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Numerical modeling of the elementary metamaterial cells for the sound-absorbing structure preparation

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Abstract The increasing popularity of acoustic absorbing metamaterials is followed by the performance problem formulation on the type of elemental acoustic cells used for structure development. The state-of-the-art investigation provided replication problems with common designs and great dispersion in the received results compared to the references, especially on the connection methods between basic metamaterial elements and their shape modification. There is a lack of basic knowledge on the consequences of using basic metamaterial cells typology and a description of its influence and interaction between the resonators. The paper will present the numerical modeling results in COMSOL Multiphysics for the basic metamaterial cells comparison under the sound absorption coefficients – Helmholtz resonators series or quarter-wavelength resonators. Different methods for resonator placement and construction will be discussed. The analysis will cover the possible pipe or cavity bending conclusions for the construction of complex metamaterial structures.

Keywords: electroacoustic, speaker enclosure, quarter-wavelength resonator, Helmholtz resonator.

1. Introduction

Acoustic metamaterials are a novel structure used for sound absorption of diffusion features. Their main advantage usually is the dimensions reduction and aim to work in the range way below the typical absorbers, such as porous media, while keeping the structure size small [1,2]. Metamaterial sound absorbers can achieve an operating frequency range such as 1/40 of wavelength [3] or even 1/223 of wavelength [4]. Typically, they are constructed by the connection of narrow-band resonator series taking the form of quarter-wavelength, Helmholtz, or their mix. Example types of common state-of-art metamaterial structures used by authors are shown in Fig. 1.

Figure 1. Examples of metamaterial structures based on the Helmholtz resonator.

In this project, the state-of-art references were investigated, and it found that the optimum metamaterial structure construction can be the spatial problem as if only the resonator placement is the main feature in most metamaterials. By multiplying them, we can achieve wider absorption ranges based on the summation of multiple resonant frequencies. However, the references usually do not cover the basic information on the consequences of different canals and cavities bounding and its influence on the structure performance. This research investigated some cases with different canal and cavity forms for basic metamaterial cells. Performing the FEM sound absorption calculation, the conclusions on possible resonator modifications regarding metamaterial construction were described.

2. Elementary cells in metamaterial structure design – FEM simulation

The previous work in resonator bending was covered by Tristan Cambonie [5]. This paper described the single-bend in the quarter-wavelength resonator and comprehensively described thermal and viscous losses occurring in the narrow canal regions. It was proved that bending a single canal quarter-wavelength resonator could raise its resonant frequency from 920 Hz to 970 Hz. However, the common metamaterial structures usually contain multiple bends and try to adapt to the minimal space with their parts by using multiple bending and cavity modification. Also, the previous works do not cover the Helmholtz resonator type. To reflect current needs in metamaterial construction, we have decided to investigate a more complex case for a quarter-wavelength resonator, including a canal that can be bent by 90 degrees several times to adjust its space to the structure. We have also investigated some fundamental Helmholtz resonators by straightening the structure described in [4]. The impedance tube measurements method is the most common method of experimental tests of basic acoustic structures [6–8]. In this case, we wanted to exclude the possible measurements, especially the problems with the proper sample preparation. Following the methodology shown in [9], to extend the knowledge of the possible shape modification of resonators, we have prepared the FEM model in COMSOL Multiphysics 5.3 by simulating the impedance tube sound absorption coefficient measurements[6], the standard method for sound absorption modeling. The drawing of the prepared model in COMSOL is shown in Fig. 2.

