Aerodynamic whistle-based ultrasonic bat deterrents

REWI webinar

Anupam Sharma[1] Zhangming Zeng[1] Charlie van Horn[2] William N. Alexander[2]

[1]Iowa State University

[2]Virginia Tech

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Overview

Motivation

Challenge/Need/Gap

- Bat mortality at wind farms
- Curtailment effective but energy loss
- Ultrasonic deterrents effective in field
- Nacelle/tower-mounted ultrasonic deterrents do not protect outboard blade region

Idea/Technology

Blade-mounted ultrasonic deterrents driven by *blade-relative air flow* → passive

Impact

- Mitigate bat mortality at wind farms with minimal energy hit
- Cost savings: no/minimal curtailment w/ proposed deterrents

Nacelle- vs. blade-mounted systems

Nacelle-mounted

- Blade tips far from deterrent
- Ultrasound decays rapidly → outer blade region not protected
- High source amplitude → adverse impact on wild/farm life

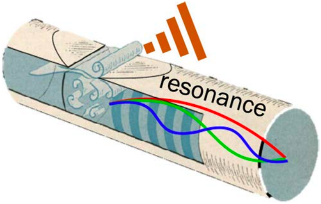
Blade-mounted

- Deterrents placed where required
- Travel $\sim$ 10 m → low source amplitude

Blade-mounted deterrents offer a unique advantage

Concept

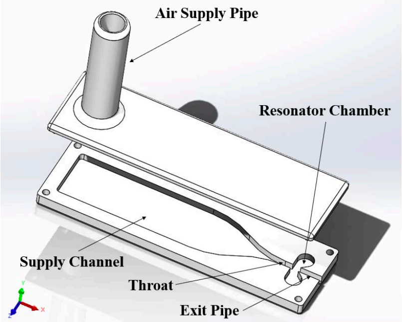
- Adaptation of dog (Galton's) whistle
- *Working principle:*
  - Flow instability + resonance → high-intensity (ultra)sound
  - No moving parts → robust design
- Multiple resonators for broad spectral coverage (20 − 50 kHz)
- Compressed air supply for **active** designs
- Blade-relative air flow for **passive operation**



Dog whistle

Active whistles

Aerodynamic whistle for ultrasound generation



CAD

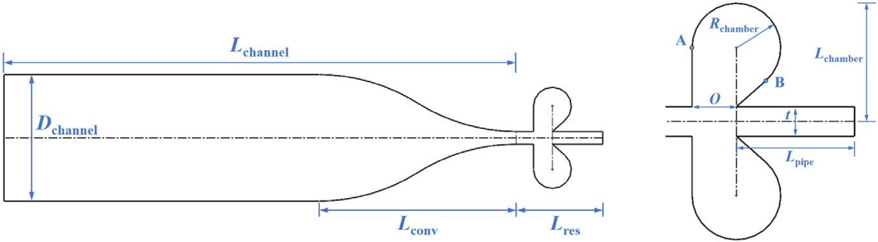
3D-printed whistle

- Follows initial design of Beeken[1]
- Dominant tone at $\sim$ 23 kHz $+$ harmonics; frequency insensitive to p_t
- Working principle: Class III whistle with resonance amplification[2]

[1] *Fluid ultrasonic generator* (US3432804A). (1969, March 11).

[2] Chanaud, R. C. (1970).Aerodynamic whistles. *Scientific American*, *222*(1), 40–47.

Whistle design parameters[3]

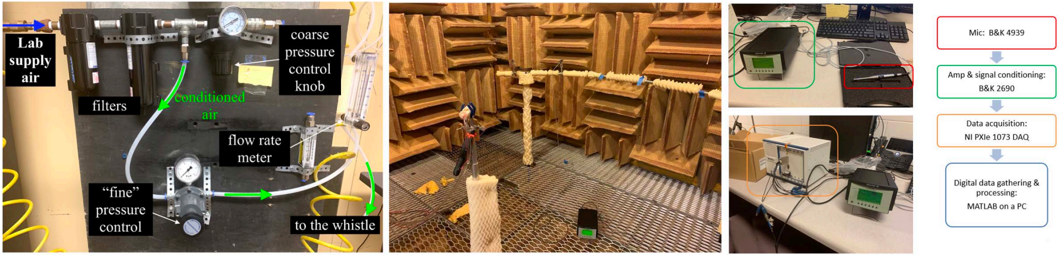


L_{channel}	L_{conv}	L_{res}	L_{chamber}	L_{pipe}	t	O	R_{chamber}	D_{channel}
65	25	11	6.4	6.4	1.6	2.4	2.4	20

[3] Zeng, Z., & Sharma, A. (2023).Aerodynamic-whistles-based ultrasonic tone generators for bat deterrence. *Physics of Fluids*, *35*(9).

Active whistles: Experiments

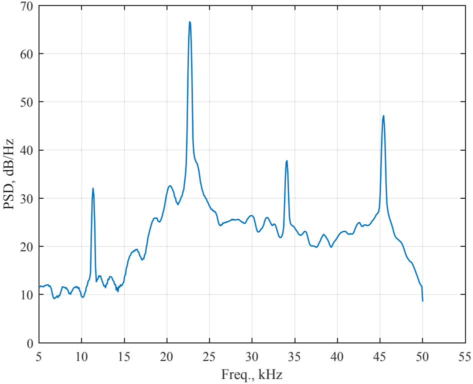
Experiment setup



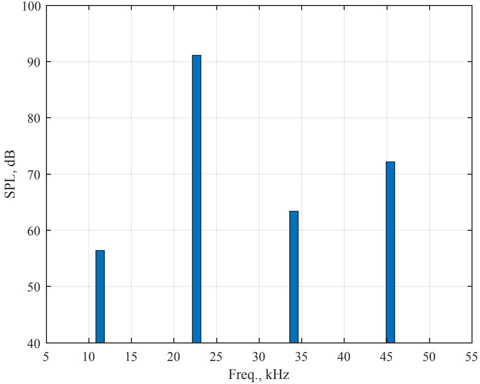
Experiment setup

- Lab air → filters → pressure → flow measurement → whistle
- Flow $M \ll 1$ → gauge pressure $\sim p_t$
- Farfield sound measurements on a circular arc
- B&K 4939 mic + signal conditioning (B&K 2690) 20 Hz $< f <$ 50 kHz

