Perfect broadband sound absorber metamaterial for noise reduction in a rocket launch

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Abstract
Metamaterials based on Helmholtz resonators represent alternatives for noise mitigation applications where traditional materials can not be used due to the environmental conditions. One such case is found in the extreme acoustic event caused by a rocket launch. Metamaterials can also be designed on demand to act on the sound waves at a specific frequency range, which depends on the particular application. In this work we present the design procedure of a metamaterial panel, with a potential use for noise mitigation during a rocket launch. The proposed sound absorber presents almost perfect sound absorption in a prescribed bandwidth. The geometrical parameters of a unit cell, the building block of the panel, are obtained by using the transfer matrix method, and the use of optimization algorithms. The effective acoustical parameters of the designed metamaterial are also obtained. Using the effective parameters, the acoustical response of a panel built from an array including a large number of unit cells is numerically computed. Finally, experiments in an impedance tube that validate the theoretical results are presented.

Keywords: metamaterials, Helmholtz, resonator, aerospace.

1 Introduction

A rocket launch is an extreme acoustic event involving very high sound pressure levels that may cause damage to the payload carried at the fairing of the rocket. This noise comes mainly from the hot and turbulent exhaust jet, which is guided along the ground by two evacuation channels or ducts located at the ground of the launchpad just below the rocket. Due to the intense pressure levels, temperatures and flows, conventional noise mitigation methods are hardly applicable. A proposal for reducing the ambient sound pressure levels by covering the ducts with an absorbing metamaterial panel is presented. The panel is designed to absorb efficiently the sound energy in the critical band from 125 Hz to 500 Hz (which corresponds to the highest levels during a launch event), behaving as a broadband noise reduction system with absorption coefficient close to unity in the whole band. To achieve this exceptional response, a careful design by using optimization methods was performed. The panel consists of multiple cells of subwavelength local Helmholtz resonators which combine the concepts critical coupling (to achieve perfect absorption at a single frequency) and the rainbow trapping effect (to extend the critical coupling concept to a given frequency band). An acoustic characterization of the metamaterial is performed under plane wave excitation conditions, by measuring the normal incidence sound the absorption coefficient in an impedance tube, demonstrating the theoretical predictions and its feasibility for the application in the particular problem and other noise reduction applications.

2 Design of the metamaterial unit cell

The acoustical response of an array of Helmholtz resonators in a waveguide can be theoretically modelled by means of the Transfer Matrix Method (TMM). This method considers plane wave propagation inside the metamaterial and is a good approximation due to the small dimensions of the slit, the neck and the cavity. Details on the application of the method for a similar problem can be found in [1-4]. The acoustic pressure and the normal acoustic flow are related at both sides of the metamaterial, and the resonators are considered as point scatterers in the middle of each waveguide segment in the panel. The model also takes into account the cross-sectional changes in the system by adding radiation correction lengths, and the visco-thermal losses in the system are considered both in the Helmholtz resonators and in the waveguide by using their effective complex and frequency dependent parameters [5]. The material used to make the acoustic metamaterial is assumed to be acoustically rigid. The analytical results from the TMM method are validated by numerical calculations based on the Finite Element Method (FEM) using COMSOL Multiphysics 5.5. The thermo-viscous losses are accounted for by using the effective parameters of the air in the ducts, i.e., by using the complex and frequency dependent density and bulk modulus. At the external sides of the panel, rigid boundary conditions were considered and viscous losses were neglected here. This is justified because losses are mainly produced by thermo-viscous processes at the narrow ducts that compose the metamaterial and the contribution of other sources is minor.

2.1 Geometry of the metamaterial unit cell

The panel will be composed by the periodic repetition of a unit cell, to achieve the desired dimensions. The unit cell consists in a sequence of Helmholtz resonators with different geometries, whose geometrical parameters are carefully calculated by optimization methods to achieve a high absorption in a frequency band that extends from 125 to 500 Hz. The resulting structure is based on the rainbow trapping concept [1-3]. Sound is trapped and dissipated within the structure at different depths, depending on its frequency.

There is not a unique solution for this problem, and different solutions satisfying the requirements can be found by the optimization process. Limitations to some critical parameters have been imposed to assure a final solution that fits with the requirements and the fabrication of the structure as the operation frequency band, the maximum depth of the panel and the number of resonators.