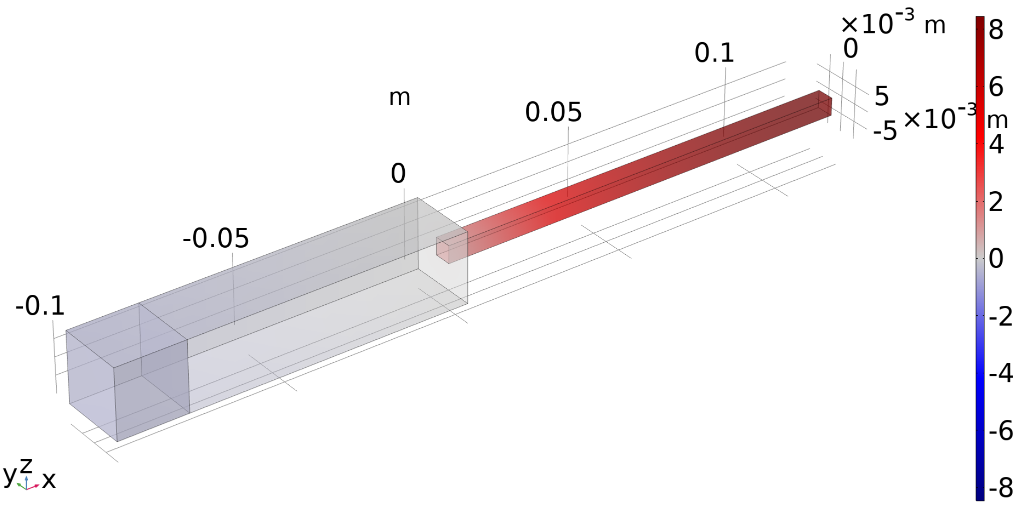

Figure 2. The FEM model for basic metamaterial cells simulation.

We have used the background pressure field acoustic condition simulating the plane wave radiation along the tube environment to prepare the correct impedance tube simulation. While preparing the physic formulation in COMSOL, we tested the different resonator problem solutions, including the narrow-region and thermoviscous acoustic models [10]. Both of them provided proper solutions. However, in very fast canal geometry changes and on the arc, the thermovicscous model seems to reflect better the model physics similar to in [5]. The narrow acoustic region physics advantage is the faster calculation time. The exact influence of using the physic formulation in FEM software should be investigated in future papers.

3. Quarter-wavelength resonator - numerical verification of metamaterial cell placement

Using the quarter-wavelength resonators in metamaterial structure preparation is popular because solid analytical models are available for solving their equations, allowing fast optimization. However, the analytical model usually does not cover the structures' geometrical arrangement or include further geometry canal modification as the metamaterial structures are usually not constructed from straight canal lines. To expand the study of basic canal bending, some geometries were prepared with a different number of bends and another bend at the canal opening. The canal length was kept the same in all cases. The tested geometries and their modeled absorption coefficient is shown in Fig. 3. For the clarity of the drawings, we kept the same scale for each element.