Measurement results



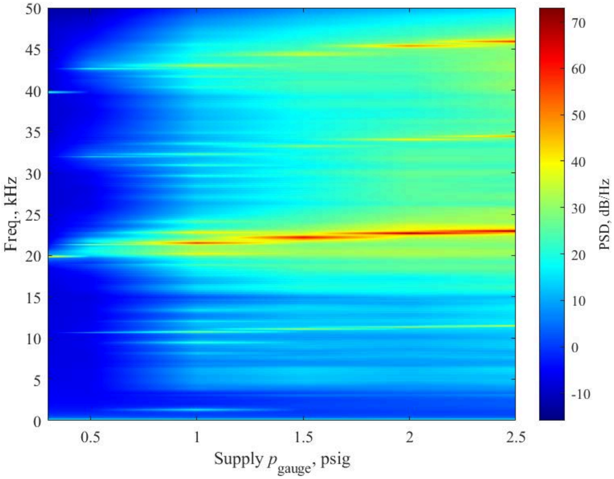
PSD spectrum



SPL of tones

Typical far-field sound spectrum of the baseline whistle, at supply pressure, $p_t = 2.0$ *psig.*

Radiated ultrasound: “spectrogram”



PSD spectra variation with supply air pressure (p_t)

Active whistles: Simulations

Governing equations

Flow equations

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_j) = 0$$

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{u}_i) + \frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_i\tilde{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(\bar{\tau}_{ij} - \overline{\rho u_i'' u_j''})$$

Acoustic equations

$$\left(\frac{\partial^2}{\partial t^2} - c_o^2 \frac{\partial^2}{\partial x_i \partial x_i}\right)(H(f)\rho') = \frac{\partial^2}{\partial x_i \partial x_j}(T_{ij}H(f)) - \frac{\partial}{\partial x_i}(F_i\delta(f)) + \frac{\partial}{\partial t}(Q\delta(f))$$

$$T_{ij} = \rho u_i u_j + P_{ij} - c_o^2\rho'\delta_{ij},$$

$$F_i = (P_{ij} + \rho u_i(u_j - v_j))\partial f/\partial x_j,$$

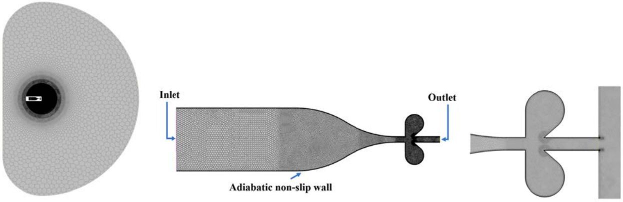
$$Q = (\rho_o v_i + \rho(u_i - v_i))\partial f/\partial x_j.$$

Numerical approach

- Compressible uRANS + low-speed preconditioning
- *Time discretization*: 2nd-order implicit dual-time stepping
- *Spatial discretization*: 2nd-order MUSCL-based Roe
- *Turbulence*: $k-\omega$ SST
- *Boundary conditions*:
  - Inlet: total conditions (p_t, T_t)
  - Outlet: static p_∞
  - Wall: no-slip, adiabatic
- *Acoustics solver*: time-domain, Farassat-1A formulation[4]

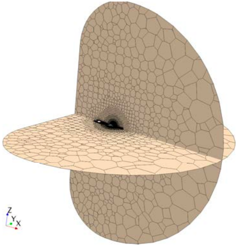
[4] Farassat, F. (2007). *Derivation of formulations 1 and 1a of farassat* (tech. rep. No. NASA/TM-2007-214853). NASA Langley Research Center.

