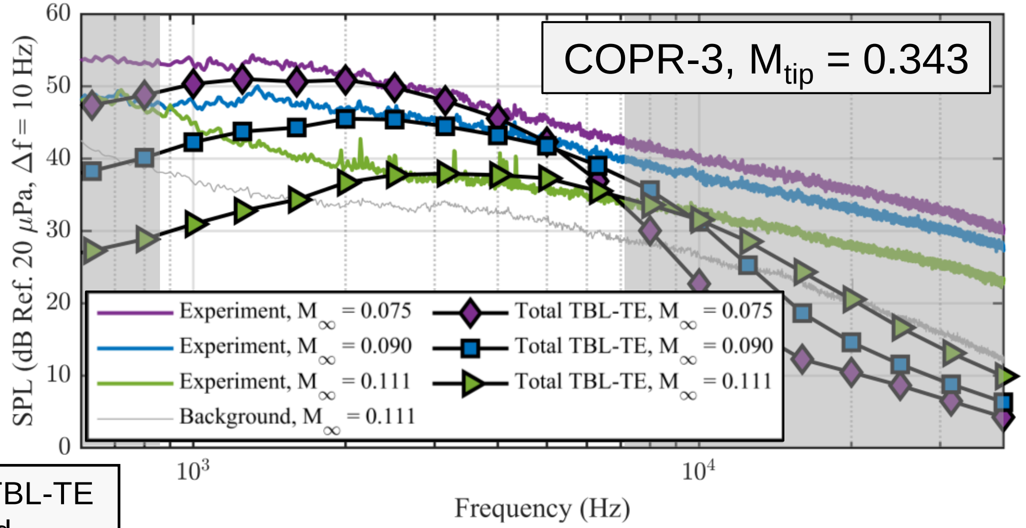
δ^*, XFOIL > δ^*, BPM
at M = 0.4, 0.6

Increasing trip
Increasing δ^*

What is the best trip setting for TBL-TE across several flight conditions?

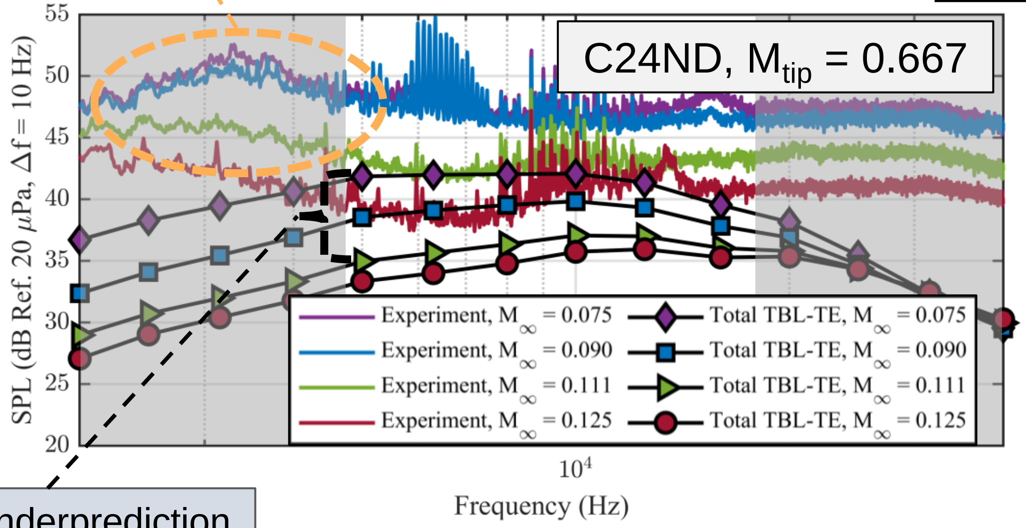
Moderately Tripped Predictions





Only Total TBL-TE plotted

Root/hub noise?



~6 dB underprediction

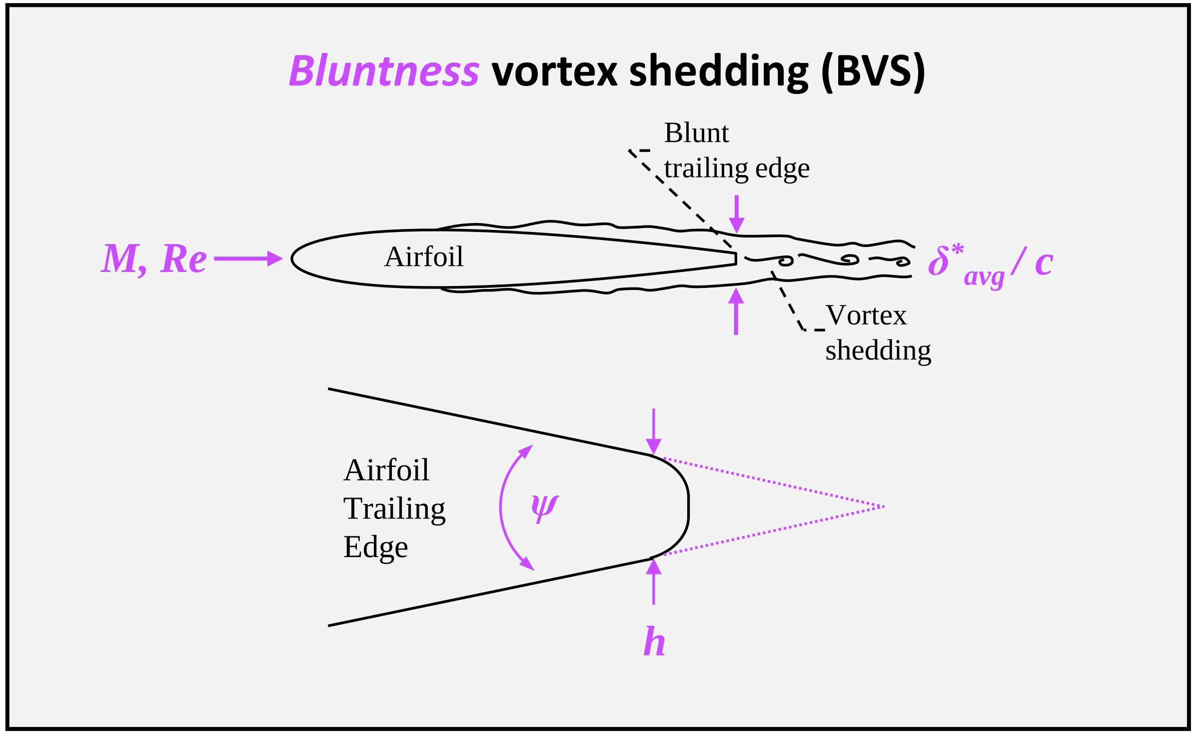
- Moderately tripped gave best predictions across several flight conditions (varying tunnel speed)
  - ⇒ Peak frequencies matched well
  - ⇒ Peak amplitude not always matched
- Mach number dependence could explain the need to increase the trip setting and δ^*

