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# COMPARATIVE ANALYSIS OF LIGHTWEIGHT METAMATERIAL PARTITIONS FOR ENHANCED ACOUSTIC PERFORMANCE AND PERCEPTUAL SOUND EVALUATION

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## ABSTRACT

Locally resonant acoustic metamaterials have shown significant potential to enhance acoustic insulation in lightweight partitions, though typically only within narrow bands. We previously developed a highly efficient numerical model of a metamaterial partition to address the coincidence dip of a single panel using equally tuned resonators. This study introduces multiresonant configurations, optimized via a genetic multi-objective algorithm, to broaden the resonators' impact on diffuse transmission loss near the critical frequency while minimizing the added mass. Comparative analyses between equally tuned and multiresonant systems are performed, evaluating both acoustic and psychoacoustic metrics to investigate the relationship between varying mass ratios and perceptual features. The findings aim to inform the design of lightweight, high-performance acoustic partitions for diverse environments.

**Keywords:** *acoustic metamaterials, sound transmission loss, optimization, building acoustics, sound quality*

## 1. INTRODUCTION

Locally resonant metamaterials have emerged as a cutting-edge solution for lightweight, high-performance sound insulation, addressing challenges where traditional methods struggle to meet environmental and mass constraints [1]. Their unique ability to manipulate wave propagation through tailored resonant structures has drawn increasing attention from both academia and industry, leading to diverse applications across multiple sectors.

Multiresonant structures have been explored as a means to enhance sound transmission loss by extending the bandwidth of attenuation. This can be achieved through the incorporation of multiple resonators within a unit cell (UC) [2] or through multimodal optimized resonators [3]. Both approaches enable the formation of multiple band gaps within a target frequency range, effectively reducing structural vibrations and noise transmission. Given the complexity of designing such systems, advanced optimization techniques —particularly topology optimization and generative inverse methods— represent some of the most promising approaches for developing realizable multimodal metamaterials [4].

This study aims to compare the acoustic performance of metamaterial-based building partitions configured with either equally-tuned or multiresonant systems, represented as independent mechanical resonators. Leveraging an efficient hybrid modeling approach, we implement a genetic algorithm for multi-objective optimization, enabling to obtain a Pareto front or set of optimal solutions. Evaluation is then conducted using both objective acoustic metrics, such as the weighted sound reduction index, and psychoacoustic metrics to assess perceptual annoyance. For this case study, we focus on single-leaf building partitions and specifically target the critical frequency dip under diffuse sound incidence.

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## 2. MODELING AND OPTIMIZATION

To enable the optimization and psychoacoustic study of the metamaterial partition, a computationally efficient model is required. This section outlines the hybrid numerical-analytical modeling approach used to evaluate the sound transmission loss of the partition wall.

### 2.1 Sound Transmission Loss

The partition wall is modeled with beam elements using an efficient Finite Element (FE) model in 1D, as detailed in [5]. The host-structure consists of standard 1/2" Gypsum board panels with density $\rho = 820$ kgm$^{-3}$, Young's modulus $E = 3.2$GPa, Poisson's ratio $\nu = 0.262$ and loss factor $\eta = 0.1$.

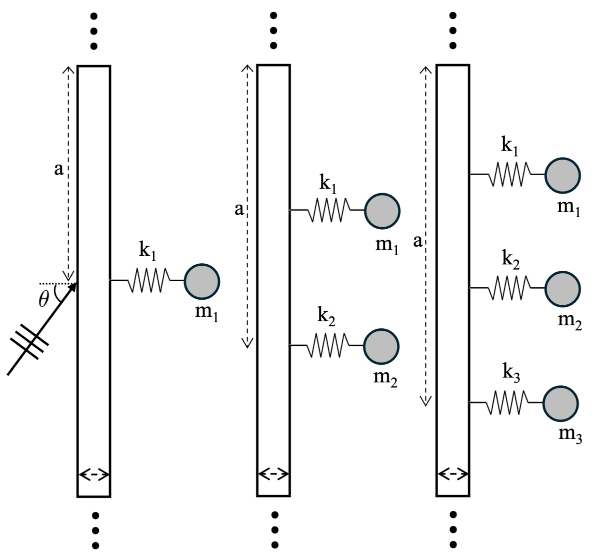


**Figure 1**. Representative scheme of modeled UCs.

A single unit cell (UC) is modeled using periodic Bloch-Floquet boundary conditions, which significantly reduce computational costs by limiting the domain to a representative repeating unit. Figure 1 presents a representation of the UC, illustrating three configurations: single, double, and triple resonator systems. Each resonator is represented as a vibrating spring-mass element with a single translational degree of freedom and massless attachment point.