The geometry of the unit cell in a rainbow trapping absorber is shown in Figure 1. A set of N Helmholtz resonators are placed in a waveguide of length L, width d_3 and height d_3. For the sound mitigation of the rocket in the launchpad we have considered as an objective to enhance acoustic absorption in a frequency band from 125 to 500 Hz. In this work, we have considered N=7.

The solution obtained is the result of an iterative optimization procedure [1]. The retrieved geometry presents a length L = 166.6 mm, a width d_1 = 19.9 mm, and a height d_3 = 99.0 mm. The ratio between the wavelength for the lowest absorbed frequency and the length is λ/L = 16.5. The parameters of each resonator shown in Figure 1 are given in Table 1. We note that 30 parameters are used in this optimization, with subindex "n" referring to the neck of the resonators, and subindex "c" to the geometry of the cavity and "w" to the waveguide.

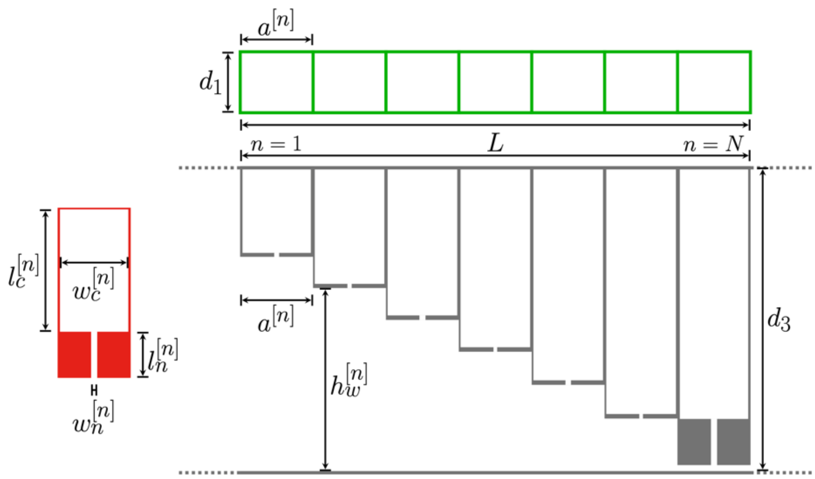

Figure 1 – Geometry of the unit cell of the rainbow trapping absorber, the detail of a single resonator (red) and the top view of the structure (green).

Table 1 –Geometric parameters of the Helmholtz resonators of the rainbow trapping absorber.

n	$a^{[n]}$ (mm)	$h_w^{[n]}$ (mm)	$w_c^{[n]}$ (mm)	$l_c^{[n]}$ (mm)	$w_n^{[n]}$ (mm)	$l_n^{[n]}$ (mm)
1	23.8	70.0	22.3	27.8	1.6	1.2
2	23.8	59.8	22.8	37.9	1.4	1.3
3	23.8	49.5	22.8	48.2	2.1	1.4
4	23.8	39.0	22.8	58.6	1.2	1.4
5	23.8	28.3	22.8	69.3	1.8	1.4
6	23.8	17.2	22.8	80.4	1.1	1.4
7	23.8	2.0	22.3	82.0	2.0	15.0

The unit cell obtained in this way (Fig. 1) may be used as a building block, to create a panel of arbitrary dimensions.

2.2 Numerical simulation of the unit cell

In this section the analytical result of the Transfer Matrix method is compared with a numerical FEM simulation of the unit cell. The geometry used for the simulation is shown in Figure 2.

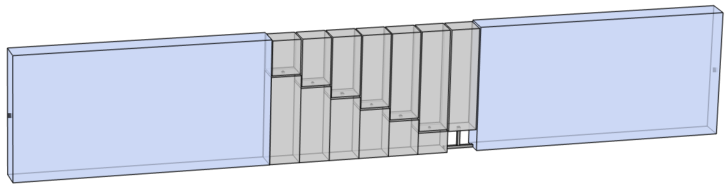

Figure 2 – Geometry used for FEM calculations.