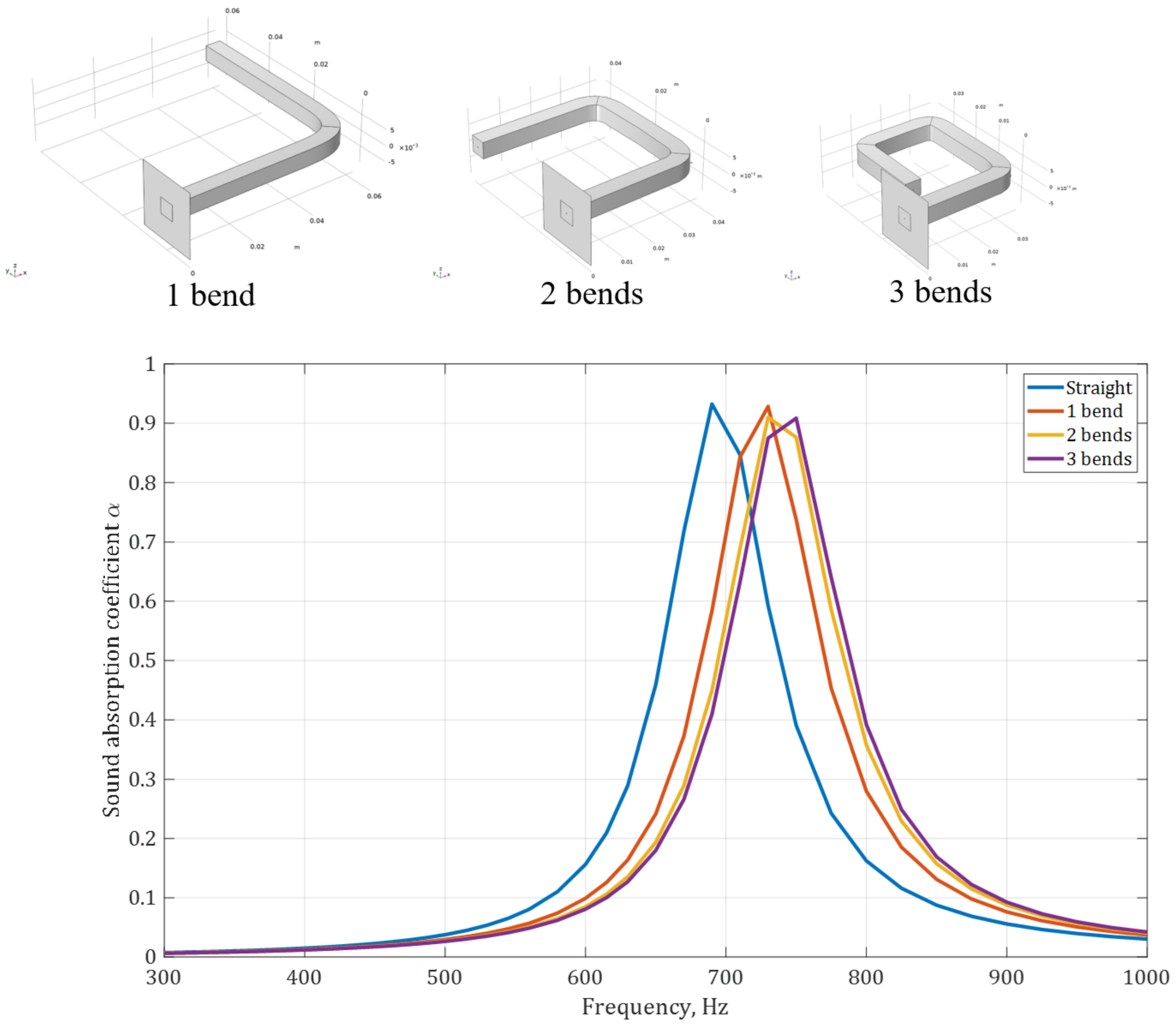

Figure 3. The effect of canal bending in quarter-wavelength resonator modeling.

The absorption peak in those models varied from 690 Hz through 730 Hz (1 and 2 bends) up to 750 Hz in the 3 bends model. Like previous research, the first bend changes the system's resonant frequency by 40-50 Hz. However, further bends like 2nd and 3rd do not affect the system as much. The change was noted at about 20 Hz from the previous frequency. To investigate this topic further, we performed additional simulations with one more band at the canal entrance and simulated the difference between sharp and rounded canal bending. The effects are shown in Fig. 4.

Following the previous research, it occurred that while the canal bend is performed for a 90-degree angle, without rounding, the frequency shift effect is significantly smaller (around 10 Hz). Also, performing the perpendicular bend right after the opening did not significantly affect the absorption coefficient. The sharp type of bending proved not to affect the absorption at all, which may lead to the conclusion that this type of connection is a much better option than rounded bending.