See paper for additional results for all trip settings

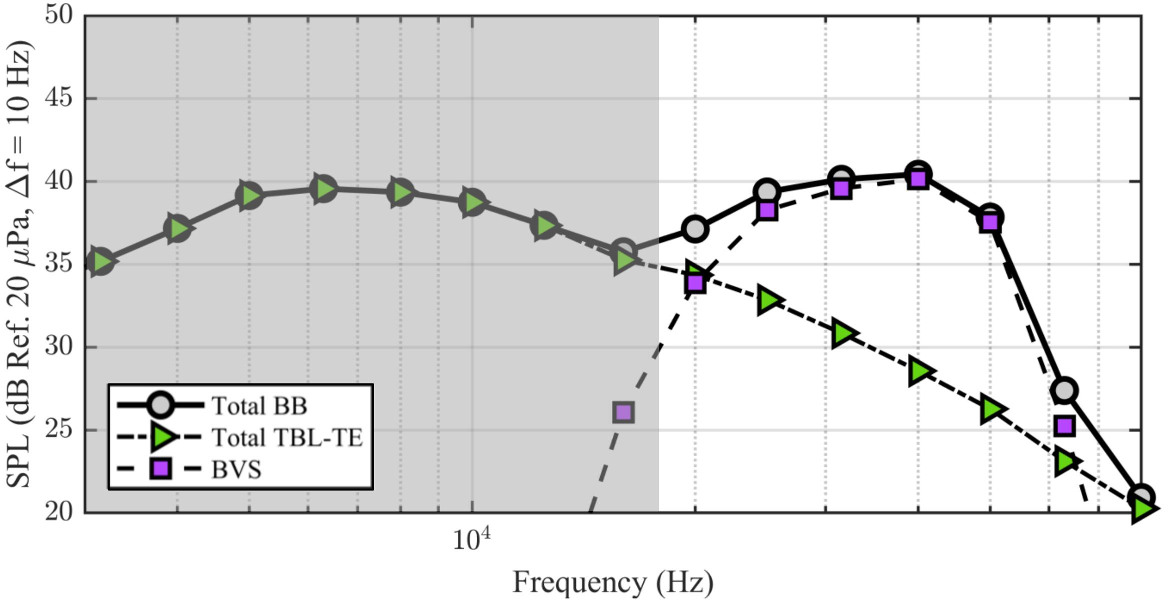
Bluntness Vortex Shedding Mechanism**

***Adapted from: Brooks, T. F., Pope, D. S., and Marcolini, M. A., "Airfoil Self-Noise and Prediction," NASA RP 1218, 1989.*

BVS



BVS model was only built on data for $\alpha = 0$



Only BVS noise is highlighted

gray boxes cover frequencies not dominated by bluntness noise

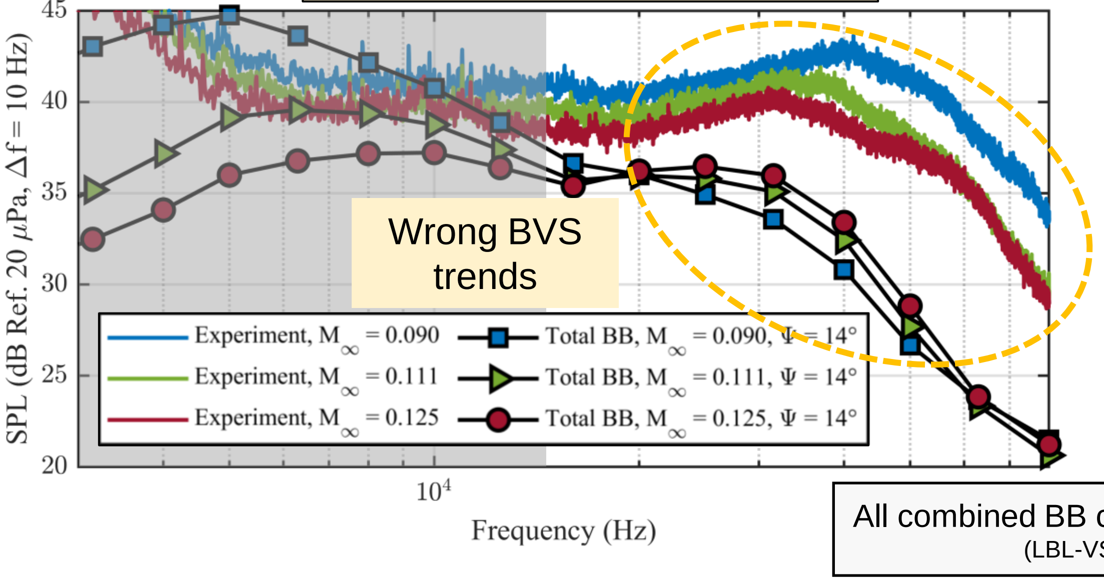
Tuning the Trailing Edge Angle (ψ)

- Trailing edge thickness, ***h***
  - ⇒ Modeled as a % of chord, **h/c**
  - ⇒ **h/c** was tuned for each proprotor
- Trailing edge angle, ψ
  - ⇒ ψ was tuned for each flight condition
  - ⇒ ψ should only depend on geometry!

