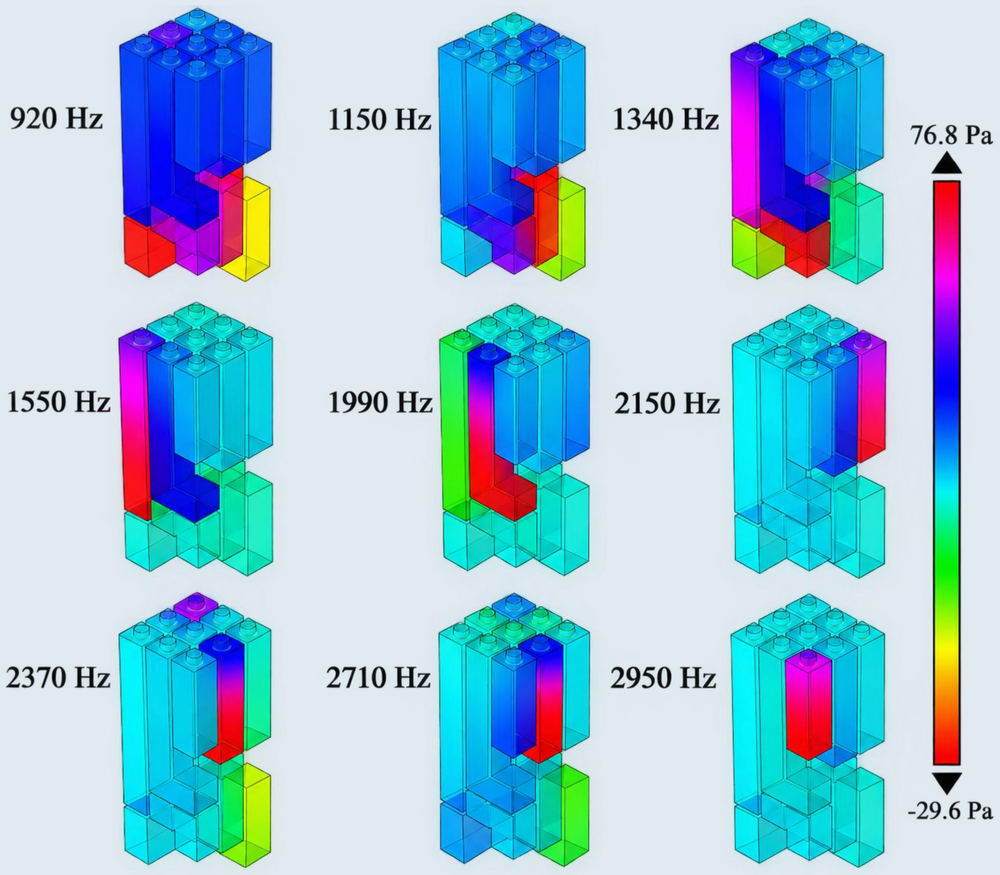


Numerical Study of Broadband Absorption in Weakly Coupled Helmholtz Resonator Metasurfaces

This study introduced weakly coupled Helmholtz resonators that use inter-cavity perforations to couple adjacent resonances, creating overlapping modes and a continuous broadband absorption response. A multi-cavity network further improves impedance matching, enabling high absorption over a wide frequency range within a thin structure.

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Introduction and Background

Noise pollution across the 20 Hz-20 kHz spectrum imposes a cumulative health burden: low-frequency noise causes vibrations, sleep disturbance and stress; mid-frequency noise interferes with speech, learning and productivity; high-frequency noise can damage hearing.

Traditional Helmholtz-resonator (HR) absorbers remain limited:

- Narrowband — effective only near resonance (single peak)
- Fixed frequency response; cannot adapt to varying conditions
- Multiple HRs needed for bandwidth → high cost / space
- Weak coupling criteria for parallel/series HRs not quantified

Motivation and Objectives

- Break the 500–1500 Hz narrow-band limit of conventional HRs for multi-tonal noise control.
- Resolve the broadband absorption vs. space-thickness trade-off under harsh environments.
- Design a parallel HR metasurface: optimized perforation merging resonance peaks into continuous broadband absorption.
- Validate weak coupling via ultra-low porosity & perforation sensitivity.
- Target: avg. α ≥ 0.9 over 500–3000 Hz in minimum thickness.