Computational mesh

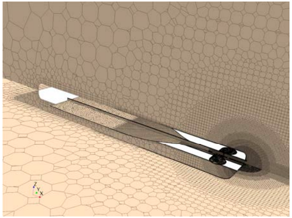


(a) 2D-CFD domain (b) whistle-interior mesh (c) interface

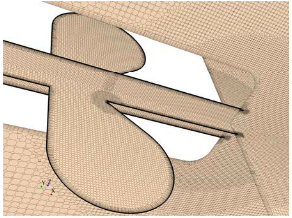
2D mesh



absorbing chamber



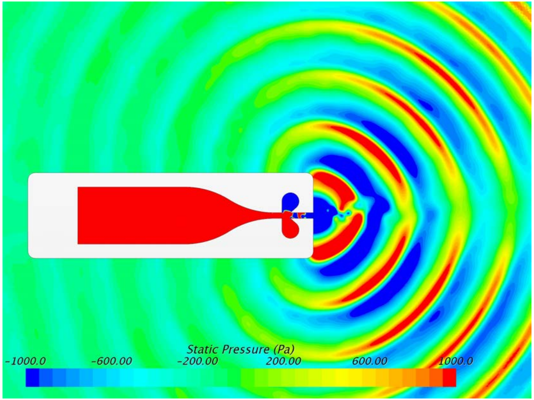
mesh inside the whistle



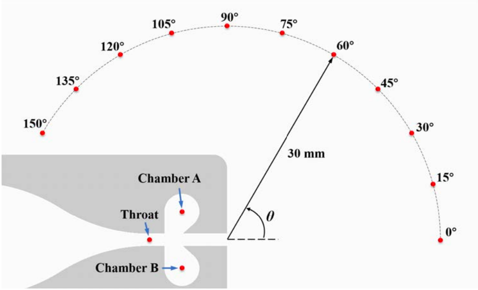
zoom view of the resonators

3D mesh

Numerical results



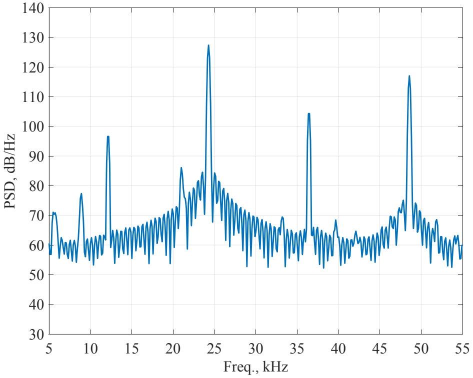
instantaneous pressure contours



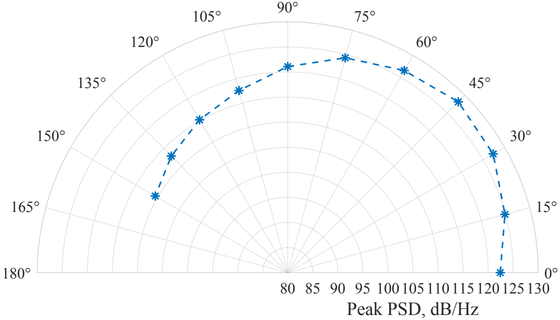
probe locations

Strong tonal ultrasound radiation

Numerical results



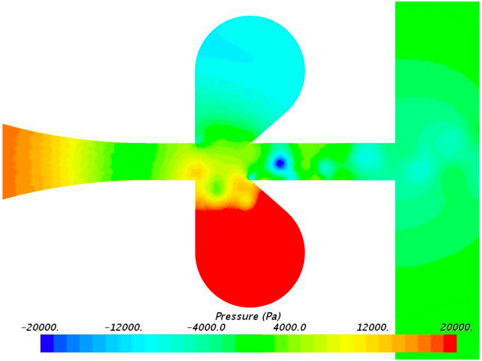
PSD of radiated sound at 30° polar angle



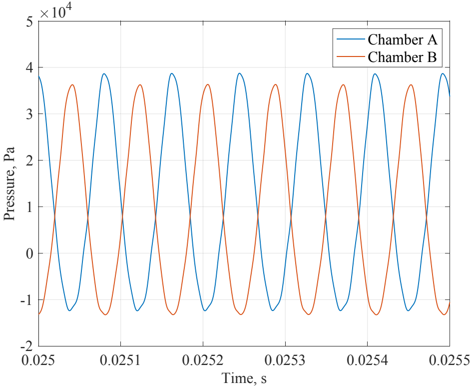
directivity of radiated sound

$f_{\text{peak,farfield}} \sim$ 24 kHz + harmonics; radiation downstream dominated

Out-of-phase chambers



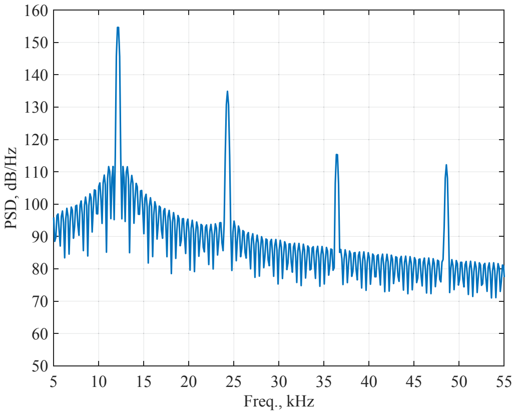
pressure field in the resonators



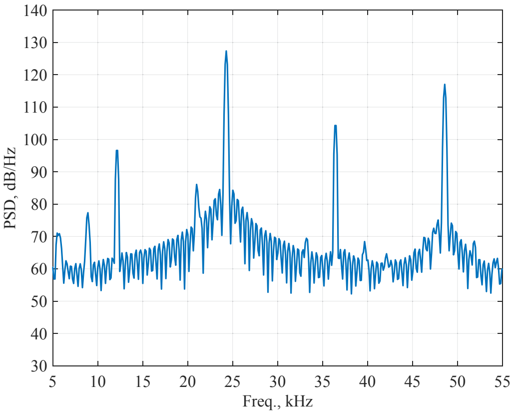
temporal variation of pressure in the chambers