NACA 0012: ψ = 14°
Flat plate: ψ = 0°

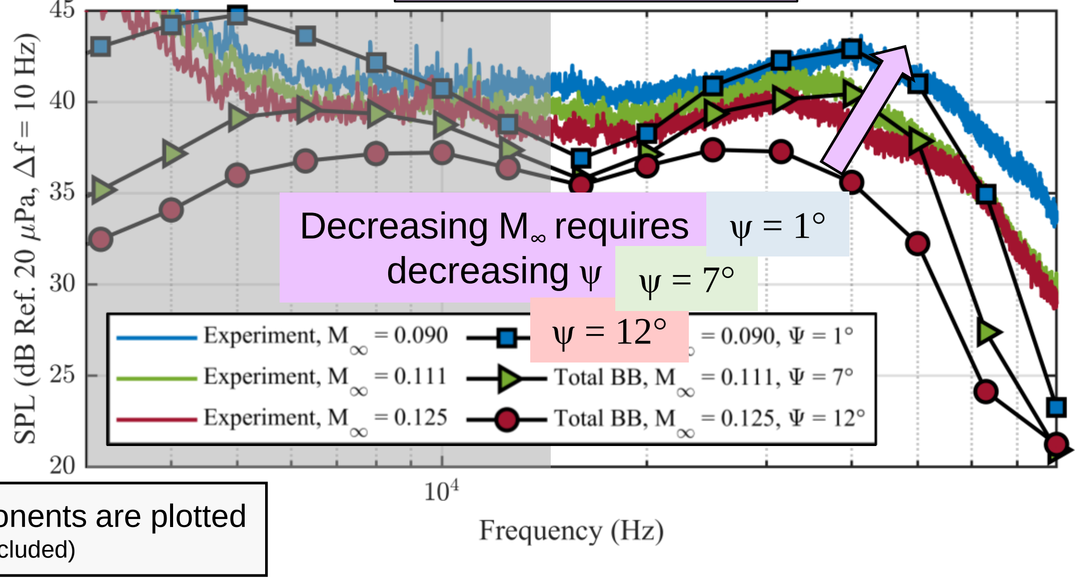
M_{tip} = 0.619
Constant **h/c** = 1.75%

OPT-III, Physical (ψ = 14°)



Wrong BVS trends

OPT-III, Tuned ψ



Decreasing M_∞ requires decreasing ψ

ψ = 1°

ψ = 7°

ψ = 12°

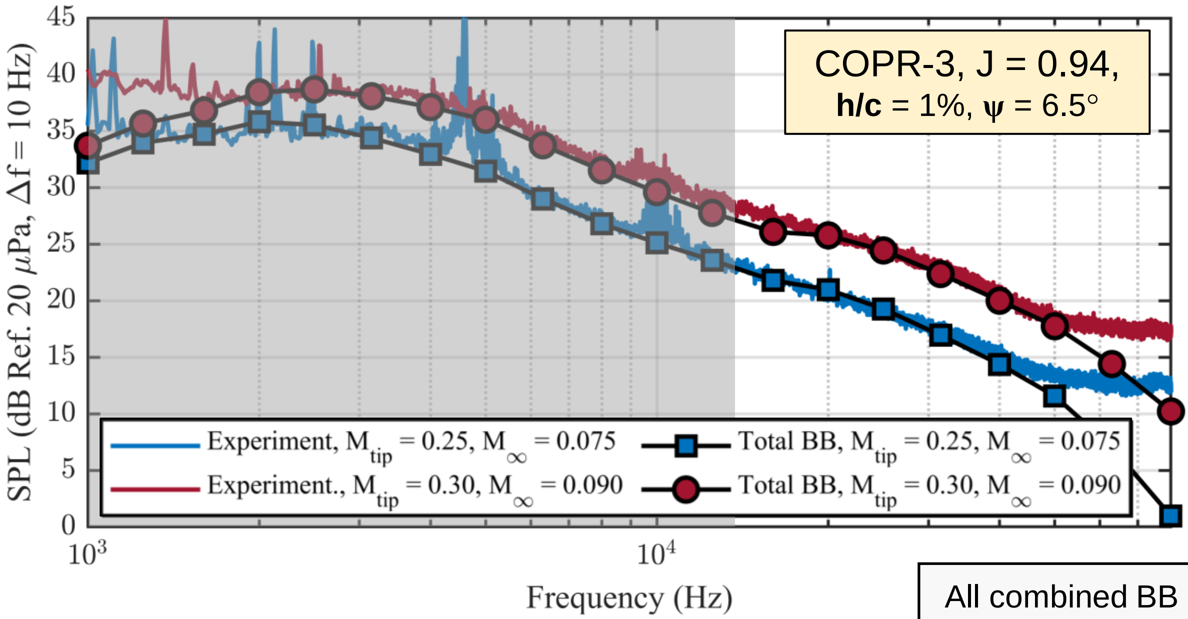
All combined BB components are plotted
(LBL-VS not included)

