Metamaterial-Based Noise Control Strategies for Residential Heat Pump Ventilation Ducts: Methods and Design Principles

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Abstract

Residential heat pumps introduce significant low-frequency aerodynamic and mechanical noise into indoor and outdoor environments, especially through compact ventilation ducts. Conventional duct silencers are often too bulky, prone to degradation, or introduce unacceptable pressure drops. Acoustic metamaterials (AMMs) offer a promising alternative due to their subwavelength behaviour, design flexibility, and ability to maintain ventilation while delivering substantial attenuation in the 31.5–2000 Hz range relevant to heat pumps. This paper presents a focused synthesis of metamaterial mechanisms, modelling approaches, and performance data framed specifically for applications in residential heat pump acoustics. The discussion emphasises the performance of resonant cavities, micro-perforated panels, membranes and interference-based structures under realistic flow conditions, including the influence of Mach number, turbulence, and duct geometry. The paper further outlines recommended modelling practices, integration strategies, and research gaps that must be addressed for widespread adoption of AMM-based silencers in heat pump ventilation systems.

Keywords: acoustic metamaterials, heat pumps, duct acoustics, low-frequency noise, aeroacoustics

1. Introduction

The widespread deployment of residential heat pumps across Europe has brought renewed attention to the acoustic impact of ventilation ducts associated with their outdoor units, façade penetrations and supply-exhaust modules. These systems generate tonal and broadband noise dominated by fan harmonics (31.5–125 Hz), compressor-related low-frequency emissions, and turbulence-induced fluctuations extending up to approximately 2000 Hz [1]. When radiated or transmitted through ducts, such emissions can compromise indoor acoustic comfort and acoustic façade performance. It is worth clarifying the range of configurations in which ventilation ducts arise in residential heat pump installations. Air-to-air and air-to-water heat pumps with split outdoor units typically connect to indoor spaces through short wall-penetrating supply and exhaust ducts, which carry both airflow and structure-borne noise from the outdoor unit into the building envelope. Ducted heat pump systems (including central air handlers and mechanical ventilation with heat recovery (MVHR) units) distribute conditioned air through an internal duct network, where fan and compressor noise propagates along the ductwork and radiates into occupied rooms. In both cases, the ventilation duct is the primary noise transmission path between the acoustic source (outdoor unit or air handler) and the receiver (indoor living spaces), and it is this path that the present paper addresses.

Traditional silencers are rarely suitable for compact residential installations. Porous absorbers degrade under humidity and dust; micro-perforated panels, although durable, require careful tuning and may not attenuate sufficiently at very low frequencies; and large reactive silencers are incompatible with the limited installation space available in residential external walls [2], [3]. Furthermore, any acoustic treatment must not cause a substantial pressure drop, as ventilation efficiency directly affects the seasonal performance factor (SPF) of heat pumps.

Acoustic metamaterials (AMMs) address these challenges through geometrically engineered unit cells that achieve strong reactive or dissipative effects at subwavelength scales [4], [5]. In the last twenty years, the trend of scientific peer-reviewed studies including the keywords “ducts” or “holed plates” with “acoustic metamaterials” or “Helmholtz resonators,” and “airflow” or “fluid dynamics” has significantly increased

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(see Fig. 1). Their ability to allow airflow while suppressing targeted frequencies makes them particularly suited for heat pump ventilation ducts [6]. The following sections summarise the most relevant results, principles and methodological insights reported in the comprehensive review by Fusaro et al. [7], with a focus on their applicability to heat pump acoustics.

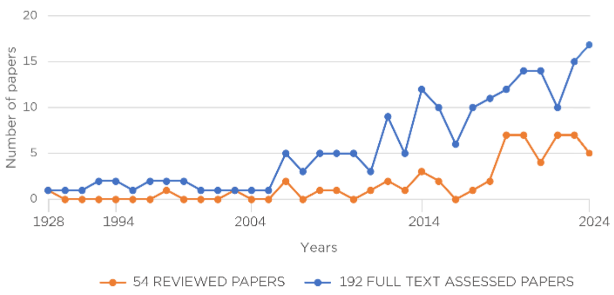

Figure 1. Trend of peer-reviewed studies combining duct acoustics keywords with acoustic metamaterials and airflow topics, based on a systematic survey of 192 full-text papers assessed between 1928 and 2024 (54 meeting inclusion criteria).