Phase cancellation → radiation at $2 \times f_{\text{peak,chamber}}$

Pressure spectra



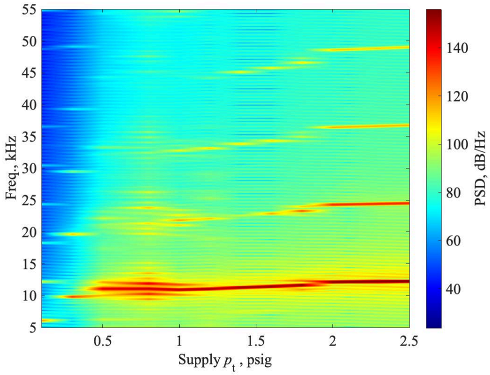
chamber center



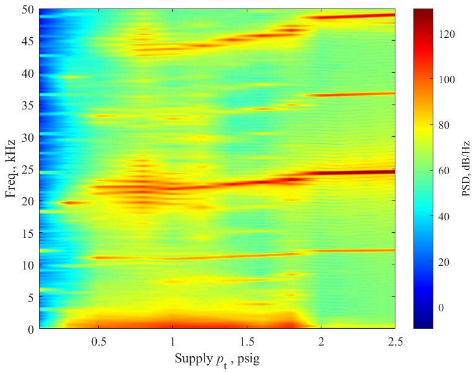
far-field

Imperfect phase cancellation → small peaks at subharmonics

PSD variation with p_t



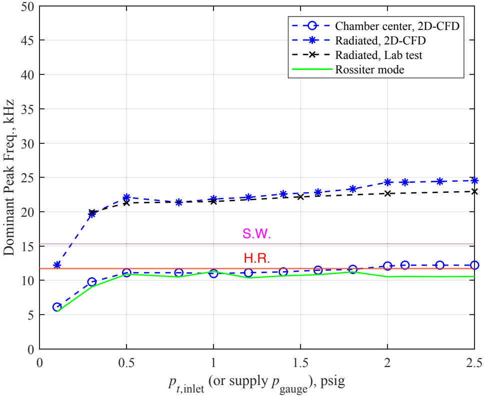
chamber center



radiated ultrasound in the far-field

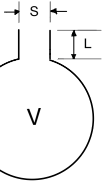
Radiation over a large range of p_t

Ultrasound generation mechanism

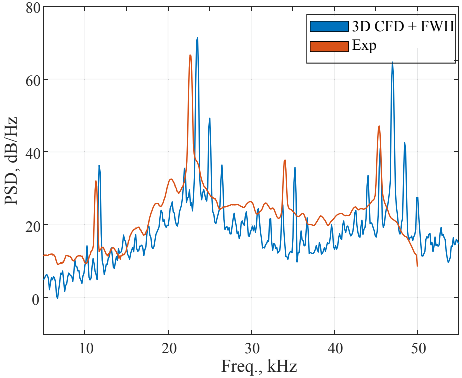


f_{peak} vs. p_t and theoretical estimates

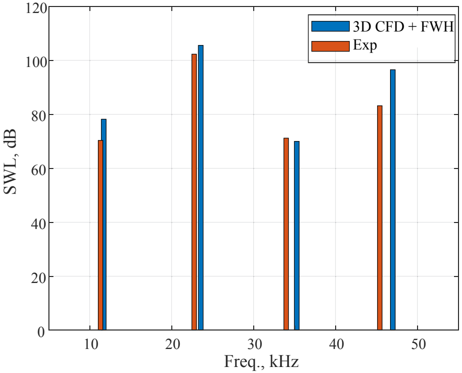
- Rossiter & Helmholtz resonance freqs. coincide
- Sound generation mechanism(s):
  1. Helmholtz resonance
  2. Rossiter modes



Verification



pressure PSD spectra



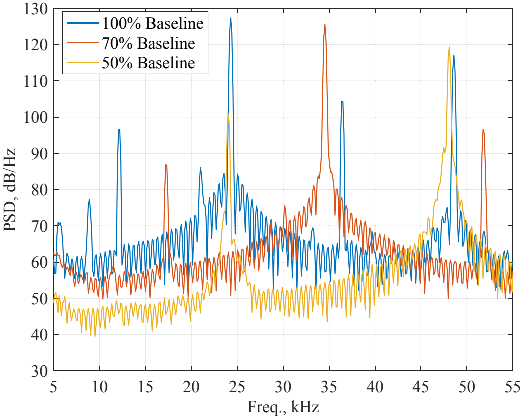
radiated acoustic power PSD

Good agreement[5]: PSD spectra and radiated power

[5] Zeng, Z., & Sharma, A. (2023).Aerodynamic-whistles-based ultrasonic tone generators for bat deterrence. *Physics of Fluids*, *35*(9).

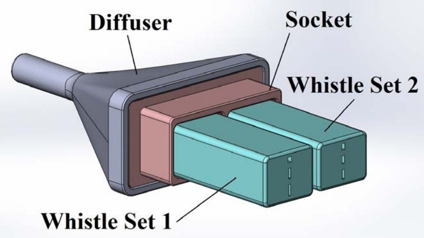
Spectral coverage

Geometrically scale whistles → change f_{peak}



multiple whistles → broad spectral coverage

Six-whistle deterrent

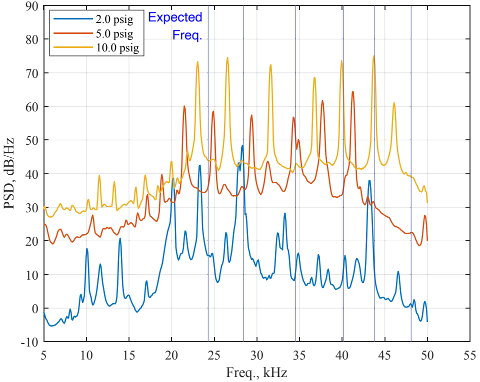


CAD model

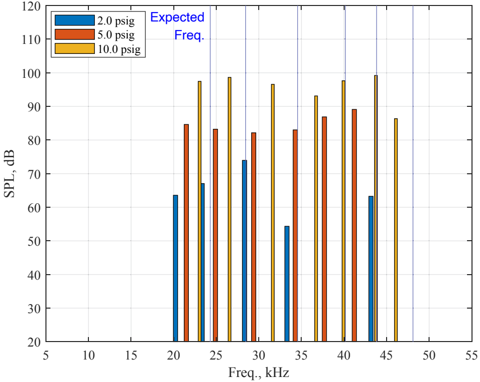
3D-printed specimen

A six-whistle active ultrasonic deterrent

Six-whistle deterrent measurements



PSD spectra



SPL spectra

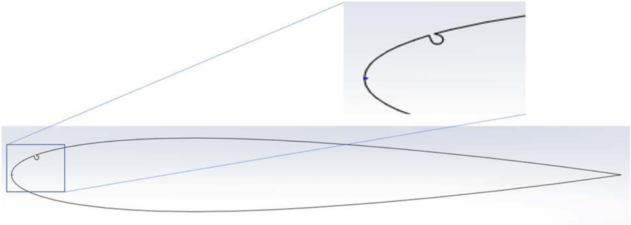
Good spectral coverage obtained using multiple whistles