The transmission coefficient of the periodic infinite structure, $\tau_\infty$, is determined as the ratio of radiated to incident sound pressure. The radiated pressure is approximated using the computed velocity of the vibrating panel, given by $|p_{\text{rad}}| = Z_0|v|$, where $Z_0$ is the air characteristic impedance and $v$ is the velocity derived from nodal displacements. For a given plane wave incidence angle $\theta$, the corresponding sound reduction index or sound transmission loss is obtained as $R_\theta = -10\log_{10}(\tau_\infty)$.

Although computationally efficient, $R_\theta$ is limited by its assumption of a single incidence angle and an infinitely extended structure, which does not accurately represent real-world conditions. In practical scenarios, sound waves arrive from multiple angles, interacting with a finite panel. To address this, additional analytical computations are performed to approximate a more realistic transmission loss, integrating the transmission coefficient over all incident angles

$$\tau_{\text{d}}(\omega) = \frac{\displaystyle\int_{\theta=0}^{\pi/2} \tau_f(\omega,\theta)\cos(\theta)\sin(\theta)\,\mathrm{d}\theta}{\displaystyle\int_{\theta=0}^{\pi/2} \cos(\theta)\sin(\theta)\,\mathrm{d}\theta}, \tag{1}$$

where $\tau_f = \tau_\infty(\sigma_R\cos\theta)$ is the transmission coefficient of the finite structure [6]. The acoustic domain is taken into account through the radiation efficiency $\sigma_R$, obtained from the real part of the normalized radiation impedance averaged over the azimuth angle [7]. A panel measuring 1.5 × 1.25 m is assumed for all computations, following ISO 10140 [8], which defines this size for laboratory measurements of sound insulation of building elements with a small test opening. Finally, the diffuse incidence sound transmission loss of the finite structure can be obtained by $R = -10\log_{10}(\tau_{\text{d}})$.

### 2.2 Multiobjective Optimization

Optimization is performed using a genetic algorithm with two cost functions: one aimed at maximizing the sound transmission loss $R_\theta$ around the critical frequency and another minimizing the added mass ratio $M_{\text{r}}$, given by the ratio between the added resonators $m_r$ and the host structure's UC mass $m_p$, which can be defined as:

$$\varphi_1 = \frac{1}{\left(\displaystyle\int_{f_l}^{f_u} R_{\theta,\text{meta}}(f, f_{res}, M_{\text{r}}, \eta_{\text{r}}) - R_{\theta,\text{bare}}(f)\,\mathrm{d}f\right)^2}, \tag{2}$$

$$\varphi_2 = M_{\text{r}} = m_r/m_p. \tag{3}$$

To prevent resonators from being tuned to the same resonance frequency $f_{res}$, constraints are imposed on the frequency range assigned to each resonator. This range is evenly subdivided based on the number of resonators in a given configuration. The optimization bounds for frequency, $f_l$ and $f_u$, are set to 1500 Hz and 3500 Hz, respectively, corresponding to the typical coincidence range for gypsum board panels [5]. Additionally, the mass ratio is constrained between 0.01 and 0.5 to ensure lightweight solutions. A structural damping factor $\eta_r$ of 5% is assumed for all resonators, implemented as a complex stiffness term. This value is chosen based on typical values obtained in realizable resonant elements [2].

To enhance the genetic algorithm's ability to explore the solution space thoroughly and avoid convergence to local minima, a population size of 500 is used in MATLAB's `gamultiobj` function. Optimization is performed at grazing incidence, as this approach has been shown to yield equivalent results with significantly reduced computation time in comparison to diffuse incidence optimization [5]. On average, a single run takes 45 seconds on a 10-core M1 Pro CPU. The resulting Pareto front consists of 175 solutions, as shown in Figure 2.