Methodologies

- Weak-coupling condition:

$$\frac{l'_p}{S_p} \sim O\left(\frac{l'_{n1}}{S_{n1}} + \frac{l'_{n2}}{S_{n2}}\right) \quad (1)$$

- Small orifice balances acoustic resistance & reactance → near-unity absorption between resonance peaks.
- In the absence of a mean flow, the specific expression of the dimensionless impedance is as follows:

$$\hat{Z}_{Total} = \frac{S_d\left\{\left(1+\frac{i\omega V_1}{\rho c^2}\frac{Z_{n1}}{S_{n1}}\right)\left(1+\frac{i\omega V_2}{\rho c^2}\frac{Z_{n2}}{S_{n2}}\right)+\frac{S_p}{Z_p}\left[\frac{Z_{n1}}{S_{n1}}+\frac{Z_{n2}}{S_{n2}}+\frac{Z_{n1}}{S_{n1}}\frac{Z_{n2}}{S_{n2}}\frac{i\omega(V_1+V_2)}{\rho c^2}\right]\right\}}{\rho c\left\{\left(\frac{Z_{n1}}{S_{n1}}+\frac{Z_{n2}}{S_{n2}}\right)\frac{i\omega(V_1+V_2)}{\rho c^2}\frac{S_p}{Z_p}+\frac{i\omega(V_1+V_2)}{\rho c^2}+\left(\frac{Z_{n1}}{S_{n1}}+\frac{Z_{n2}}{S_{n2}}\right)\frac{i\omega V_1}{\rho c^2}\frac{i\omega V_2}{\rho c^2}\right\}} \quad (2)$$

- Perfect absorption: Re(Ẑ) = 1, Im(Ẑ) = 0 (impedance matched to air)

$$\alpha = \frac{4\,\mathrm{Re}(\hat{Z}_{Total})}{(\mathrm{Re}(\hat{Z}_{Total})+1)^2+\mathrm{Im}(\hat{Z}_{Total})^2} \quad (3)$$

- **Design strategy:** Dual parallel HRs coupled by micro-perforation → 9 parallel-arranged HRs unit cell (30 mm dia., 57 mm high) → 5 unit cells → Metasurface (60 mm dia.
- **Structure:** back cavity chambers + front panel with variable apertures
- **Unit cell:** four pairs of dual HRs + one single HR (6 mm side each), interconnected by small perforations (d_p = 0.5 mm, l_p = 1 mm)
- Broadband metasurfaces designed for infinite expansion in practical applications.

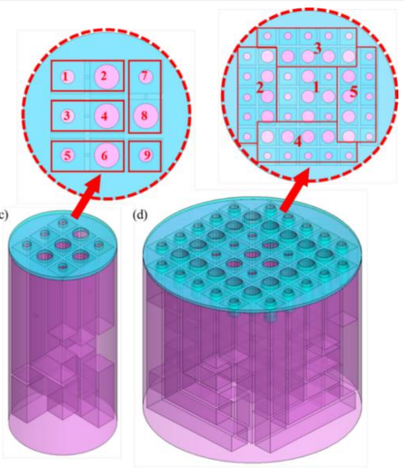


Figure. 1- Schematic diagram of the proposed acoustic metasurface structure: (a) 2D view of the basic unit of dual HRs with micro perforation, (b) 3D model of the dual HRs with small perforation, (c) 3D model of the parallel-arranged multiple HRs based metamaterial unit cell, and (d) 3D model of multi-mixed parallel-arranged acoustic metasurface structure.

