Particle Image Velocimetry (PIV) Investigation of Drag in a Tunable Helmholtz Resonator Array under Grazing Flow

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Motivation

It is well-known that drag and noise reduce performance and efficiency in commercial aircraft. Building on the successful results of Boeing's perforated trailing-edge design, this project advances the concept by **optimizing perforation geometry** to enable broader flow control and enhanced noise reduction. This research focuses on Helmholtz Resonators (HRs) in particular.

Innovation

- **Noise Reduction:** Geometric tuning of resonator-lined surfaces attenuates turbulence-induced noise across a range of frequencies. Pertaining to take-off and landing, our target frequency is ~1000 Hz.
- **Efficiency:** Lowering drag and actuation power contributes to Boeing's 55% greenhouse emission reduction by 2030.

Approach

- This work is **funded by JCATI (Joint Center Aerospace Technology Innovation).**
- Computational and experimental analyses of HR-lined surfaces are conducted in collaboration with Boeing's aeroacoustics R&D team.
  - The computational team (Prof. Habtour, Julius Naehrig) uses COMSOL to model fluid-structure and acoustic-structure interactions and optimize resonator design for drag and noise reduction.
  - The experimental team (Prof. Dabiri, Federico Baldan, Jeffery Zhang) uses a benchtop wind tunnel, a series of acoustic microphones, and 3D-PIV to validate the models.

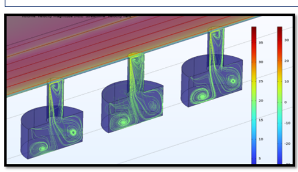


Figure 1: COMSOL Simulation of Flow Streamlines within Helmholtz Resonators

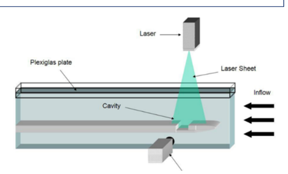


Figure 2: PIV Setup of Cavity Flow (Haigemoser et al.)

Project Description

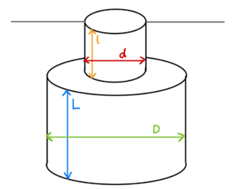


Figure 3: Schematic of a Helmholtz Resonator

A **Helmholtz Resonator (HR)** attenuates specific sound frequencies by acting as a mass-spring system.

- The neck (diameter d, length l) contains a plug of air that acts as a vibrating mass-spring system.
- When sound at the resonant frequency enters, the air mass of air oscillates, which in turn absorbs and dissipates acoustic energy. The resonant frequency has a closed-form, analytical solution for the cylindrical configuration.

Computational Modeling

- As of now, damping coefficients and coupling effects between freestream-aligned resonators have been characterized. The goal is to maximize these coefficients (proxies to acoustic efficiency) by adjusting the space between HRs.
- Efforts now focus on characterizing the cross-sectional boundary layer to evaluate drag effects.

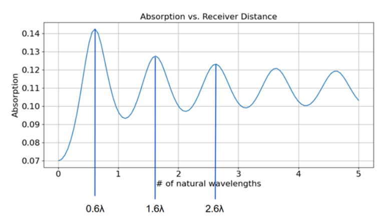


Figure 3: 3D Plot of Resonator Coupling Phenomenon. Absorptivity vs. Distance btw. HRs

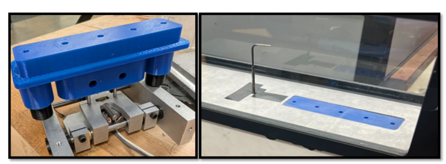
$$\eta_{c_{ij}} = \frac{d_{N_j}^4}{d_{N_i}^3} \frac{\sqrt{V_{c_i} l_{N_i}/\pi}}{8 l_{N_i}} \left(\frac{w_j}{c}\right)^2 H_2^{(0)}\left(\frac{d_R w_j}{c}\right)$$

$$\mu_i = \sqrt{\frac{V_{c_i} l_{N_i}}{\pi}} \left(\frac{d_{N_i}\omega_i^2}{8 l_{N_i} c^2} + \frac{4}{d_{N_i}^2 c}\sqrt{\frac{\nu\omega_i}{2}}\right)$$

Eq. 1: Normalized Characteristic Eqns. for Damping and Coupling Coefficients

Experimental Setup

- Experimental Setup was successfully fabricated and integrated within the JetStream 500 subsonic wind tunnel. Now setting up PIV measurement system and integrating microphones to be flush w/ top of test section.
- After running PIV, the results will be validated w/ previous PIV from Hassanein et al. (2024), Ghaemi et al. (2012), and others.
- Strategic placement of acoustic microphones still underway.



Figures 4 & 5: Experimental Setup of 5x1 HR Array Config.

Anticipated Impact

- These systems support Boeing's goals by contributing to Boeing's commitment to a 55% Greenhouse emission reduction by 2030 and compliance with future acoustic standards as they become more and more strict.
- This approach is generalizable to VTOLs, UAVs, and noise-sensitive transport systems, helping reduce environmental noise in urban and airport areas.

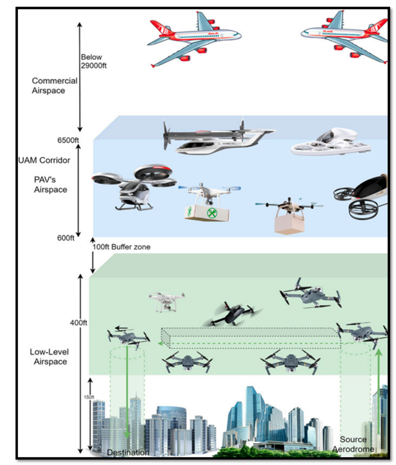


Figure 7: Urban Air Traffic Management at different Altitude Regimes (Shrestha, et al.)

Path Forward

- Definitively quantify the trade-off between acoustic and aerodynamic performance.
- Evaluate the HRs' performance for different angles of attack (AoA).
- Evaluate acoustic and aerodynamic behavior in different atmospheric conditions and flow regimes.
- Develop solutions for HR geometry when geometric constraints are present.
- Develop active control systems to change the HRs' dimensions during different stages of flight.