In both cases, the structure shown in Figure 2 presents a nearly flat absorption band from 150 Hz to 475 Hz (see Fig. 3). The absorption spectrum shows peaks of perfect absorption corresponding with the resonance frequencies of the resonators that were tuned to maximize broadband performance, as shown in Figure 3. Increasing the number of resonators in the structure leads to an improved absorption behaviour (flatter curve, with values of absorption coefficient closer to unity in all the band), however the thickness of the structure also increases. Therefore, a compromise must be achieved depending on the problem specifications.

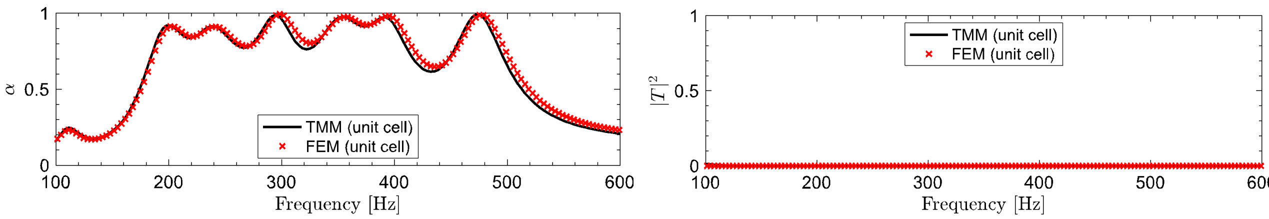

Figure 3 – Absorption and transmission of a single unit cell with TMM and FEM.

In Figure 4, the local behaviour of the whole structure in terms of sound absorption is shown. For that, we plot the acoustic field as obtained from the simulation. We clearly appreciate that sound is concentrated in each resonator at selected frequencies (f_1 = 476 Hz, f_2 = 355 Hz, f_3 = 395 Hz, f_4 = 241 Hz, f_5 = 298 Hz, f_6 = 201 Hz, f_7 = 109 Hz).

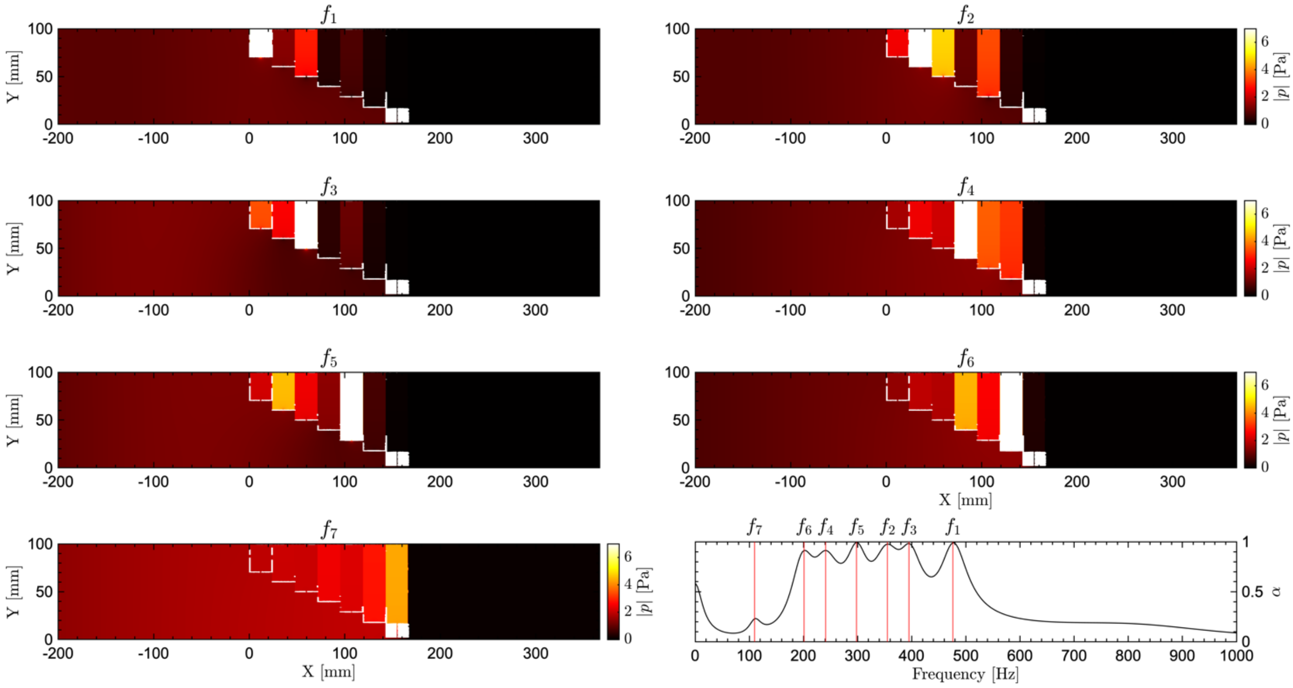

Figure 4 –Acoustic field obtained by FEM simulations at different frequencies. Remark that each frequency excites a different set of resonators.