2. Metamaterial principles for residential heat pump ducts

Among the metamaterial principles identified across the 54 studies reviewed between 1928 and 2024, four mechanisms stand out as highly compatible with residential heat-pump installations.

Resonant cavities (including Helmholtz, coiled-up and labyrinthine structures) are the most extensively used solutions [8]–[10]. Their geometry allows accurate tuning toward low-frequency bands characteristic of heat-pump fans and compressors, protecting indoor environments against external heat pump sounds. Coiled geometries achieve long acoustic paths within minimal thickness, and labyrinthine channels combine reactive behaviour with appreciable viscothermal losses, especially when incorporated into compact duct modules [10], [11]. Practical results reported in the literature show transmission loss values between roughly 8 and 30 dB over frequency bands of direct interest for heat pump devices. To clarify how resonant cavities can be tuned to the dominant low-frequency components generated by heat-pump fans and compressors, the resonance frequency may be estimated using the classical Helmholtz relation shown in Eq. (1).

$$f_c = \frac{c}{2\pi}\sqrt{\frac{A}{V L_{eff}}} \tag{1}$$

where A is the neck cross-sectional area, V is the cavity volume, L_{eff} is the effective neck length (includes end corrections), and c is the speed of sound.

Micro-perforated panels (MPPs) offer robust and hygienic resistance-based attenuation in the 200–2000 Hz interval, where turbulence and duct-borne broadband noise typically dominate [12]. In contrast to porous linings, MPPs maintain their properties under variations in humidity and dust loading. When coupled with appropriately sized back cavities, they provide extended low-frequency performance and can be integrated into thin façade-mounted duct sections.

Membrane-type AMMs constitute another compact solution that is particularly effective between 50 and 900 Hz [2]. Their tunable compliance and mass allow designers to address prominent low-frequency tonal components, including those produced by rotating equipment in heat pumps. Experimental studies demonstrate reductions in transmitted sound pressure level reaching 10–15 dB within restricted geometrical envelopes.

A further category relevant to residential ducts is represented by interference-based structures such as Fano-like resonators and metacages. These exploit abrupt impedance contrasts across adjacent regions to produce destructive interference, enabling high transmission loss-often above 25 dB-without meaningfully obstructing the flow [13], [14]. Their effectiveness over broad frequency bands and the possibility of accommodating large openings make them suitable for ventilated façade elements.

3. Flow-acoustic interactions and their relevance to heat pumps

Because residential heat pump ducts operate under non-negligible mean flow, the interaction between fluid motion and metamaterial performance must be considered. Mach numbers typically remain below 0.2, though even values around 0.05 can shift resonance frequencies, alter impedance, and reduce the peak performance of resonant cavities. Turbulent flow regimes characteristic of Reynolds numbers above 2300 change the velocity distribution and influence the rotational components of the acoustic field. These phenomena require multi-physical simulations rather than purely acoustic ones. Since even modest ventilation velocities can modify the acoustic impedance of metamaterial units, the influence of airflow is commonly characterised through the Mach number and Reynolds number defined in Eq. (2) and (3)[15]:

$$M = \frac{u}{c} \tag{2}$$

where u is the mean flow velocity and c the speed of sound,

$$Re = \frac{\rho u L}{\mu} \tag{3}$$

where ρ is the density of the fluid, u is the velocity of the fluid, L is a characteristic length (such as the diameter of a pipe or a linear dimension that defines the scale of the physical problem), and μ is the fluid's dynamic viscosity.

The literature shows that the Mach number and the associated convective effects influence both reactive and dissipative mechanisms. For resonant cavities, mean flow tends to move the effective resonance frequency to higher values and decrease peak transmission loss. For MPPs, flow through perforations affects both the resistive and reactive components of impedance, and thus their low-frequency behaviour. Membranes and interference-based metamaterials also exhibit sensitivity to grazing flow, although the reported effect is smaller in structures exploiting broadband interference.

