DOI: 10.61782/fa.2025.0715

PSYCHOACOUSTICAL DESIGN OPTIMIZATION FOR ACOUSTIC METAMATERIALS USING GLOBAL SENSITIVITY ANALYSIS

Jiahua Zhang[1,2*] **Jacques Cuenca**[1] **Laurent De Ryck**[1]
Lucas Van Belle[2,3] **Elke Deckers**[3,4]
[1] Test Division, Siemens Digital Industry Software, Belgium
[2] Department of Mechanical Engineering, KU Leuven, Belgium
[3] Flanders Make@KU Leuven, Belgium
[4] Department of Mechanical Engineering, Campus Diepenbeek, KU Leuven, Belgium

ABSTRACT

While acoustic metamaterials have shown promising noise reduction capabilities, their design optimization has traditionally focused on physical acoustic properties rather than perceived sound quality. This research introduces a design methodology that integrates psychoacoustic metrics into the optimization of metamaterial architectures. The methodology uses a previously developed Global Sensitivity Analysis scheme as a basis for an optimization framework that specifically targets desired psychoacoustic outcomes while maintaining practical design constraints. Micro-perforated panels are used as a preliminary case study. The design optimization is validated with multiple prototypes and measured in an impedance tube, with results analyzed for both traditional acoustic measurements and psychoacoustic metrics including loudness and sharpness. The experimental validation demonstrates how optimized designs can achieve specific sound quality targets while remaining practically manufacturable.

Keywords: *sound quality, acoustic metamaterial, sensitivity analysis, micro perforated panel*

1. INTRODUCTION

Acoustic metamaterials have revolutionized the field of noise control with their ability to manipulate sound waves beyond conventional materials. Their unique structures enable exceptional sound absorption, transmission loss, and wavefront manipulation capabilities [1]. Traditionally, metamaterial design has been guided by physical acoustic properties such as absorption coefficients and transmission loss. However, these objective parameters do not fully correlate with human perception of sound quality. Previous research revealed that acoustic metamaterials can significantly alter psychoacoustic metrics, sometimes in directions contrary to what traditional acoustic measurements might suggest [2]. This potential disconnect between objective measurements and subjective perception creates a design challenge when optimizing metamaterials for human-centered acoustic environments.

This paper builds upon a recently developed sensitivity analysis approach for micro-perforated panels (MPPs) [3], extending the methodology into a full optimization workflow, and including an experimental validation of the psychoacoustic metrics. The research objective is to develop a framework for designing acoustic metamaterials with desired psychoacoustic features as targets, while maintaining practical design constraints. The focus is specifically on a simplified single-panel MPP configuration to establish the foundation for more complex systems.

The rest of the paper is structured as follows: Section 2 described the MPP model, design optimization and validation methodologies. In Section 3 the results are shown. Discussion of the results and a summary can be found in Section 4.

**Corresponding author*: *jiahua.zhang@siemens.com.*

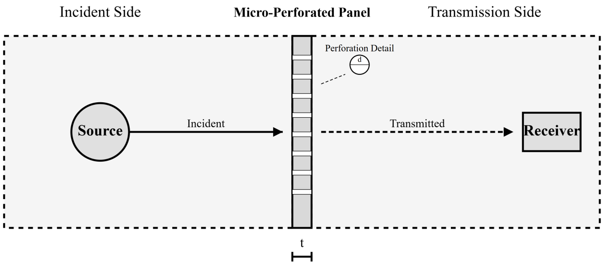

Figure 1. Overview of the problem configuration.

2. METHODS

2.1 Micro-Perforated Panel Modeling

The analysis is simplified to focus on a single MPP, 1-D transmission configuration, as shown in Figure 1, to establish a clear relationship between design parameters and sound quality metrics. For the MPP analysis, 3 key parameters are determined, with parameter bounds carefully defined by balancing theoretical acoustic principles, manufacturing feasibility constraints, and the desired transmission loss (TL) performance targets [4]:

- Perforation diameter (d): 0.03 to 3 mm,
- Porosity (ϕ): 0.2% to 3.14%,
- Panel thickness (t): 1.5 to 2.0 mm.

The acoustic behavior of the MPP was modeled using Atalla and Sgard's approach [5], where the surface impedance for transmission is calculated as:

$$Z_t = \left(\frac{4t}{d} + 4\right)\frac{R_s}{\phi} + \frac{1}{\phi}(2\epsilon + t)j\omega\rho_0 + \rho_0 c, \quad (1)$$

where ω is the angular frequency, $\epsilon = 0.24\sqrt{\pi d^2}(1 - 1.14\sqrt{\phi})$ represents the end correction factor, R_s is the surface resistivity, ρ_0 is the air density, and c is the speed of sound. Then, with the characteristic acoustic impedance $Z_0 = \rho_0 c$, the transmission coefficient can be derived as:

$$\tau = \frac{1 + R_s}{Z_t/Z_0} = \frac{2\rho_0 c}{Z_t + \rho_0 c}. \quad (2)$$

TL values in decibels (dB) can then be calculated as $\mathrm{TL} = 10\log(1/\tau)$.