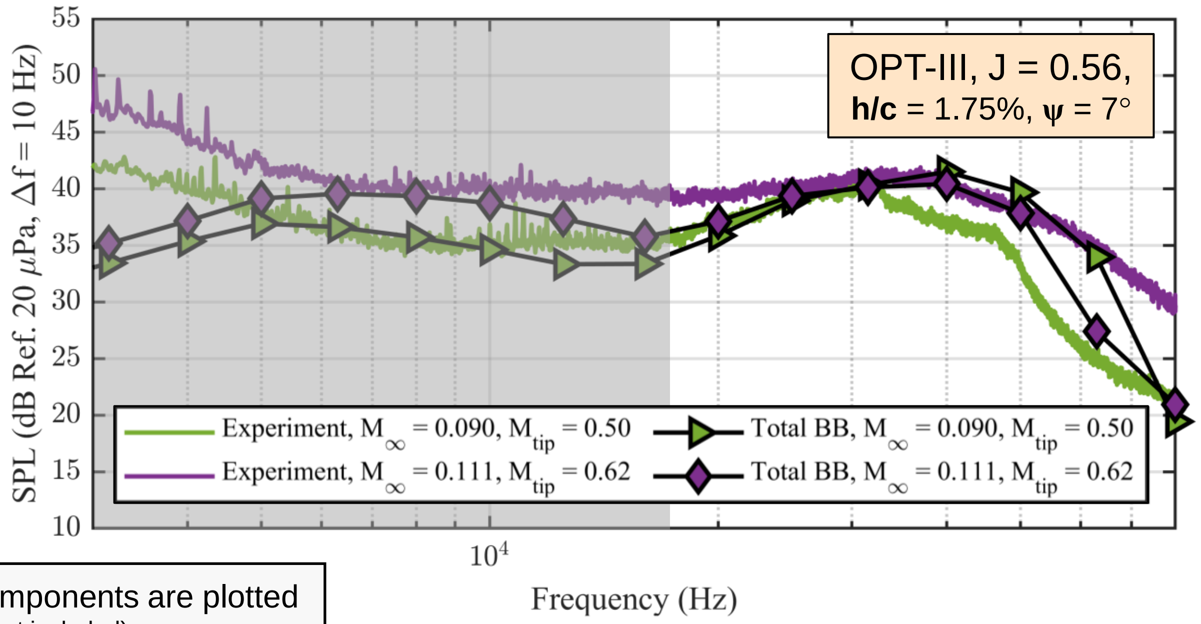
See paper for additional results

α changes with M_∞: BVS model does not accurately capture the physics for a change in α

BVS Trends For A Constant Advance Ratio (J)

- Assume that BVS also depends on α
- If α distribution is the same, should *not* have to retune **ψ**
- Same J = same α distribution





All combined BB components are plotted
(LBL-VS not included)

BVS likely varies with α

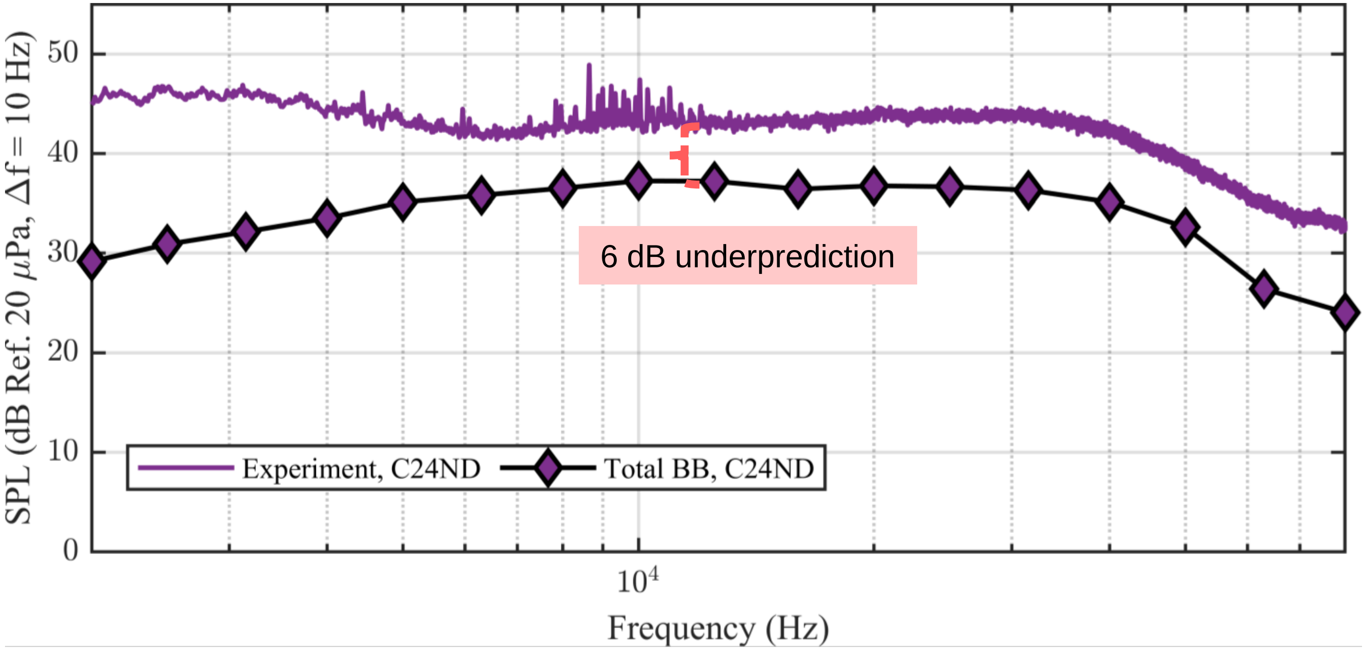
Trends for All Three Proprotors

Design Condition:

$M_\infty = 0.111$

Moderately tripped

h/c, ψ tuned



6 dB underprediction

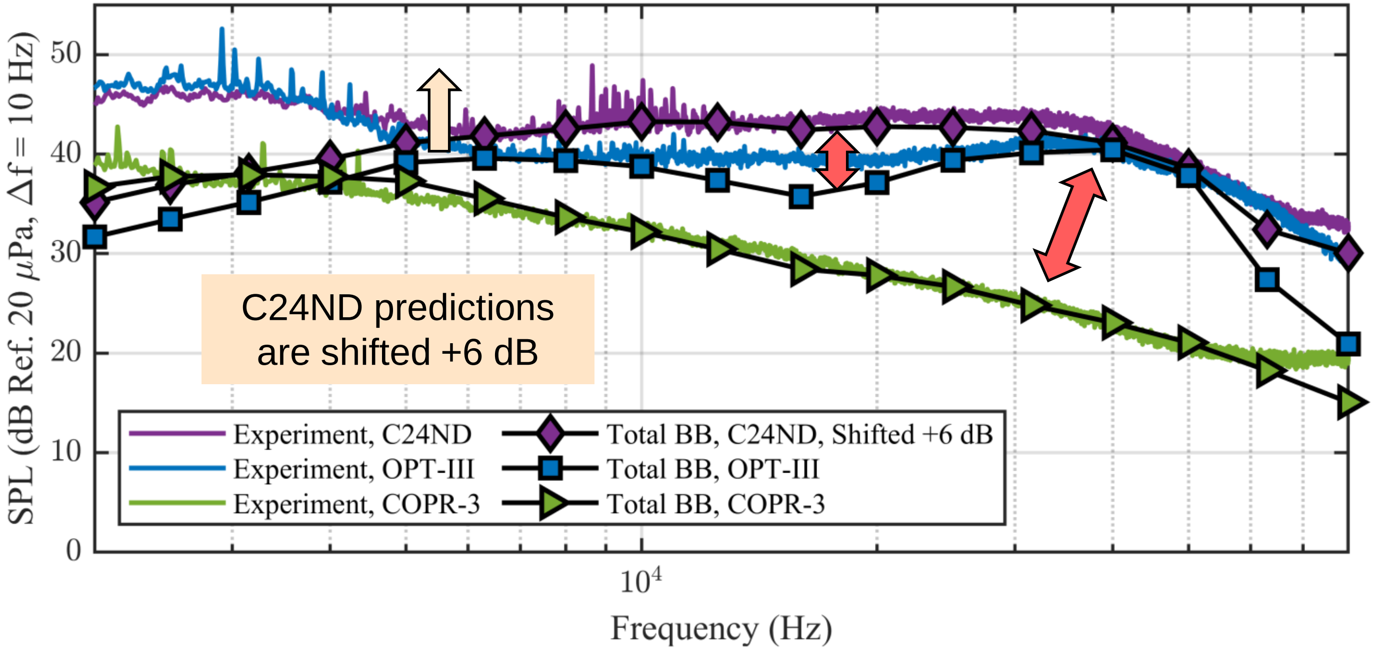
Total combined BB components are plotted
(LBL-VS not included)

- Amplitude not predicted well for C24ND (baseline) proprotor
  - ⇒ 6 dB underprediction possibly due to $M_{tip} = 0.667$
  - ⇒ Difficult to compare noise reduction during design iterations

Trends for All Three Proprotors

Design Condition:
$M_\infty = 0.111$

Moderately tripped
h/c, ψ tuned



C24ND predictions
are shifted +6 dB

Total combined BB
components are plotted
(LBL-VS not included)

- Amplitude not predicted well for C24ND (baseline) proprotor
  - ⇒ 6 dB underprediction possibly due to $M_{tip} = 0.667$
  - ⇒ Difficult to compare noise reduction during design iterations
- Spectral shapes and frequency trends are predicted well
  - ⇒ Required tuning TBL-TE and BVS inputs!
  - ⇒ Possible root/hub noise below 5 kHz
- **With tuning and amplitude shift, trends between proprotors are acceptable for low-fidelity predictions**

Conclusions

- Key takeaways
  - ⇒ Trends can be matched by tuning BPM parameters
    - Moderately tripped boundary layer setting worked best across a range of flight conditions despite no physical trip in experiments
    - BVS trends matched by adjusting h/c for each proprotor and ψ for each flight condition
  - ⇒ **BPM needs to be improved and expanded**
    - δ^* may depend on Mach number, which was not considered in the BPM model
    - BVS may depend on α, which was not considered in the BPM model

- Questions for future study
  - ⇒ How does δ^* vary with Mach number?
  - ⇒ Can we determine a variation of BVS with α?
  - ⇒ How accurate are the other BPM models (LBL-VS, tip vortex noise)?

Thank you.

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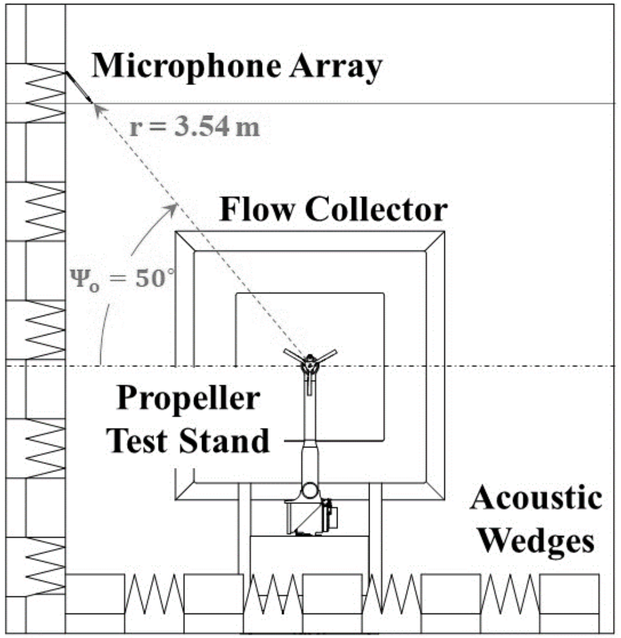
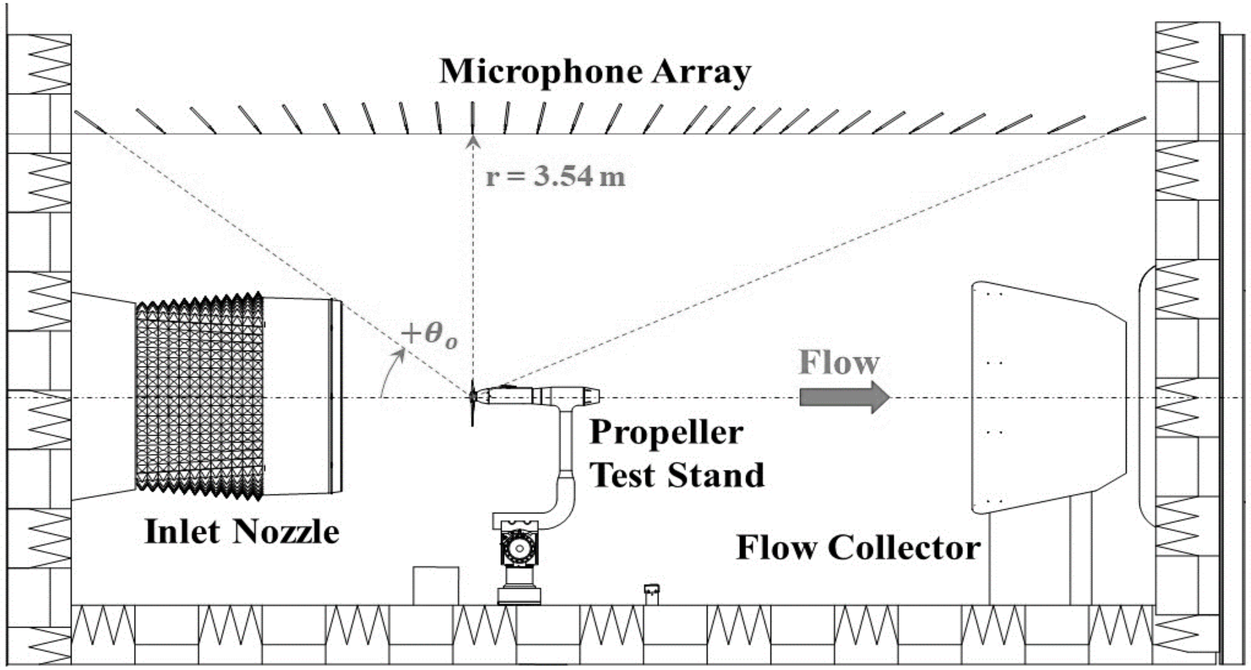
Backup Slides