Another relevant phenomenon is self-generated noise, which can arise from vortex shedding or aeroacoustic feedback mechanisms at perforated or cavity openings. Studies indicate that this risk increases when the Strouhal number associated with the flow (geometry interaction falls within approximately 0.2-0.5). In the context of residential ducts, typical Mach numbers remain sufficiently low to avoid strong tonal self-excitation, but geometries must still be selected carefully to minimise potential whistling.

Minimising pressure drop constitutes a fundamental design constraint for heat pump systems. AMMs are particularly promising in this regard, since several principles-including metacages, coiled resonators with lateral access and interference-based units-can be configured to offer substantial ventilation area with limited aerodynamic penalties. The generation of turbulence-induced noise at perforations or resonator necks can be interpreted in the framework of Lighthill's acoustic analogy shown in Eq. (4)[15]:

$$\frac{\delta^2 p}{\delta t^2} - c^2 \nabla^2 p = \frac{\delta^2 T_{ij}}{\delta x_i \delta x_j} \quad (4)$$

4. Modelling and validation approaches

A key insight from the reviewed body of work is the methodological divide between monophysical and multiphysical studies. Only a small fraction of the literature employs fully coupled acoustic–fluid dynamic models, although this approach is necessary to predict metamaterial behaviour under realistic operating conditions. Most studies either treat acoustics independently or analyse acoustic and fluid dynamic fields in parallel without evaluating their interaction explicitly.

Analytical methods still play an important role in preliminary tuning of resonant cavities, especially through closed-form formulations such as Helmholtz resonance models and Fabry–Pérot-type approximations. However, these analytical approaches generally require simplifying assumptions that break down in the presence of flow.

For realistic heat pump ducts, finite-element and computational fluid dynamics (CFD) simulations provide more reliable insights. Coupled aeroacoustic simulations, typically based on the linearised Navier–Stokes equations, can account for turbulence-induced attenuation and convective propagation, enabling more accurate prediction of metamaterial performance. The most advanced models incorporate boundary-layer effects, frequency-dependent impedance corrections and fluid–structure interaction, enabling direct comparison with experimental data.

Experimental validation remains essential. Typical setups include impedance tubes modified to allow bias or grazing flow, wind-tunnel-based testing of duct modules and hybrid measurements combining sound pressure with structural vibration. The few studies including realistic flow conditions confirm that metamaterials can achieve significant attenuation even under low Mach numbers, although a decrease in peak performance is consistently observed. To compare different metamaterial configurations under both static and flow conditions, transmission loss, defined in Eq. (5), remains the most widely adopted performance metric.

$$TL = 10 \log \left(\frac{W_{in}}{W_{out}} \right) \quad (5)$$

where W_{in} and W_{out} are respectively the incident and transmitted sound power in the inlet coming towards the sound reduction system and going downstream in the outlet of the system.

5. Performance ranges and design implications for heat pumps

Across the reviewed literature, the attenuation performance of AMMs spans a wide range depending on geometry, operating frequency and flow conditions. For small ventilation openings between 0.5 and 3 cm, resonant and membrane-based structures have succeeded in reaching transmission loss values approaching 40 dB at selected frequencies under no-flow conditions. Micro-perforated and interference-based structures typically provide moderate broadband attenuation in this size range. Because higher-order duct modes begin to propagate only above the cut-on frequency, given in Eq. (6), most heat-pump ducts operate predominantly in the plane-wave regime [16], [17]:

$$f_c = \frac{\chi_{mn} c}{2\pi a} \quad (6)$$

where χ_{mn} is the first non-zero root of the derivative of the Bessel function associated with mode (m, n)[18], [19]. For medium openings (4–6 cm), relevant to small façade penetrations or wall vents, performance becomes more sensitive to the specific metamaterial principle adopted. The presence of even modest flow can reduce peak attenuation, especially near resonant frequencies. Nonetheless, several studies report retention of 10–20 dB attenuation across substantial frequency intervals [7].

In the case of larger openings (7–10 cm), suitable for high-efficiency heat pump ventilation, the attenuation trends tend to be smoother and somewhat lower in amplitude due to the larger duct cross sections. Interference-based AMMs and metacages emerge as effective solutions in these situations because they preserve unobstructed flow while maintaining 10–15 dB of consistent attenuation.