2.2 Global Sensitivity Analysis Framework

The global sensitivity analysis (GSA) approach used in this study follows the Sobol method [6], which quantifies the contributions of individual parameters and their interactions to the variance in model outputs. This approach is particularly valuable for complex systems like metamaterials where multiple parameters may exhibit nonlinear and interdependent effects on acoustic performance. The GSA process preserves the quasi-random properties of Sobol sequences while ensuring that each parameter's individual and interactive effects can be isolated through variance decomposition.

In order to sufficiently explore the design space, a sampling method is needed. A sampling procedure was implemented through the SALib library's `saltelli.sample` function [7–10], resulting in 4096 distinct parameter combinations for the 3-parameter MPP system. With each parameter combination, a unique acoustic transmission coefficient is computed and documented, preparing for the sound quality metrics prediction.

2.3 Sound Quality Prediction and Design Optimization

For the design optimization phase, conventionally, MPP parameters are directly calculated from objective acoustic (sound absorption or transmission loss) behaviors. However, in this research, the general goal is to predict MPP parameters using psychoacoustic metrics (loudness and sharpness) as targets. The motivation for using these psychoacoustic metrics comes from their direct relation with human perception, offering an intuitive approach to acoustic design than traditional physical metrics alone. Loudness quantifies the subjective intensity of sound perceived by listeners, while sharpness characterizes the high-frequency content often contributing to annoyance. Hence, the sound quality prediction process follows this systematic workflow:

1. Generation of acoustic filters (impulse responses) based on transmission coefficients from MPP parameters;
2. Convolution with pre-recorded noise stimuli;
3. Calculation of psychoacoustic metrics: loudness from ISO 532-1:2017 C code [11] and sharpness using Python library MosQiTo [12].

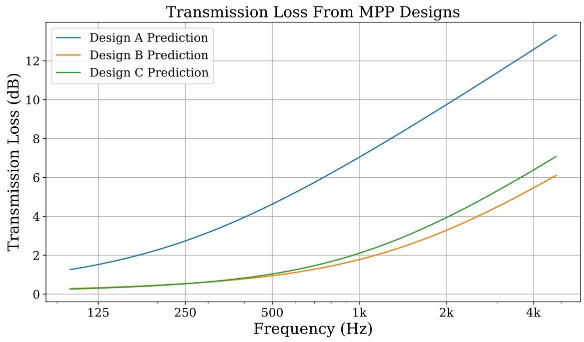

Figure 2. Predicted transmission loss curves for the MPP design A, B, and C.

Key parameters were predicted based on earlier GSA results and targeted toward specific sound quality goals:

- Design 1: Minimize loudness and sharpness.
- Design 2: Maximize loudness and sharpness.

2.4 Prototype Designs and Acoustic Performance

Based on the 4096 Satelli samples from GSA, three distinct MPP designs: Panel labels A, B, and C were manufactured with parameters shown in Table 1, and Figure 2 shows their predicted transmission loss performances. Panel A is designed to have in overall lowest loudness and sharpness metrics, panel B and C are designed to have high loudess and sharpness, but having parameters that differ enough. Hereby, panel samples are manufactured using a photomask laser cutter with a precision of 5 µm. With this tolarance, the TL deviation is maximally 0.04%, ensuring minimal impact from engineering errors.

Table 1. MPP design parameters for the three prototype configurations.

Design	Diameter (mm)	Porosity (%)	Thickness (mm)
A	0.94	0.594	2
B	0.47	2.99	2
C	0.73	1.94	1.5

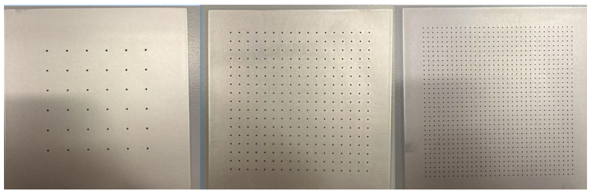

Figure 3. Stainless steel panels A, B, and C, laser cut with 0.005 mm precision.