Passive whistles

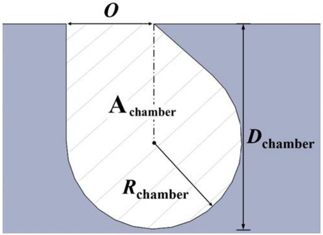
Passive whistle design

Concept

Use blade-relative flow to excite cavity resonance

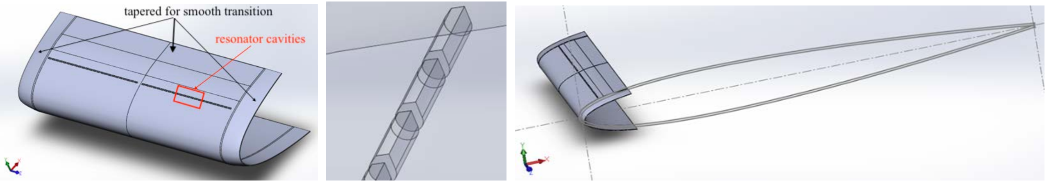


Passive whistle



Design parameters

CAD model



Whistles printed on a sleeve *Zoomed view* *Sleeve mounted on an airfoil*

Computer model of the passive deterrent design

- "Sleeve" design for wind tunnel safety
- Test different deterrents on same baseline airfoil model
- 3D printing → inexpensive

Passive whistles: Experiments

Deterrent model

Rapid prototyping

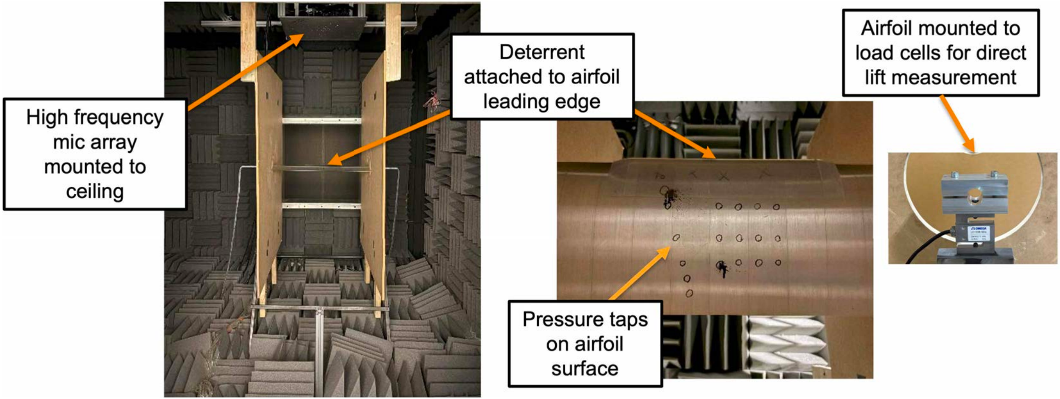
- 3D-printed resin
- Several resonators closely spaced
- Printer constraints → multiple parts
- End parts (3&4) tapered for aero

Two deterrents

1. Low-freq (LF): $f_{\text{peak}} \sim 12$ kHz
2. High-freq (HF): $f_{\text{peak}} \sim 24$ kHz

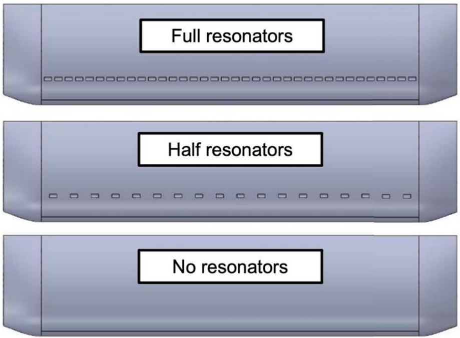
Virginia Tech SMART facility

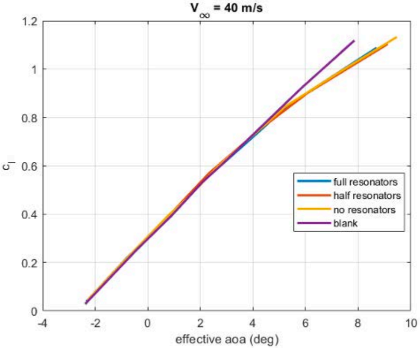
VT Subsonic Modular Anechoic Research Tunnel (SMART)



- Measure aero performance & acoustics
- Low max speed $\rightarrow$ LF deterrent only
- Explore bigger design space