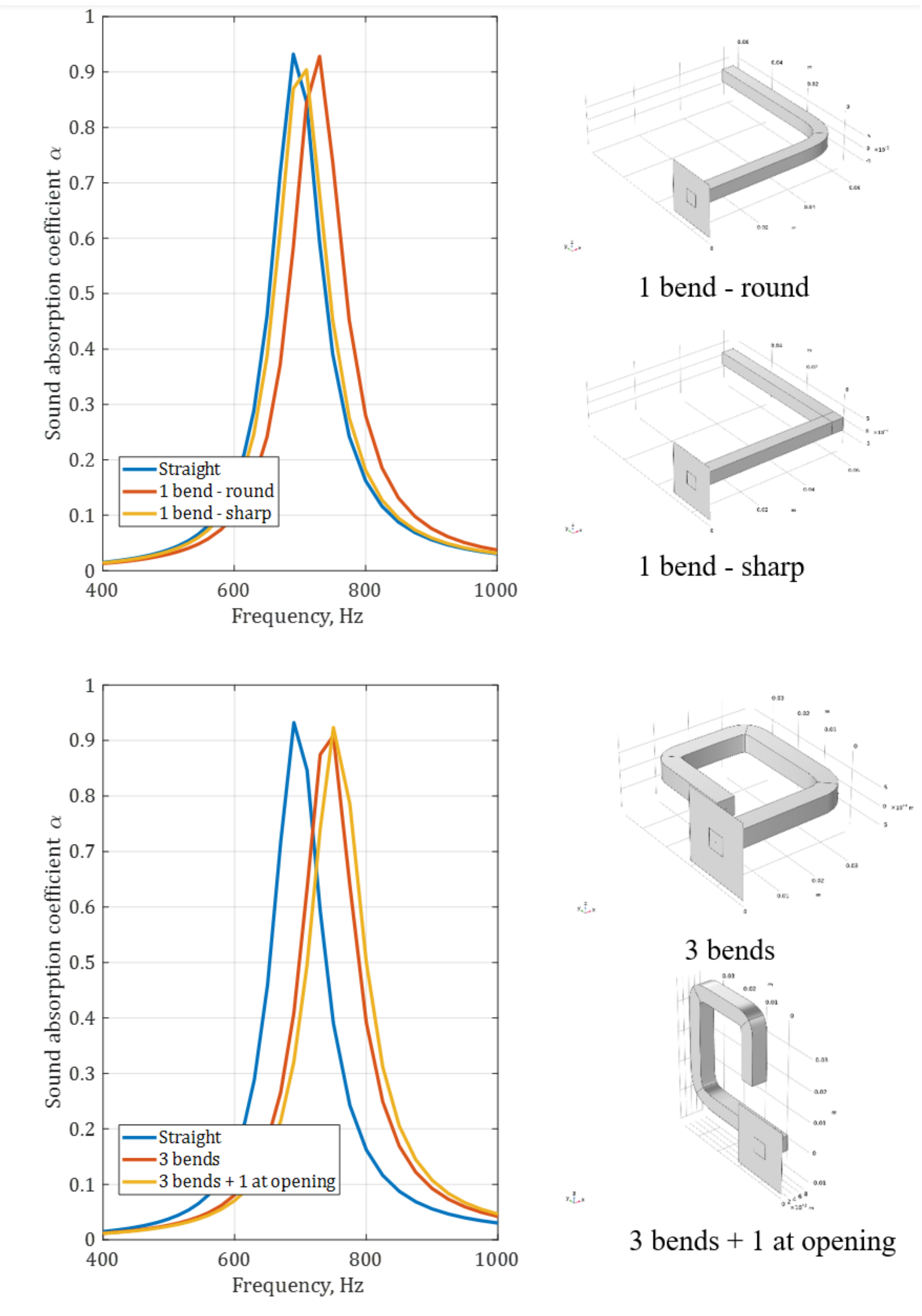

Figure 4. The effect of canal bending in quarter-wavelength resonator modeling – sharp vs. round bending and additional entrance bending.

It was proved that sharp bending in the quarter-wavelength resonators has a significantly smaller effect on the structure work, which may be necessary for optimized metamaterial structure generation. Further investigation with thermoviscous loss analysis is required for this type of connection.

4. Helmholtz resonator – numerical verification of metamaterial cell placement

The second analyzed object type was the Helmholtz resonator. Based on the lumped parameter model, the crucial parameters are the aperture parameters and cavity volume [11], so the exact shape and length of the cavity usually are neglected. In this case, we performed the sample metamaterial cell based on [4], which is the form of Helmholtz resonator. Two structure versions were prepared, tuned for 150 Hz and 550 Hz. Calculated sound absorption is shown in Fig. 5. and 6.