The results Depicted in Table 1 suggest that a combination of metamaterial mechanisms may be required to simultaneously address low-frequency tonal components and turbulence-dominated broadband noise. Hybrid configurations (including resonant cavities combined with MPPs or porous layers) appear promising for achieving broadband performance without excessive pressure drop.

To illustrate practical sizing, consider a wall-penetrating duct of circular cross-section with inner diameter a = 0.10 m serving a split-system heat pump. Using Eq. (6) with the first non-zero root $\chi_{11} \approx 1.841$ for the (1,1) mode, the plane-wave cut-on frequency is approximately $f^{Ti} \approx 1.841 \times 343 / (2\pi \times 0.05) \approx 2010$ Hz, confirming that the entire frequency range of heat-pump concern (31.5–2000 Hz) lies within the plane-wave regime for this duct diameter and below. A Helmholtz resonator targeting the dominant 63 Hz fan tone can be dimensioned using Eq. (1): choosing a neck area $A = 3 \times 10^{-4}$ m², cavity volume $V = 6 \times 10^{-4}$ m³, and effective neck length $L^{eff} = 0.05$ m yields $f^{c} \approx (343 / 2\pi) \times \sqrt{(3 \times 10^{-4} / (6 \times 10^{-4} \times 0.05))} \approx 63$ Hz, which matches the target. These illustrative examples demonstrate how the analytical tools reviewed in this paper can be directly applied to preliminary sizing for residential heat pump scenarios, before committing to full numerical optimisation [7].

Table 1. Summary of Metamaterial Principles Relevant for Residential Heat-Pump Duct Acoustics

Metamaterial Principle	Typical Effective Freq. Range	Ventilation Compatibility	Reported Acoustic Perform.	Relevance to Heat-Pump Ducts
Resonant cavities (Helmholtz, coiled, labyrinthine)	50-6k Hz	High (can maintain large openings)	8-30 dB TL depending on geometry	Suitable for low-freq. fan & compressor tones
Micro-perforated panels (MPPs)	200-2k Hz	Moderate (pressure drop increases with flow)	7-15 dB TL	Suitable for turbulence-dominated mid-freq. noise
Membrane-type AMMs	50-900 Hz	High	10-15 dB TL (narrow-band)	Effective for low-freq. tonal attenuation
Fano-like interference structures	100-3k Hz	Very high (large unobstructed openings)	25-30 dB TL	Suitable for façade-integrated ventilation with broadband noise
Porous + metamaterial hybrids	100-3k Hz	Moderate	10-20 dB TL	Suitable as complementary broadband absorbers

6. Future directions for integration in heat pump systems

The integration of AMM-based silencers into the ventilation duct assemblies of residential heat pumps (including wall-penetrating ducts, façade-mounted silencer sections, and centralised air-handler duct networks) calls for enhanced multi-domain simulation workflows and more systematic experimental validation. The literature highlights the need for improved modelling approaches that couple acoustics, fluid dynamics, thermal effects and structural vibrations into unified frameworks.

Emerging research directions include the use of machine-learning-assisted optimisation to explore large design spaces, programmable metamaterials capable of adapting their response to operational changes, and sustainable manufacturing processes that enable large-scale deployment in residential HVAC systems. From a practical standpoint, advances in additive manufacturing (3D printing) can further reduce production costs while allowing highly complex geometries.

The development of standardised measurement protocols for metamaterials under realistic flow is equally necessary. Rigorous flow-inclusive characterisation would facilitate the direct comparison of different solutions and support the formulation of design guidelines transferable to heat pump manufacturers.

7. Conclusions

Acoustic metamaterials represent a compelling solution to the noise-control challenges associated with residential heat pump ducts. The principles reviewed-resonant cavities, membranes, micro-perforated structures and interference-based designs-demonstrate strong potential for achieving substantial low-frequency attenuation within compact geometries and with minimal pressure drop.

Considering the influence of mean flow, turbulence and duct geometry, multi-physical models and experimentally validated designs are essential for reliable integration into real-world systems. Although significant progress has been made, further research is required to develop robust guidelines and scalable, industry-ready solutions. As heat pump adoption continues to grow, the role of metamaterials in achieving acoustically comfortable residential environments appears increasingly promising.

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