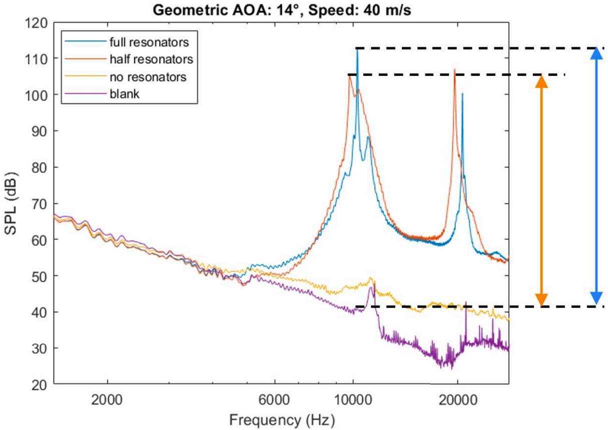
Aero impact





C_l impacted by the sleeve, not by the resonators

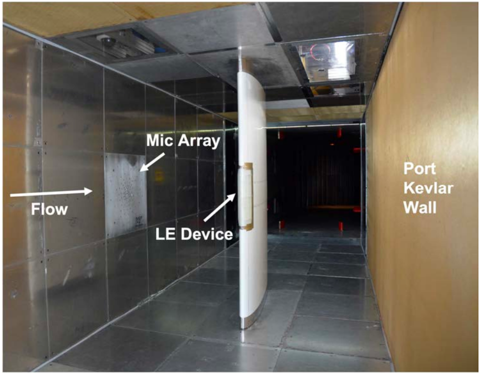
Acoustics



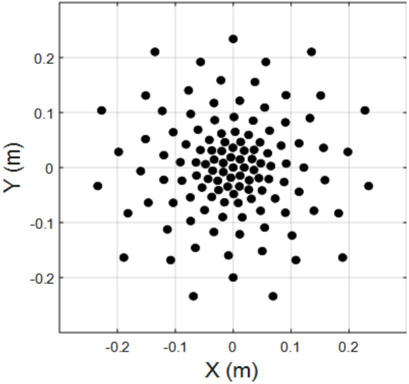
- Only the LF deterrent tested
- Both "full" and "half" resonator configurations produce significant tonal sounds

Robust and loud tonal acoustic radiation

Virginia Tech Stability Wind Tunnel



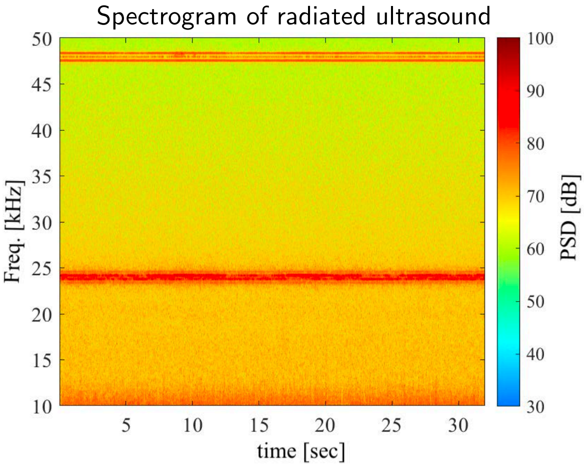
Stability Wind Tunnel



Microphone array

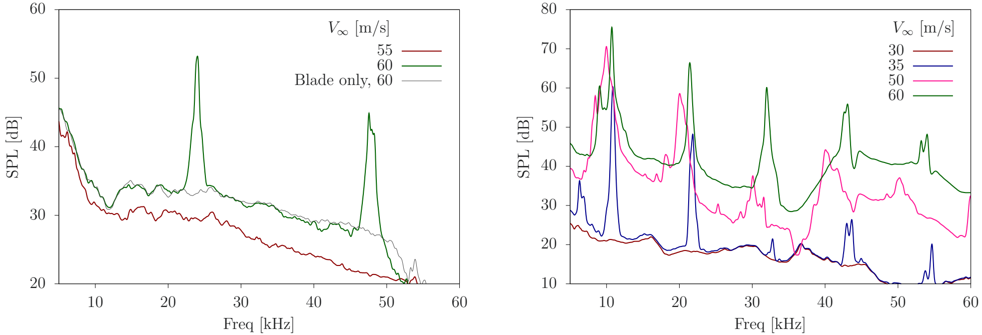
- Acoustic measurements only
- 65m/s max speed $\rightarrow$ HF & LF deterrents
- Phased-array for acoustic source diagnostics

Measured spectrograms



- *Steady* radiation
- $f_{\text{peak}} \sim 24$ kHz; harmonic ~ 48 kHz
- **No subharmonics**
- Operating conditions:
  - $V_\infty = 60$ m/s
  - $\alpha = 0^\circ$

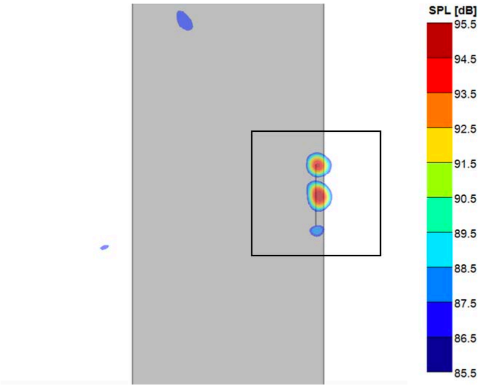
Variation with speed



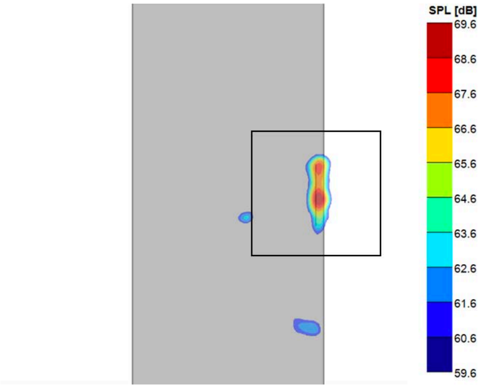
HF deterrent *LF deterrent*

- $V_\infty = 30, 35, 50, 55, 60$ m/s
- Baseline blade (no deterrent) $\rightarrow$ no ultrasonic tones
- HF deterrent *cut-on* for $V_\infty \geq 60$ m/s; LF cut-on for $V_\infty \geq 35$ m/s

Source diagnostics: acoustic beamforming



10.6 kHz

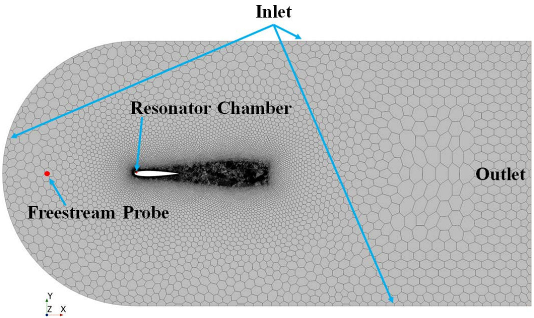


11.2 kHz

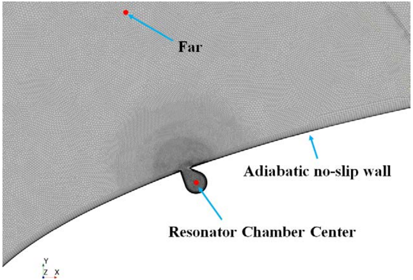
- $V_\infty = 60$ m/s and $\alpha = 0°$
- Acoustic hotspots over deterrents