3 Acoustic response of the metamaterial panel

Because of the complexity of the structure, in particular when the panel is formed by a large number of unit cells, the acoustical response of the panel can not be simulated numerically with available computational tools. For this reason, in this section we obtain the effective parameters of an acoustically equivalent material, which are later used to simulate numerically the acoustical response.

3.1 Effective parameters of the equivalent material

We briefly describe the procedure to obtain the effective bulk modulus and density of the metamaterial designed before by the optimization method (for use specifically in numerical simulation FEM, using equivalent parameters applied to the entire volume of the material instead of simulating the entire geometry). The coefficients of the Transfer matrix, T_{11}, T_{12}, T_{21} and T_{22} are known from the TMM analysis in the preceding section. From them, we can obtain the transmission coefficient as:

$$T = \frac{2e^{jk_0L}}{T_{11}+\frac{T_{12}}{Z_0}+Z_0T_{21}+T_{22}},$$

where $k_0 = \omega/c_0$ is the wavenumber in the air and $Z_0 = \rho_0 c_0$the acoustic impedance in the air. Similarly, the reflection coefficient is found from

$$R = \frac{T_{11} + \frac{T_{12}}{Z_t - T_{21} Z_t - T_{22}}}{T_{11} + \frac{T_{12}}{Z_t} + T_{21} Z_t + T_{22}},$$

where $Z_t = \frac{\sqrt{\rho_0 K_0}}{S}$, with K_0 the bulk modulus of the air and $S=d_1 \cdot d_3$ the transverse section of the cell.

The acoustic input impedance of the equivalent material can be computed from R and T as

$$Z_{\text{in}} = Z_0 \left(\frac{1-R}{1+R}\right)\left(\frac{1-T}{1+T}\right).$$

Finally, both the effective bulk modulus and density of the panel can be obtained as:

$$K_{\text{eff}} = Z_{in} \frac{\omega}{k_{\text{eff}}} \ ,$$

and

$$\rho_{\text{eff}} = Z_{in} \frac{k_{\text{eff}}}{\omega}.$$

where the effective wavenumber along the metamaterial can be also obtained from the TMM coefficients as

$$k_{\text{eff}} = \frac{1}{L} \text{acos}\left(\frac{T_{11} + T_{22}}{2}\right).$$

Numerical FEM simulations can be carried out with a pair of these effective parameters with the same results: the acoustic input impedance and wavenumber, or the bulk modulus and density.

3.2 Numerical model of the panel with effective parameters

The acoustic response of the panel, and how its presence modifies the surrounding acoustic environment, can be computed numerically using FEM simulations. However, due to the huge computational cost of simulating the panel in 3D with the specific geometry of the resonators, instead an equivalent panel with the same effective parameters as calculated in section 3.1 is simulated.

A sound monopolar source is placed at a distance of 2 m from the panel, as shown in Figure 5. Simulations are performed at four different frequencies, all in the working frequency range of the panel, that is from 80 Hz to 500 Hz. A rigid panel is also simulated as a reference (Figure 6).