Experimental Setup



LSAWT: Front View



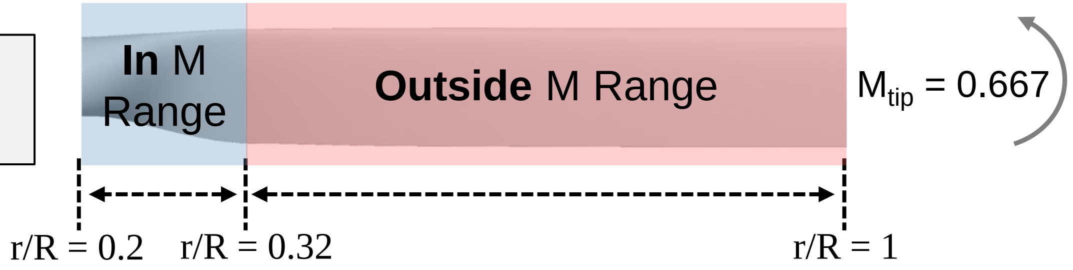
LSAWT: Side View

Summary of TBL-TE and BVS Noise Investigation

- Moderately tripped gave best TBL-TE predictions across a range of flight conditions for all proprotors
  - ⇒ Untripped boundary layer setting underpredicted TBL-TE
  - ⇒ Proprotors were untripped in the experiments!
  - ⇒ Possible dependence of δ^* on Mach number was discovered and may explain the need for increasing the boundary layer trip
  - ⇒ C24ND underpredicted peak TBL-TE by 6 dB, possibly due to high tip Mach number
  - ⇒ Possible root stall or hub noise observed in C24ND experimental data
- Predicting BVS noise correctly required tuning h/c for each proprotor and ψ for each flight condition
  - ⇒ BVS model does not accurately capture the physics for a change in α
  - ⇒ Predictions at a constant advance ratio (same α distribution) did not require retuning ψ
  - ⇒ BVS may vary with α
- **See paper for plots and additional details**

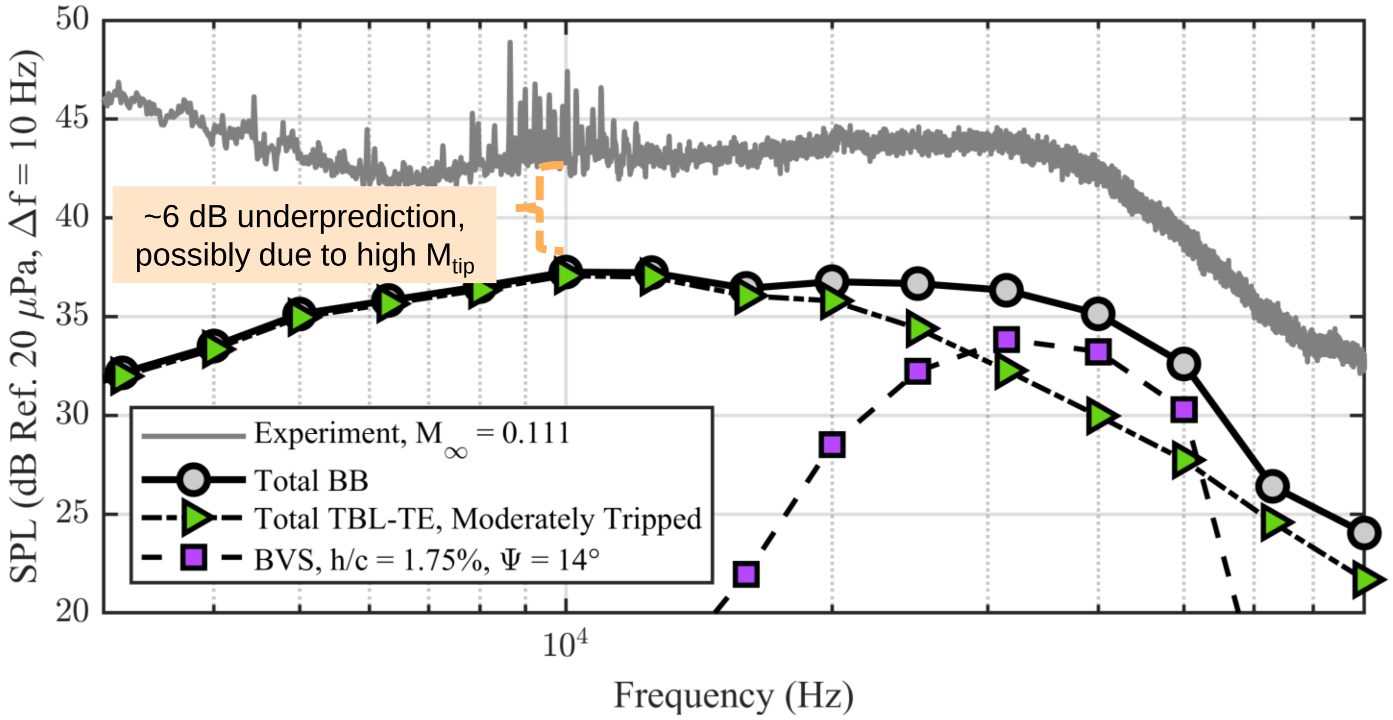
Predictions at the Design Condition: C24ND