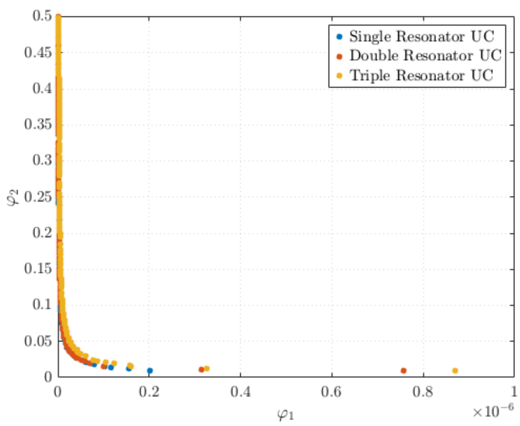


**Figure 2**. Pareto front of modeled UCs.

By computing the diffuse sound transmission loss for each solution point using Equation 1, the single-value rating $R_w$ can be determined according to ISO 717-1 [9]. The resulting ratings can be then plotted as a function of the mass ratio (Figure 3) for each resonator configuration.

In terms of the weighted sound reduction index, sound insulation improves steadily with increasing mass ratio.

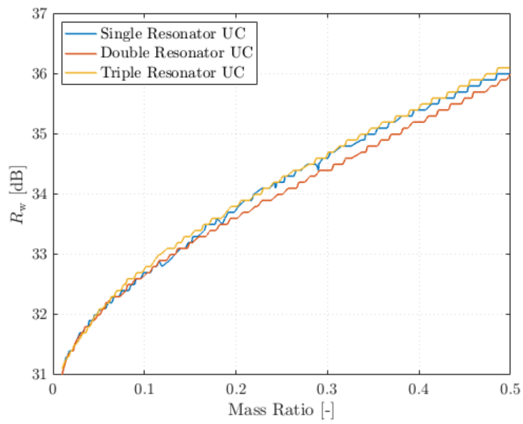


**Figure 3**. Weighted sound reduction index in function of mass ratio.

However, for the critical dip in gypsum board panels, the improvements achieved with multi-resonant configurations appear too small to be significant. This is because $R_w$ accounts for the overall increase in sound insulation across one-third-octave frequency bands from 100 Hz to 3150 Hz and is not designed to capture narrowband improvements in $R$, such as those introduced by metamaterials. Taking the pareto optimal solution (i.e. the points of each pareto front closer to the origin) we can plot the optimal solution found for each resonator configuration (Figure 4).

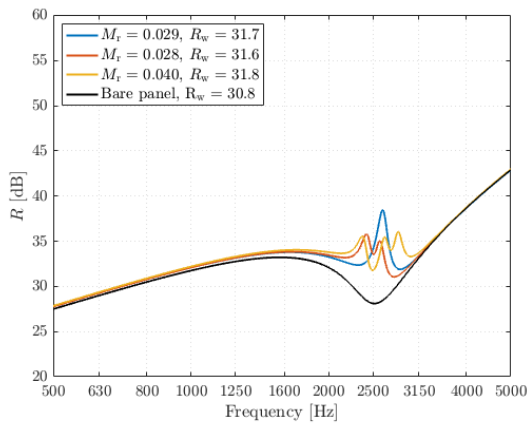


**Figure 4**. Sound reduction curves for pareto optimal solutions.

### 2.3 Sound quality evaluation

A sound quality evaluation, incorporating psychoacoustic metrics, was conducted to explore additional assessment criteria for the metamaterial partitions. The optimized Pareto front solutions were analyzed using their random incidence curves, computed across the complete audible range with a 10 Hz frequency resolution.

The impulse response for each solution point was obtained by applying an inverse Fourier transform to the transmission magnitude. A random phase spectrum, generated from precomputed values between 0 and $2\pi$, was added to the transmission spectrum to ensure a more accurate translation of the signal into the time domain [10]. Finally, the impulse response was convolved with a pink noise signal.

For this study, the Psychoacoustic Annoyance (PA) metric was employed, as it integrates multiple perceptual attributes —including loudness, tonal characteristics, and temporal structure— into a single measure [11]. It is calculated as:

$$\mathrm{PA} = N_5 \left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \tag{4}$$

$$w_S = \begin{cases} (S - 1.75) \cdot 0.25 \log(N_5 + 10) & S > 1.75 \\ 0 & S \leq 1.75 \end{cases} \tag{5}$$

$$w_{FR} = \frac{2.18}{N_5^{0.4}}(0.4F + 0.6R) \tag{6}$$

where $N_5$ is the percentile loudness in sones, $S$ is the sharpness metric, $F$ the fluctuation ratio, and $R$ the roughness metric. These psychoacoustic metrics were computed using MATLAB according to ISO 532-1 [12], and a virtual calibrated microphone with a 1 kHz reference signal assuming a SPL meter reading of 84 dB.