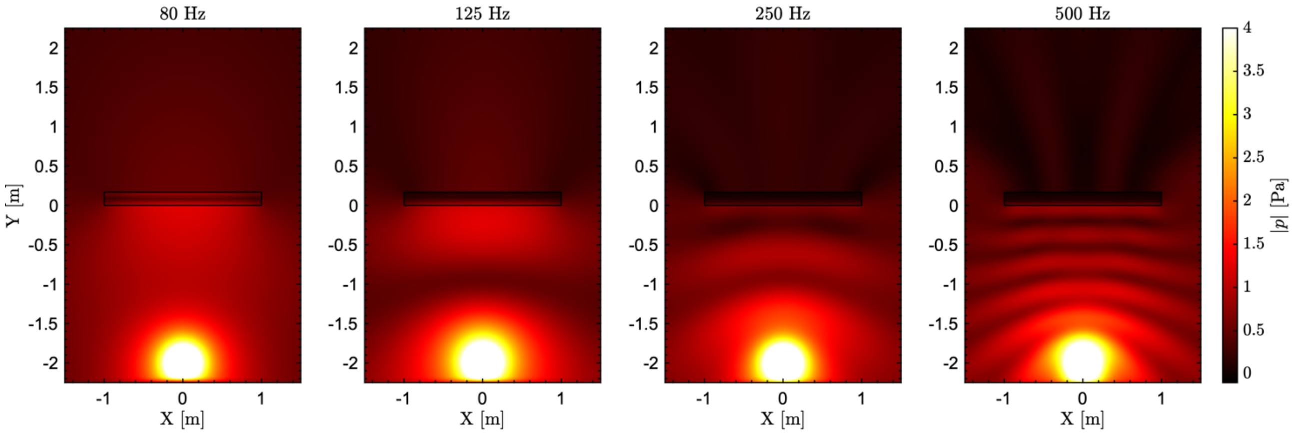

Figure 5 – Acoustical pressure around the metamaterial panel radiated by a monopolar source (FEM simulations using effective parameters).

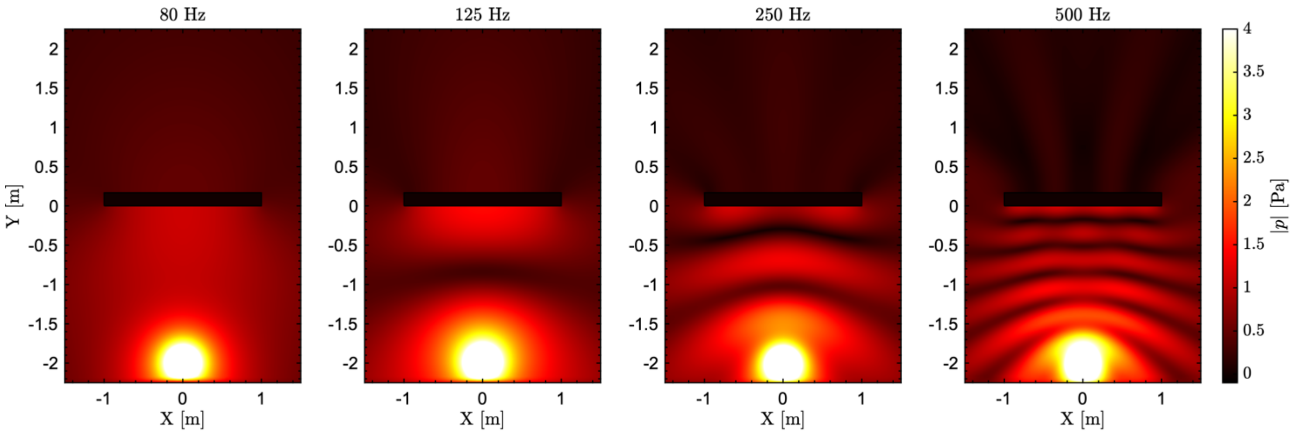

Figure 6 – Acoustical pressure around the rigid panel radiated by a monopolar source (FEM simulations).

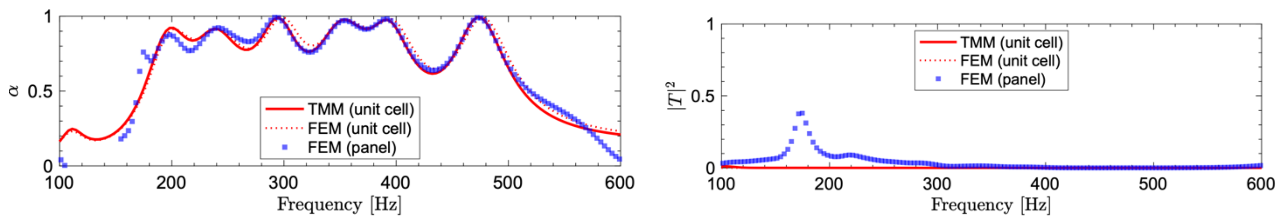

Figure 7 – Acoustic absorption and transmission of the metamaterial a 1.5 m x 2 m panel panel with effective parameters computed with TMM and FEM. Numerical simulations of the single unit cell are plotted (in red)

4 Sample fabrication and experimental test

In this section we describe the design process of the metamaterial unit cell, which will be the building block of the metamaterial panel, its fabrication with the injection technique, and the experimental characterization of the fabricated sample in an impedance tube.