Passive whistles: Simulations

Computational mesh



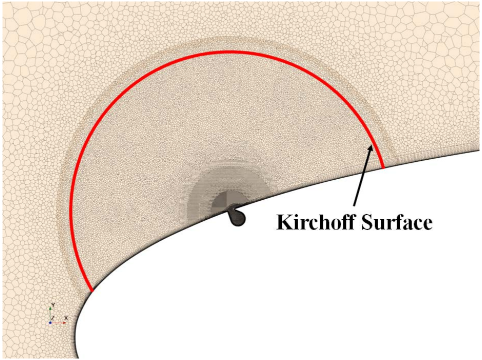
CFD domain



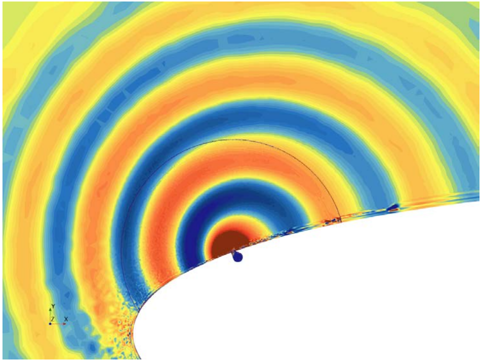
resonating cavity

- Mesh designed to capture flow around the resonator
- Farfield mesh coarse → dissipate acoustic wave . . . reduce reflections
- Use FW-H to predict farfield ultrasound

Ultrasound radiation (visualization)



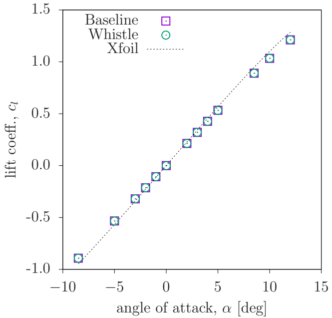
Kirchoff surface



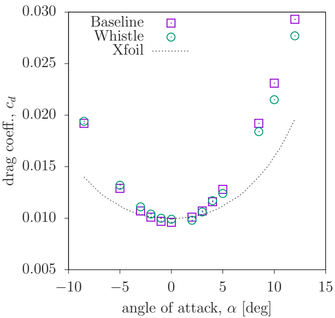
radiating ultrasound

- Integration (Kirchoff) surface for noise prediction
- Radiated ultrasound field

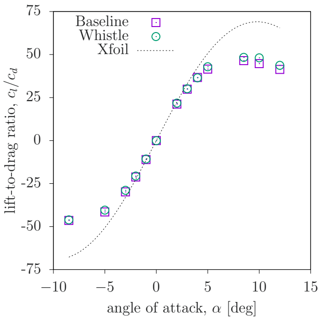
Aerodynamic impact assessment (simulations)



lift coefficient, c_l



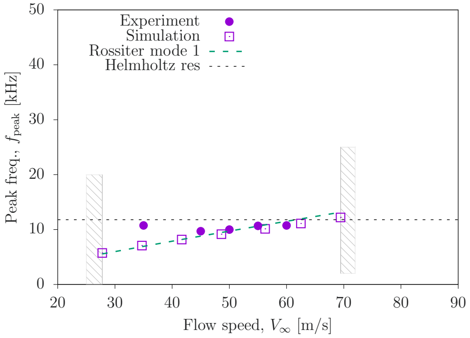
drag coefficient, c_d



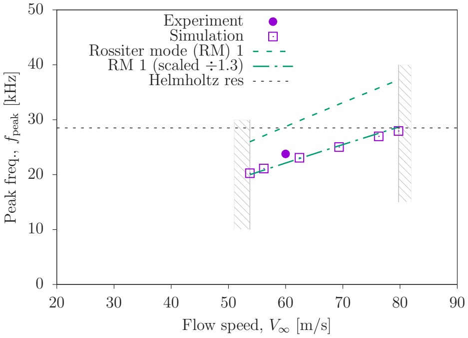
lift-to-drag ratio

Negligible adverse impact if deterrents “embedded” in blades

Mechanism of ultrasound generation



LF

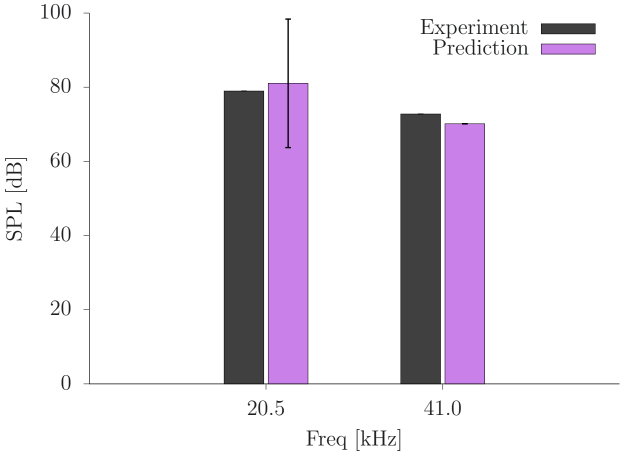


HF

- Variation of f_{peak} with V_∞ for the LF and HF deterrents
- Predictions align with theoretical Rossiter modes

Ultrasound generation due to Rossiter modes

Verification[6]