C24ND
M_∞ = 0.111



- Design condition: $M_\infty = 0.111$
- Moderately tripped setting
- BVS tuned for each case
  - ⇒ **C24ND: *h/c* = 1.75%, ψ = 14.0°**
  - ⇒ OPT-III: *h/c* = 1.75%, ψ = 7.0°
  - ⇒ COPR-3: *h/c* = 1.00%, ψ = 9.0°

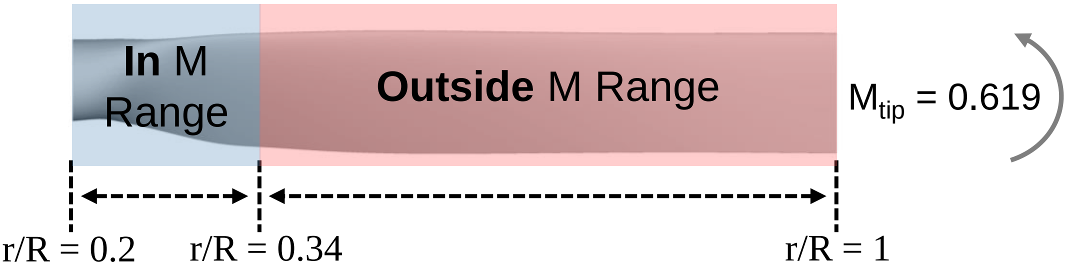
Total combined BB components are plotted
(LBL-VS not included)



~6 dB underprediction, possibly due to high M_{tip}

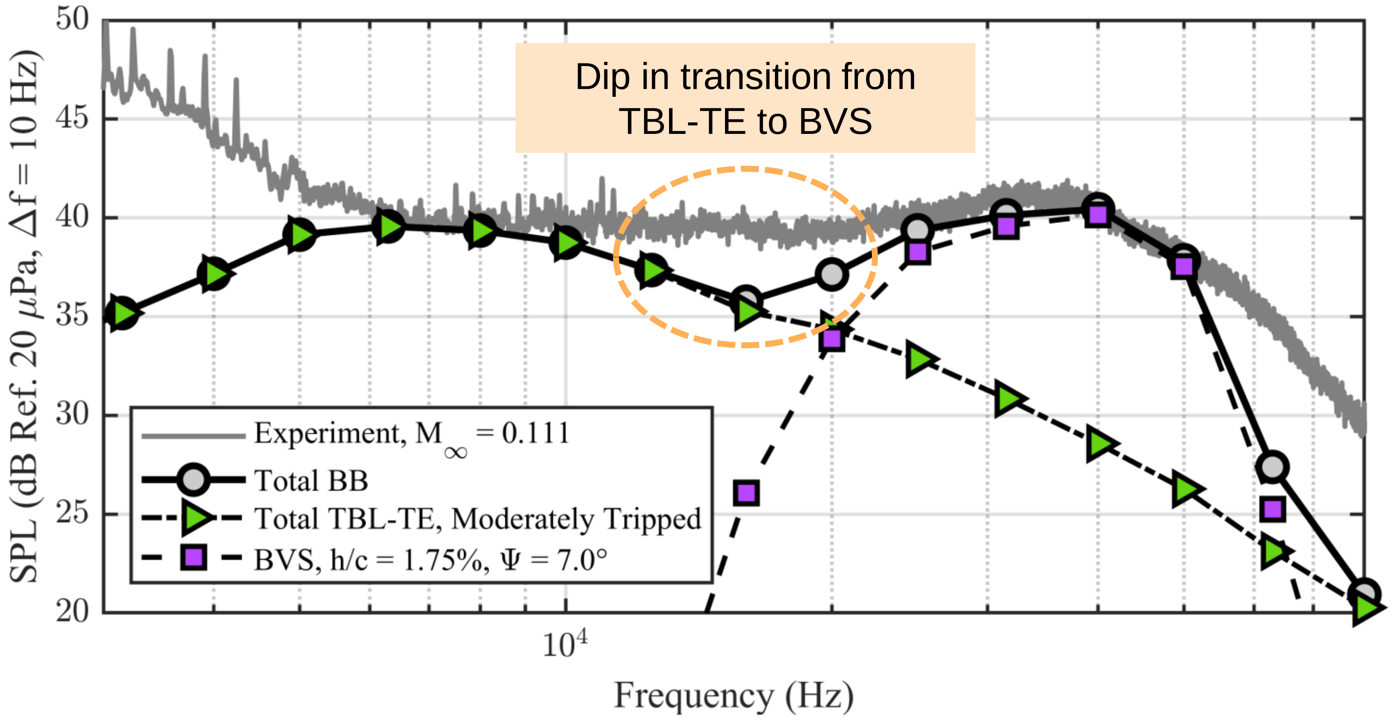
Predictions at the Design Condition: OPT-III