The computed annoyance values plotted against the mass ratio, are shown in Figure 5. Across all configurations, annoyance levels were lower than those of the bare panel. For mass ratios below 5%, the configurations exhibited similar annoyance values. However, as the mass ratio increased, differences became more pronounced. Notably, the triple-resonator configuration achieved the greatest reduction in annoyance, with its advantage becoming increasingly significant at higher mass ratios.

Beyond a 20% added mass ratio, perceived annoyance plateaued —unlike the single-value rating, which suggested a steady improvement in sound insulation with increasing $M_\mathrm{r}$. This discrepancy can be attributed to the trend in loudness (Figure 6), as loudness carries the highest perceptual weighting in annoyance calculations. Additionally, higher $M_\mathrm{r}$ values lead to a more pronounced dip in insulation following the resonators' peak performance. This trend is reflected in the Sharpness metric, which consistently increases with $M_\mathrm{r}$ across all configurations.

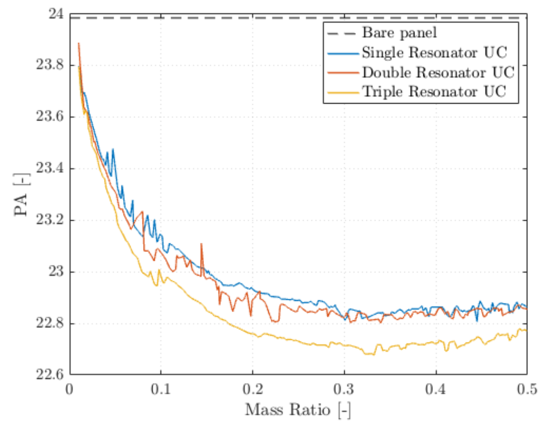


**Figure 5**. Zwicker's Annoyance metric of the optimized metamaterial panels.

## 3. CONCLUSION

This work presents an efficient modeling and optimization approach for a partition wall with multiple local resonators, designed to enhance sound insulation around the critical frequency while minimizing the added mass ratio. Additionally, psychoacoustic metrics are introduced as an evaluation tool, complementing traditional single-value ratings by providing deeper insights into specific configurations. This holistic approach is particularly relevant for applications where human acoustic comfort is a priority. Future research could explore additional psychoacoustic metrics and their integration into the optimization process.

## 4. ACKNOWLEDGMENTS

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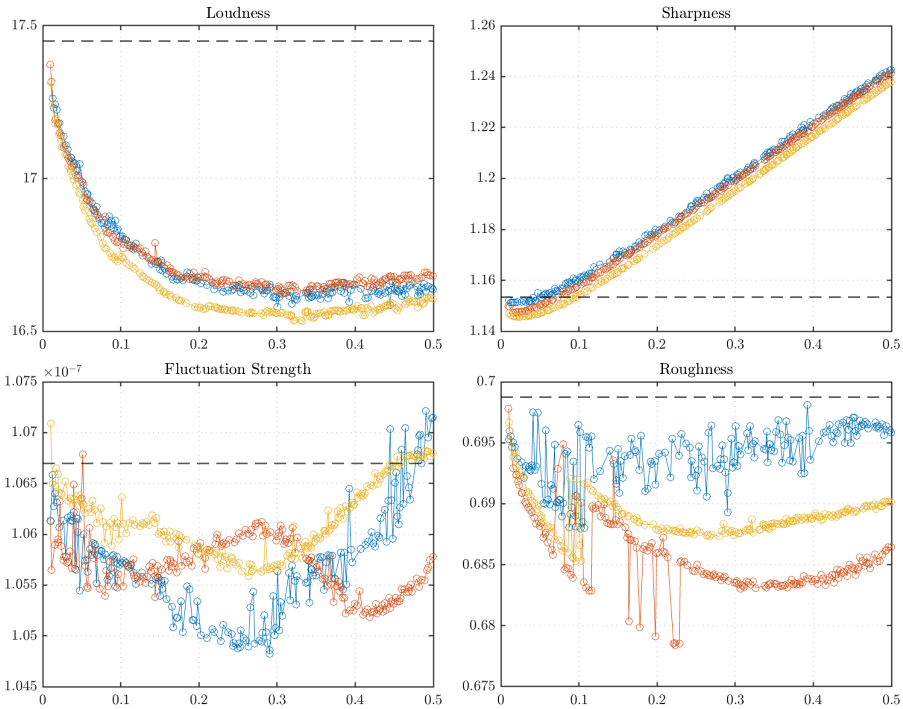


**Figure 6**. Psychoacoustic metrics computed in function of mass ratio.

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