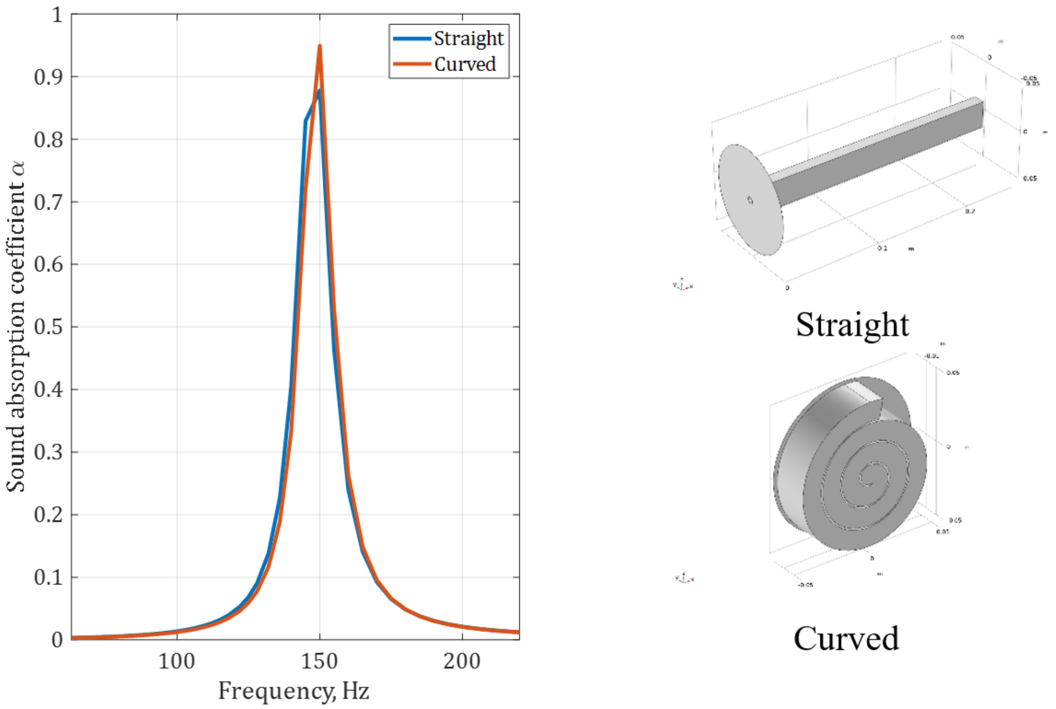

Figure 5. The effect of canal and cavity bending in Helmholtz resonator modeling – metasurface tuned for 150 Hz absorption.

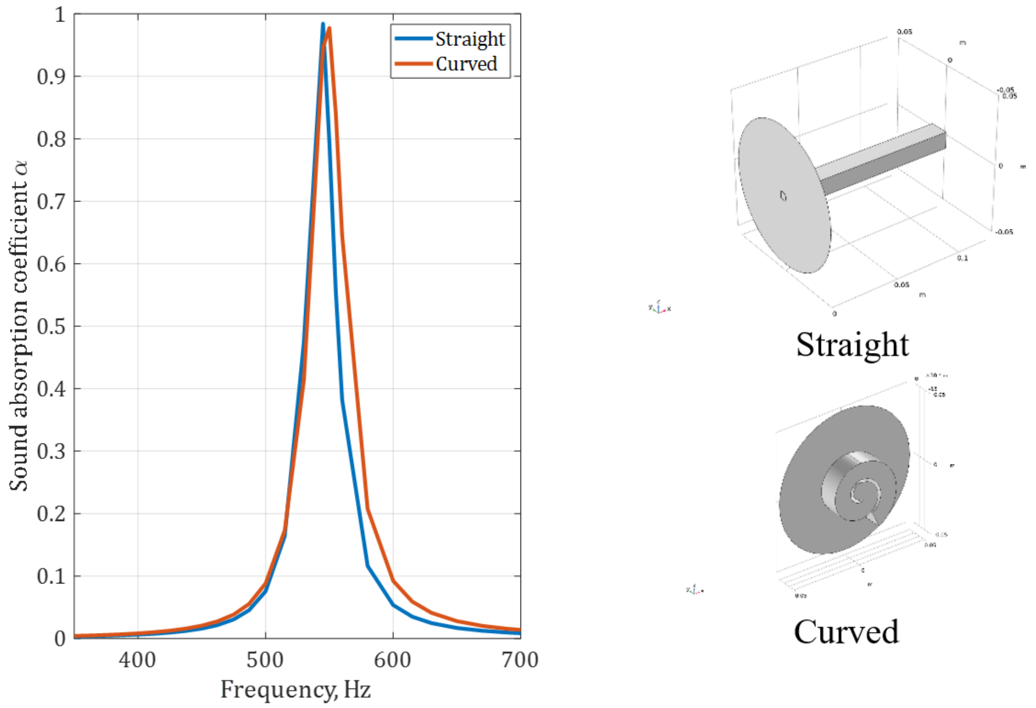

Figure 6. The effect of canal and cavity bending in Helmholtz resonator modeling – metasurface tuned for 550 Hz absorption.

Two resonators on two resonant frequencies were modeled to check if the frequency shift effect may be relative. In both cases, we did not observe significant resonant frequency shifts for the Helmholtz resonator metamaterial cell. It may be caused by a different type of absorption mechanism relying on the air mass closed in the space after the aperture, which may be less sensitive to narrow geometry regions and shape changes until the mass and volume remain the same. This is an important finding and should lead to further investigation into cavity shape modification. The viscous losses should also be investigated, similar to the methods proposed in [5].

5. Summary and future works

The current research aimed to verify selected cases of resonant metamaterial cell placement and shape modification and asses their influence on the simulated sound absorption coefficient. Based on the investigated cases, to avoid the resonant frequency shift with the modification of the quarter-wavelength resonator shapes, the following conclusions are proposed:

- Sharp bending I opposite to rounded one,
- Perpendicular bending at the opening,
- More than 2 bends in the same canal.

In the tests of the Helmholtz resonator, we did not observe significant resonant frequency shifts, so this type of structure may be easier to use in further optimization-based structures prepared with analytical solutions. The proposed findings can lead to better space management and optimization in metamaterial structure construction, emphasizing the size reduction feature for this type of acoustic material.

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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