2.5 Experimental Setup for Micro-Perforated Panel Measurements

The acoustic transmission characteristics of micro-perforated panels (MPPs) were experimentally investigated using an impedance tube configuration corresponding to the modeled 1-D setting described in Figure 1. The experimental apparatus consists of a Mecanum impedance tube, Siemens SCADAS Mobile data acquisition frontend with Simcenter Testlab 2406.0002 "Sound transmission loss using impedance tube," six G.R.A.S. 46BD quarter inch microphones, following the procedure in ASTM standard [13]. The manufactured panels are shown in Figure 3. The frequency range of this measurement is between 100 Hz and 5000Hz, with a resolution of 5 Hz. Considering that the sharpness metric is greatly impacted by the contrast between high and low frequency content, sound stimuli in this research is designed not to contain much frequency information above 5000 Hz, minimizing potential impact when validating in the impedance tube.

3. RESULTS

Figure 4 shows the measured transmission loss (TL) curves for each design: Design A, B, and C from Table 1. Design A demonstrates higher TL values across all frequencies, especially in the mid to high-frequency range, while Design B and Design C offer moderate TL performance. The impulse responses corresponding to the simulation are then calculated from the transmission coefficients, shown in Figure 5.

The simulated and measured impulse responses are compared with normalized mean square error (NMSE) and normalized rood mean square error (NRMSE) over dynamic range. Panel B has the best overall match, with an NMSE of 0.176 and an NRMSE over the dynamic range of 0.016. Panel A has an NMSE of 0.457 and an NRMSE of 0.025, while Panel C has an NMSE of 0.425 and an NRMSE of 0.0212. These higher NMSE

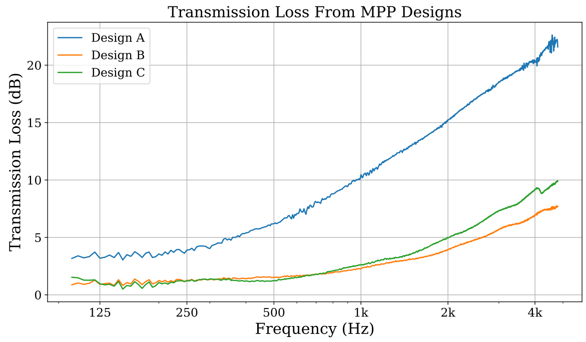

Figure 4. Measured transmission loss curves for the MPP design A, B, and C.

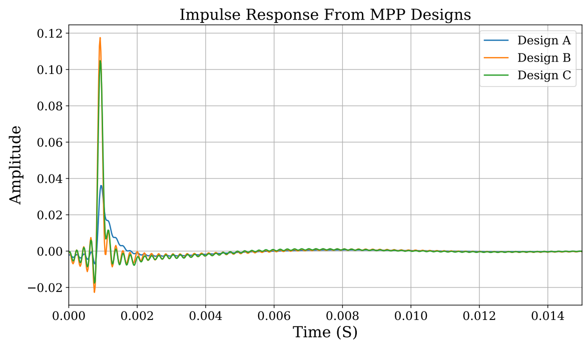

Figure 5. Impulse responses derived from the MPP design A, B, and C.

and NRMSE values for panel A and C indicate a moderate match between the simulated and measured impulse responses for these MPPs.

3.1 Psychoacoustic Performance

The predicted and measured psychoacoustic metrics for the three designs are presented in Table 2.

The results show agreement between predicted and measured psychoacoustic metrics, with deviations less than 6% for loudness and sharpness. Design A, with its smaller perforation rate and larger diameter, achieved the lowest loudness (22.2 sone) and sharpness (0.82 acum), aligning with our optimization target. Design B, featuring the average perforation diameter and perforation rate, resulted in the highest loudness (26.4 sone) and sharpness (0.97 acum), as expected from GSA predictions.

Table 2. Predicted vs. measured psychoacoustic metrics for the three designs.

Design	Loudness (sone)		Sharpness (acum)	
	Predicted	Measured	Predicted	Measured
A	23.5	22.2 (-5.5%)	0.87	0.82 (-2.0%)
B	27.0	26.4 (-5.7%)	0.99	0.97 (-4.5%)
C	26.8	25.6 (-2.2%)	0.99	0.94 (-5.1%)

4. DISCUSSION AND CONCLUSION

This study demonstrates the effectiveness of using global sensitivity analysis (GSA) as a framework for optimizing acoustic metamaterials based on psychoacoustic metrics. The findings confirm that this computational model can accurately predict complex relationships between psychoacoustic metrics such as loudness and sharpness, and the design parameters of the micro-perforated panels (MPP) such as thickness, hole diameter, and perforation rate.

