# Finite Element Design of Acoustic Metamaterial Based on Parallel Helmholtz Resonators With Embedded Membranes

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## 1 Introduction

Noise pollution reduction is an environmental necessity. Acoustic metamaterials based on periodic Helmholtz resonators can offer high efficiency in attenuating multi-tonal noise at low frequencies. Laly et al. [1] used the finite element method to develop designs of acoustic metamaterials made of parallel assemblies of Helmholtz resonators, which are periodically embedded within a porous material. The proposed metamaterial designs show multiple transmission loss (TL) peaks. Porous material combined with embedded periodic Helmholtz resonators that contain a membrane in the cavity was investigated numerically by Laly et al [2]. The use of a membrane in the resonator cavity induces multiple TL peaks while only one TL peak is observed with a conventional resonator. They illustrate the influences of the membrane thickness and position on the TL. Guo et al. [3] studied a checkerboard absorber constituted by parallel assemblies of Helmholtz resonators for sound absorption improvement. Mahesh and Mini [4] characterized a parallel assembly of Helmholtz resonators using a parallel transfer matrix method and the analytical results show good agreement with finite element method results. An increase of the sound absorption bandwidth was observed when parallel arrangement of dissimilar Helmholtz resonators was used.

In this study, a design of acoustic metamaterial based on a parallel assembly of four Helmholtz resonators with extended necks is proposed and studied numerically using COMSOL Multiphysics. A damping material in the form of a membrane is inserted into each sub-cavity. The parallel assembly of four Helmholtz resonators is periodically distributed within a porous material. Four TL peaks are observed with the parallel assembly of four resonators without embedded membranes. For membranes with free boundary conditions inside each sub-cavity, eight resonant TL peaks are obtained and for fixed boundary conditions, the TL presents twenty resonant frequencies.

## 2 Design of acoustic metamaterial based on parallel Helmholtz resonators with embedded membranes

Figure 1(a) shows a parallel assembly of four Helmholtz resonators with extended necks. The cylindrical cavity is partitioned into four sub-cavities with the same volume that are separated from one another by a wall. A membrane is inserted within the cavity of each resonator. The air inside each neck is characterized using the thermo-viscous acoustic interface to account for the viscous and thermal dissipations effects. The parallel assembly of resonators is embedded periodically within a porous material that is modeled using Johnson-Champoux-Allard model. The geometry of the Periodic Unit Cell (PUC) is illustrated in Fig. 1(b) and the mesh in Fig. 1(c), which consists of 37 580 domain elements and 10 673 boundary elements. Periodic boundary conditions are applied on all parallel plans.

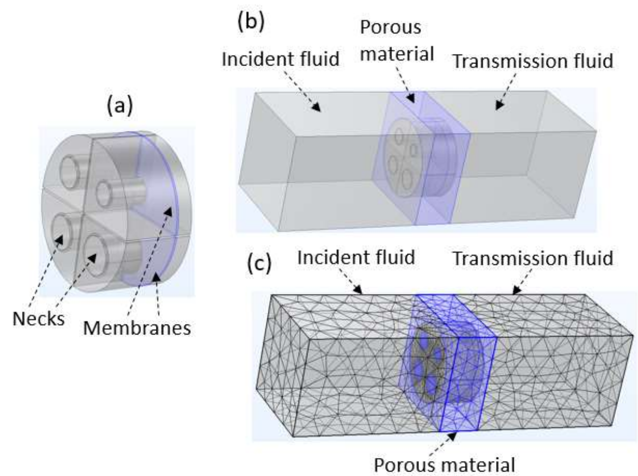


**Figure 1**: Acoustic metamaterial: (a) parallel assembly of four Helmholtz resonators with embedded membranes (b) geometry of the PUC (c) mesh of the PUC.

The airflow resistivity of the porous material is 26 000 N s m $^{-4}$ with a porosity of 99%. The tortuosity is 1.02, and the characteristic viscous and thermal lengths are respectively 150 μm and 300 μm. The membrane is ethylene-vinyl acetate rubber material with Young's modulus of 5 MPa, a density of 660 kg/m$^3$ and a Poisson's ratio of 0.45. It is modeled as a linear isotropic material using a solid mechanics interface. The thickness of the membrane is set to 1 mm; the diameter of the global cylindrical cavity is 80 mm with a length of 40 mm that is equal to the thickness of the porous layer. The wall of the resonators is considered rigid. The radii of the necks are respectively 6 mm, 8 mm, 9 mm and 10 mm with the same length of 20 mm. Each membrane inside each sub-cavity is located at 10 mm from the bottom inner wall of the cavity. A normal incidence plane wave with

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pressure amplitude of 1 Pa is applied on the inlet plane while plane wave radiation condition is applied on the inlet and outlet planes. The sound transmission loss is given by

$$TL = 10\ log_{10}\ (\frac{W_{\text{in}}}{W_{\text{out}}}) \tag{1}$$

with $W_{\text{in}}$ and $W_{\text{out}}$ the incoming power at the inlet plane and the outgoing power at the outlet plane.