4.1 Unit cell

The unit cell designed by TMM was implemented in CAD, and samples were fabricated for the experimental testing. Figure 8 shows printed samples of both the unit cell and the block composed by 5 unit cells glued together. In this way, the samples fit perfectly into the impedance tube with squared section, where absorption coefficient can be measured and compared with the prediction.
The construction material was in acrylonitrile butadiene styrene (ABS). The sample was constructed by injection in a mold previously fabricated in aluminium. During the manufacture of the unit cell, small modifications were made to the designs to facilitate the joining of multiple cells. Pictures of the fabricated samples are shown in Figure 8.

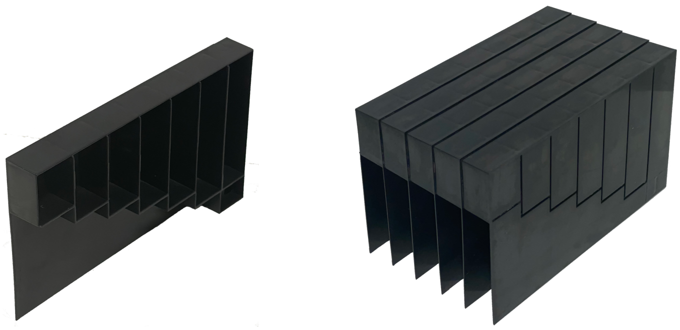

Figure 8 – Experimental prototypes of the unit cell (left) and a block of 5 unit cells with the dimensions of the impedance tube (right). Samples were fabricated in ABS material.

With his method, a panel of arbitrary dimensions can be built, by simply stacking the necessary number of unit cells, which on the other hand can be easily obtained from the mold.
The results of the absorption and transmission coefficients obtained experimentally in an impedance tube are shown in Figure 9 (crosses), together with the theoretical results from TMM (black lines) and FEM simulations (red lines), where a good agreement is observed.

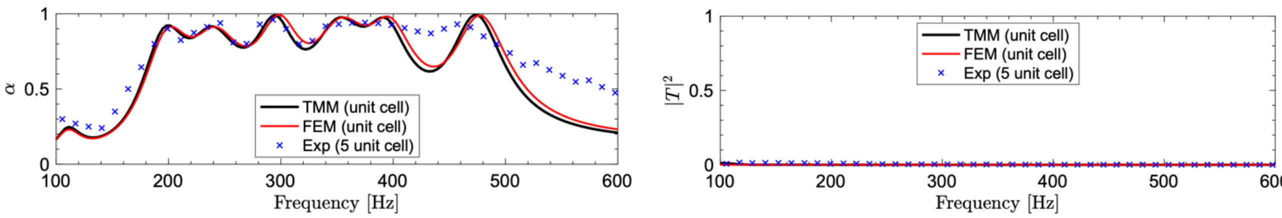

Figure 9 – Experimentally measured absorption and transmission coefficients of a stack of 5 unit cells and comparison with TMM y FEM simulations.

5 Conclusions

In this work we have proposed the use of a metamaterial panel for noise mitigation in aerospace applications, in particular during a rocket launch. Using optimization and transfer matrix methods, a metamaterial presenting broadband absorption is designed. The design procedure of the metamaterial is described, to show an efficient acoustic response in a prescribed frequency band. Samples have been also fabricated and experimentally rested in an anechoic tube.
The acoustic behaviour of a panel formed by nearly 1600 unit cells, with total dimensions of 1.5x2m, has been simulated by using effective acoustical parameters. Future work will consider the fabrication of such a panel,

and its measurement in an anechoic chamber. We expect to observe diffraction effects at the borders of the panel (since wavelengths are comparable with the panel dimensions) which will decrease sound isolation as compared with theoretical predictions for infinite walls and may be relevant for the proposed application.

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