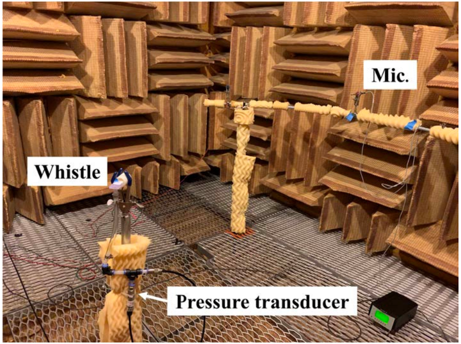
Tone SPLs

- SPLs 1 m away from source
- Fundamental (20.5 kHz) and the second harmonic (41 kHz)
- Predictions corrected for atmospheric absorption

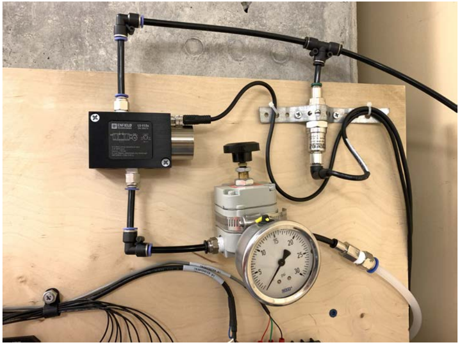
[6] Zeng, Z., Huang, S.-F., Alexander, W. N., & Sharma, A. (2025).A passive, blade-mounted ultrasonic bat deterrent for wind turbines. *Applied Acoustics*, *229*, 110392.

Signal modulation

Deterrence signal modulation[7]



setup in the anechoic chamber

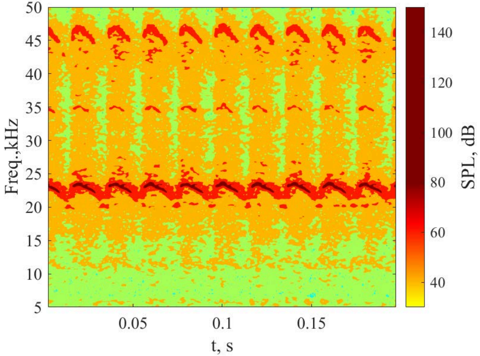


equipment to modulate supply pressure

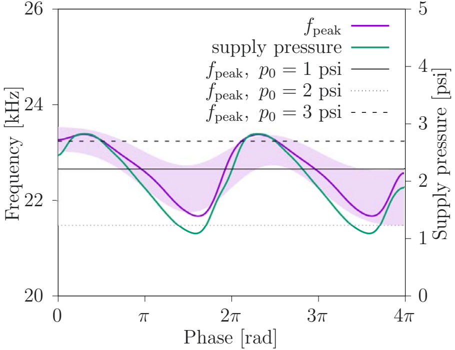
- Supply air pressure modulated periodically
- Supply pressure & flow rate monitored

[7] Zeng, Z., & Sharma, A. (2025).Frequency modulation of an aerodynamic whistle-based bat deterrent. *Applied Acoustics*, *228*, 110276.

Modulation results: experiments



Farfield pressure spectrogram



f_{peak} and p_t variation

- $f_m = 50$ Hz, $p_m = 1.0$ psi, sine-wave modulation
- Frequency modulation possible; larger Δf desirable

Simple approach to modulate deterrence signal

Conclusions & future work

Conclusions

- Demonstrated ultrasonic tone generation via aerodynamic whistles
- Methods:
  - *Simulations:* CFD (uRANS) + acoustic analogy (FW-H)
  - *Experiments:* ISU anechoic chamber, VPI tunnels: Stability & SMART
- Developed *active* & *passive* ultrasonic deterrents
- **Active** designs:
  - Nacelle/tower mounted w/ compressed air supply
  - Demonstrated ultrasound generation over a range of p_t
  - Sound generation mechanism: *Helmholtz resonance*
  - Spectral coverage: geom. scale & combine whistles
  - Demonstrated *signal modulation* . . . reduce habituation
- **Passive** designs:
  - Blade mounted
  - Sound generation mechanism: *Rossiter modes*
  - Work for $V > V_{\mathrm{cut-off}}$
  - Verified simulation methodology

Future work

- Deterrent optimization for maximum intensity ultrasound radiation
- Laboratory (Stability wind tunnel) testing (planned):
  - Aero impact with the HF deterrent
  - Understand coupling between resonators
  - Sound source diagnostics
- Full-scale testing (planned):
  - SAFL UMN 2.5 MW full-scale wind turbine
  - Measure SCADA data + ultrasound generation
- Impact on bats (not yet planned)
  - Controlled lab tests
  - Field tests

Publications

Journal

1. Zeng, Z., & Sharma, A. (2025).Frequency modulation of an aerodynamic whistle-based bat deterrent. *Applied Acoustics*, *228*, 110276
2. Zeng, Z., Huang, S.-F., Alexander, W. N., & Sharma, A. (2025).A passive, blade-mounted ultrasonic bat deterrent for wind turbines. *Applied Acoustics*, *229*, 110392
3. Zeng, Z., & Sharma, A. (2023).Aerodynamic-whistles-based ultrasonic tone generators for bat deterrence. *Physics of Fluids*, *35*(9)

Conference

1. Zeng, Z., Sharma, A., S-F., H., & Alexander, W. N. (2022).Passive operation of a blade-mounted, ultrasonic bat deterrent using an exhaust diffuser. *28th AIAA/CEAS Aeroacoustics 2022 Conference*, 3101
2. Zeng, Z., & Sharma, A. (2021).Experimental and numerical aeroacoustic analysis of an ultrasound whistle. *AIAA Aviation Forum*

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Questions?

Anupam Sharma | sharma@iastate.edu
www.aere.iastate.edu/sharma