## 3 Finite element results of the proposed metamaterial design

Figure 2 shows the transmission loss of the metamaterial without membranes and the case where the boundaries of each membrane within each sub-cavity are free. In Figure 3, the TL is illustrated for membranes with fixed boundaries conditions.

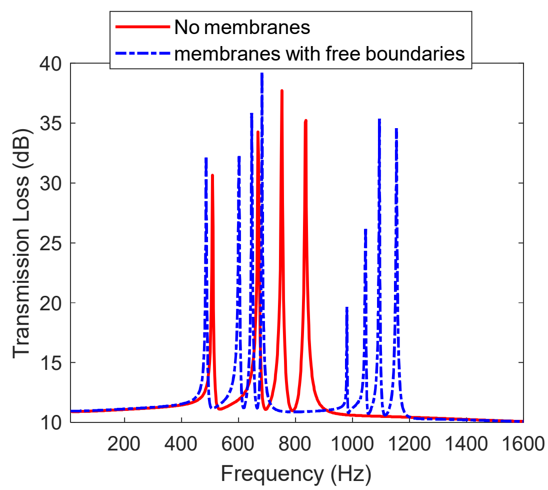


**Figure 2:** Transmission loss of acoustic metamaterial made of parallel assembly of four Helmholtz resonators.

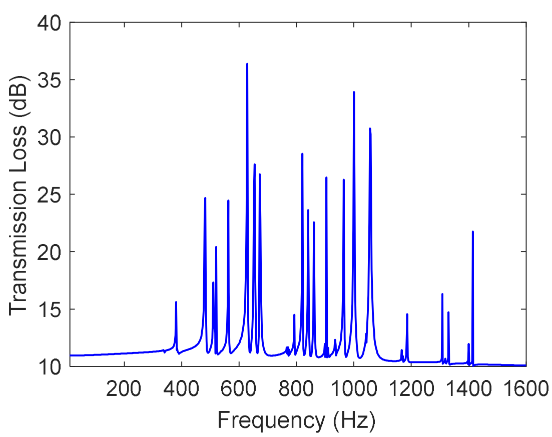


**Figure 3:** Transmission loss of acoustic metamaterial made of parallel assembly of four Helmholtz resonators containing membranes with fixed boundaries.

In Fig. 2, when there are no membranes within the sub-cavities of the resonators, there are four transmission loss peaks, which are 30.6 dB, 34.27 dB, 37.72 dB and 35 dB at respective frequencies of 508 Hz, 668 Hz, 752 Hz and 836 Hz. When a membrane is inserted within each sub-cavity with free boundary conditions, the TL presents eight resonant frequencies in Fig. 2, which are 486 Hz, 602 Hz, 646 Hz, 682 Hz, 980 Hz, 1046 Hz, 1094 Hz and 1154 Hz where the values of the TL peaks are respectively 32.24 dB, 32.35 dB, 35.84 dB, 39.26 dB, 19.64 dB, 26.27 dB, 35.37 dB and 34.55 dB. In Fig. 3 where the boundary conditions of each membrane within each sub-cavity are fixed, the TL present 20 resonant peaks. The use of the membrane within each sub-cavity induces multiple TL peaks. This design can be useful for noise mitigation at multiple frequencies simultaneously.

## 4 Conclusions

A design of acoustic metamaterial made of a parallel assembly of four Helmholtz resonators is proposed and investigated numerically using the finite element method. The cylindrical global cavity is partitioned into four sub-cavities with equal volume, which are separated from one another by rigid walls and an extended neck is connected to each sub-cavity. A damping material in the form of a membrane is inserted into each sub-cavity. The parallel assembly of four Helmholtz resonators is periodically distributed within a porous material. The transmission loss of the parallel assembly of four resonators without embedded membranes presents four resonant peaks. When a membrane is inserted within each sub-cavity with free boundary conditions, eight resonant TL peaks are obtained and for fixed boundary conditions, the transmission loss presents 20 resonant peaks. The proposed acoustic metamaterial design can be used in many industrial applications for multi-total noise reduction.

## Acknowledgments

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## References

[1] Z. Laly, C. Mechefske, S. Ghinet, and C.T. Kone. Numerical design of acoustic metamaterial based on parallel Helmholtz resonators for multi-tonal noise control. In Proceedings of 2022 Inter-national Congress on Noise Control Engineering, INTER-NOISE 2022, 21-24 August 2022, Glasgow, UK.

[2] Z. Laly, C. Mechefske, S. Ghinet, and C.T. Kone. Numerical modelling of acoustic metamaterial made of periodic Helmholtz resonator containing a damping material in the cavity. In Proceedings of 2022 Inter-national Congress on Noise Control Engineering, INTER-NOISE 2022, 21-24 August 2022, Glasgow, UK.

[3] J. Guo, Y. Fang, Z. Jiang, and X. Zhang. Acoustic characterizations of Helmholtz resonators with extended necks and their checkerboard combination for sound absorption. *Journal of Physics D: Applied Physics, 53,* 505504, 2020.

[4] K. Mahesh, and R.S. Mini. Investigation on the Acoustic Performance of Multiple Helmholtz Resonator Configurations. *Acoustics Australia* 49, 355–369, 2021.