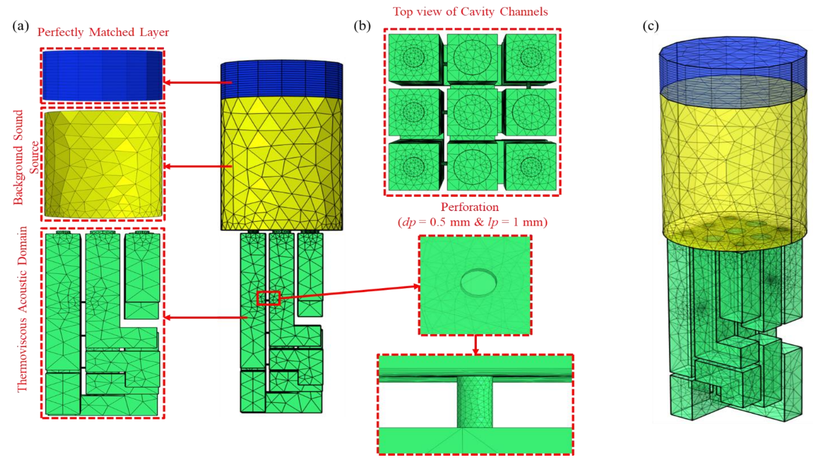


Figure 2- 3D finite element simulation model for the parallel-arranged HRs acoustic metamaterial unit cell in COMSOL Multiphysics. (a) complete numerical simulation details with suitable boundary conditions, (b) top view of the model with relevant parameters, (c) complete numerical simulation mesh model.

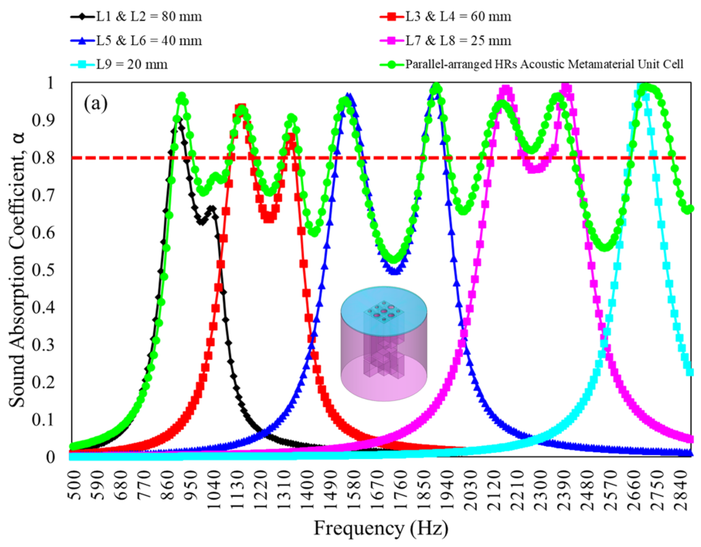


Figure 3- Comparison and distributions of sound absorption coefficients of the optimized dual-HRs pairs with variable cavity-based unit cells and parallel-arranged acoustic metamaterial unit cell, for the target with all the sound absorption coefficients above 0.9.

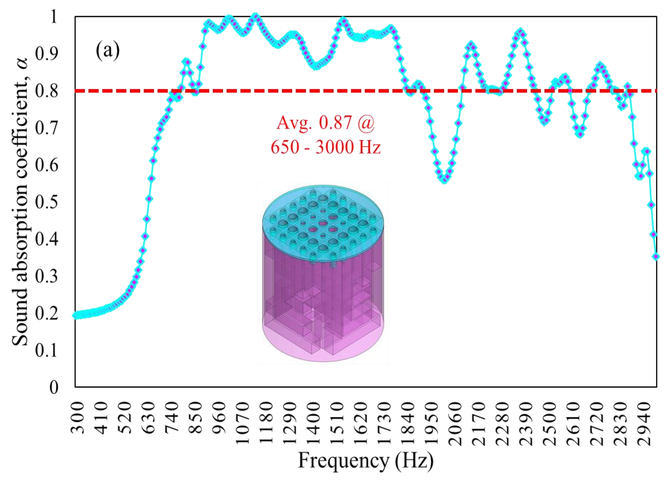


Figure 4- Sound absorption performance of the mixed multi-cavity parallel-arranged HRs acoustic metasurface, highlighting performance where all coefficients exceed 0.9.

Results

- A small, optimally tuned perforation between adjacent cavities can smooth the acoustic impedance transition across resonance frequencies, thereby bridging absorption peaks and expanding effective bandwidth.

The optimum ratio of the cross-sectional area to the effective length of the orifices should be of the same order of magnitude as that of the resonator necks.

- Nine-HR metamaterial unit cell: **avg. α = 0.82 @ 750–3000 Hz**
- Multi-cavity metasurface: **avg. α = 0.85 @ 750–3000 Hz in 57 mm**
- Mixed-cavity metasurface: **avg. α = 0.87 @ 650–3000 Hz in 57 mm** — ≥55% wider bandwidth than prior designs.
- Continuous Broadband absorption, Overlapping Resonance Bands, and Enhanced Low-to-mid frequency performance without thickness added.

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