The experimental validation of the theoretical predictions has yielded several important insights:

First, the disagreements between predicted and measured values are within 6% for both loudness and sharpness metrics. Considering the loudness parameter sone is on a relative scale, this deviation on loudness can be considered negligible. For instance, Design A has a loudness deviation from 23.5 sones predicted to 22.2 sones measured, which are correspondingly converted to 73.5 dB and 72.7 dB. This difference (0.8 dB) is within the just-noticeable difference (1 dB) of human hearing. This finding suggests the reliability of the prediction.

Second, this research provided a basis for design optimization. By establishing quantitative relationships between design parameters of MPP and sound quality metrics, it becomes possible to navigate the design space to achieve specific sound quality targets. Design B and C have distinct design parameters but share the same sharpness (0.99 acum predicted). This confirms that GSA-based design optimizations can be trusted for practical design applications.

Third, the workflow presented bridges the gap between objective acoustic properties to subjective auditory perception. It allows acousticians directly compare the sound quality metrics derived from material parameters. These metrics represent perceptually relevant features that correlate with subjective impressions, providing a more intuitively valid assessment of acoustic performance compared to abstract measurements of TL numbers and IR curves across the spectral and temporal domains. This approach extends the material design range by incorporating human perception into the design process, which is valuable for applications where sound quality, rather than mere noise reduction, is the primary design goal.

While this study focused on a simplified MPP configuration to establish methodologies, the workflow can be extended to more complex setups. Future work may explore periodic media exhibiting metamaterial behavior, starting with periodic arrangements of MPPs.

In conclusion, this study validates the use of GSA as an effective tool for sound quality driven metamaterial design. The agreement between predicted and measured psychoacoustic metrics suggests that this approach can guide the design optimization using sound quality as targets. By integrating acoustic modeling with sound quality metrics, this methodology provides a framework for designing materials that address not only physical performance requirements but also human perceptual preferences.

5. ACKNOWLEDGMENTS

The European Commission is gratefully acknowledged for their support of the Horizon Europe DN METAVISION project (GA 101072415). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them. The research of L. Van Belle (fellowship no. 1254325) is funded by a grant from the Research Foundation – Flanders (FWO).

6. REFERENCES

[1] S. A. Cummer, J. Christensen, and A. Alù, "Controlling sound with acoustic metamaterials," *Nature Reviews Materials*, vol. 1, no. 16001, 2016.

[2] L. D. Ryck and J. Cuenca, "Perceptual evaluation of metamaterials as insulation partitions - a listening test within the cost action denorms ca15125," in *Proc. of Int. Conf. on Noise and Vibration Engineering (ISMA)*, (Leuven, Belgium), 2018.

[3] J. Zhang, L. D. Ryck, J. Cuenca, L. V. Belle, and E. Deckers, "Impact of design variations of micro-perforated panels on psychoacoustic metrics of transmitted sound," *Proc. Mtgs. Acoust.*, vol. 55, no. 1, 2024.

[4] R. Huysse, *Analysis of the micro-perforated panel parameters in a modal filter for tonal and broadband damping*. PhD thesis, KU Leuven, 2021.

[5] N. Atalla and F. Sgard, "Modeling of perforated plates and screens using rigid frame porous models," *J. Sound Vib.*, vol. 303, pp. 195–208, 2007.

[6] I. M. Sobol, "Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates," *Math. Comput. Simul.*, vol. 55, pp. 271–280, 2001.

[7] J. Herman and W. Usher, "SALib: An open-source python library for sensitivity analysis," *The Journal of Open Source Software*, vol. 2, jan 2017.

[8] T. Iwanaga, W. Usher, and J. Herman, "Toward SALib 2.0: Advancing the accessibility and interpretability of global sensitivity analyses," *Socio-Environmental Systems Modelling*, vol. 4, p. 18155, May 2022.

[9] A. Saltelli, "Making best use of model evaluations to compute sensitivity indices," *Computer Physics Communications*, vol. 145, pp. 280–297, May 2002.

[10] A. Saltelli, P. Annoni, I. Azzini, F. Campolongo, M. Ratto, and S. Tarantola, "Variance based sensitivity analysis of model output. design and estimator for the total sensitivity index," *Computer Physics Communications*, vol. 181, pp. 259–270, 2 2010.

[11] "Acoustics – methods for calculating loudness – part 1: Zwicker method," standard, International Organization for Standardization, Geneva, Switzerland, 2017. Standard.

[12] G. F. Coop, "MOSQITO," Apr. 2024.

[13] ASTM International, "Standard test method for normal incidence determination of porous material acoustical properties based on the transfer matrix method," Standard E2611-19, ASTM International, West Conshohocken, PA, 2019.