OPT-III
$M_\infty = 0.111$



- Design condition: $M_\infty = 0.111$
- Moderately tripped setting
- BVS tuned for each case
  - ⇒ C24ND: h/c = 1.75%, ψ = 14.0°
  - ⇒ **OPT-III: h/c = 1.75%, ψ = 7.0°**
  - ⇒ COPR-3: h/c = 1.00%, ψ = 9.0°

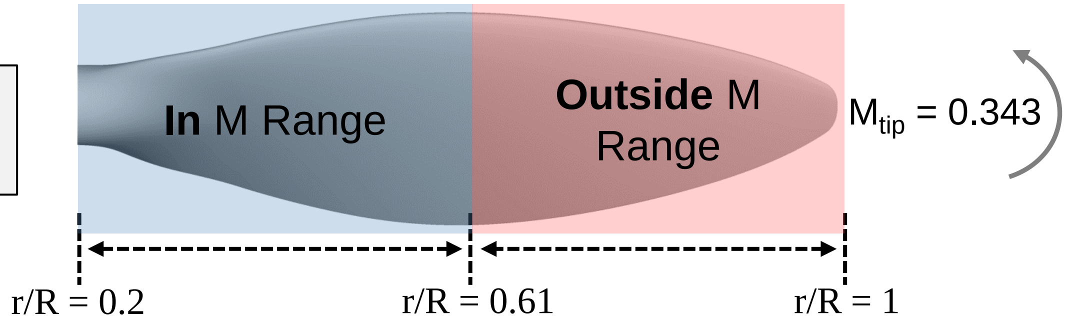
Total combined BB components are plotted
(LBL-VS not included)



Dip in transition from TBL-TE to BVS

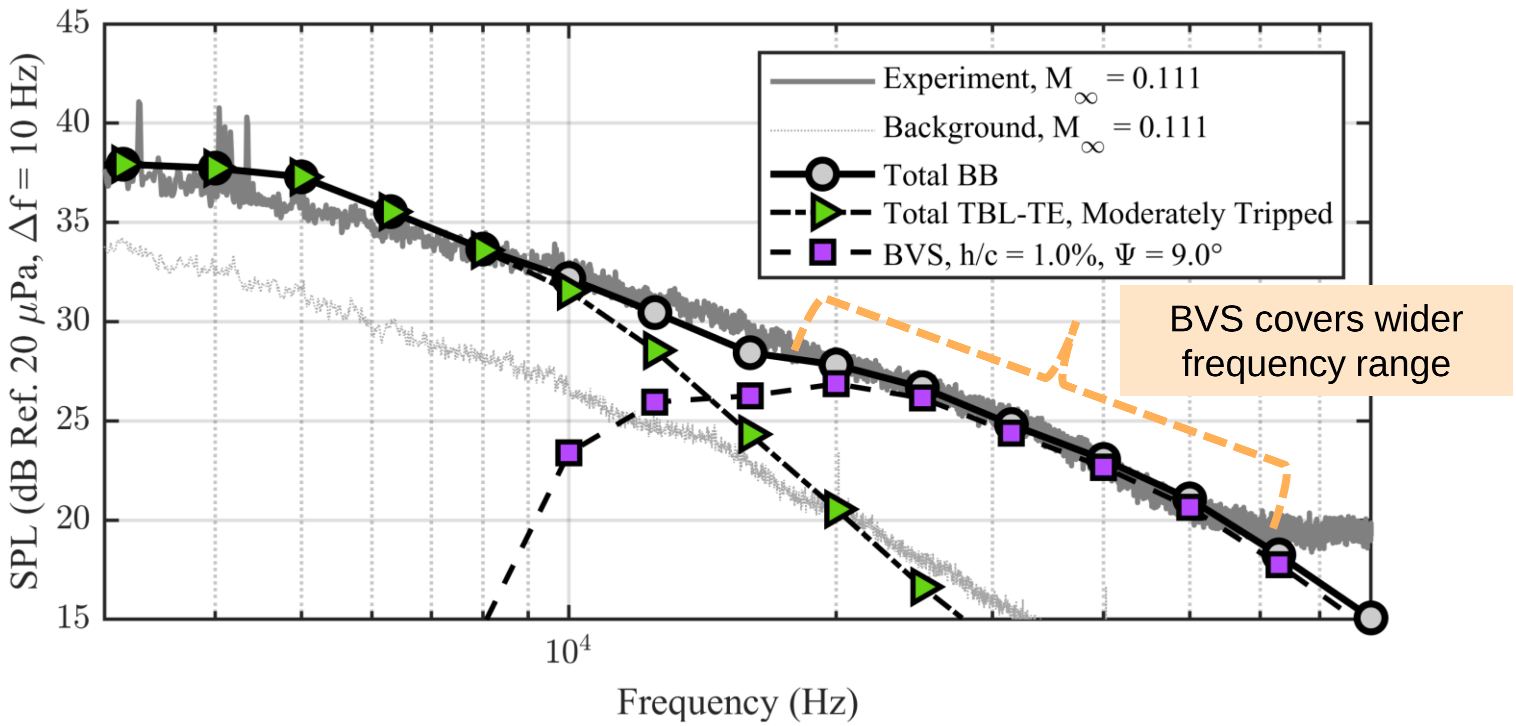
Predictions at the Design Condition: COPR-3

COPR-3
$M_\infty = 0.111$



- Design condition: $M_\infty = 0.111$
- Moderately tripped setting
- BVS tuned for each case
  - ⇒ C24ND: $h/c = 1.75\%$, $\psi = 14.0°$
  - ⇒ OPT-III: $h/c = 1.75\%$, $\psi = 7.0°$
  - ⇒ **COPR-3: $h/c = 1.00\%$, $\psi = 9.0°$**

Total combined BB components are plotted
(LBL-VS not included)



BVS covers wider frequency range