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Thin sound absorbers with coiled and coupled resonators

Krushynska, Anastasiia1[1]
ENTEG, Faculty of Science and Engineering, University of Groningen
9747 AG Groningen, the Netherlands

ABSTRACT

Acoustic metamaterials offer fascinating opportunities for manipulating sound and the development of compact devices with broadband performance. The ability of resonant-based metamaterials to induce slow sound has recently been exploited to design thin sound absorbers at deep subwavelength frequencies. In this work, we show that the combination of the slow sound conditions with the space-coiling and/or coupled-resonator mechanisms allows further reducing the panel thickness and overcoming the narrow-band performance imposed by the resonant nature of the wave dispersion. The space coiling implies here spatial folding of the resonator aimed at reducing the overall structural sizes, while a coupled resonator is represented by a Helmholtz resonator with a cavity partitioned into two or more parts by one or several supplementary necks. We show that the coupled resonator possesses an additional absorption peak at low frequencies, whose frequency can be tuned by varying the resonator geometric parameters. The advantages of the proposed design ideas are demonstrated numerically, and experimental validation for 3D-printed prototypes is envisioned. We hope that the proposed results provide possible directions that could be further investigated and could increase the potential of acoustic metamaterials for industrial applications.

Keywords: Sound Absorption, Acoustic Metamaterial, Helmholtz Resonator
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1. INTRODUCTION

Recent advances in acoustic metamaterials have enabled us to achieve unprecendented properties going far beyond of those for conventional materials [1–5]. For instance, the ability of manipulating low-frequency acoustic waves by subwavelength meta-structures has paved the way to the development of compact sound absorbers [2, 6]. One of the well-studied absorption mechanisms is based on the use of Helmholtz resonators (HRs), which can perfectly absorb sound at low frequencies if the critical coupling conditions are

[1]akrushynska@gmail.com

satisfied [7]. The resonant nature of this mechanism results in narrow-band performance limiting application possibilities of the meta-structures.

Here we numerically analyze two promising approaches for extending sound absorption in HR-based acoustic metamaterials to broadband frequencies by reducing the overall structural thickness. The first approach relies on the interactions of coiled detuned HRs sharing the spatial location. We demonstrate that proper detuning of the HR eigenfrequencies enables broadband absorption due to merging isolated absorption peaks of the individual HRs. The second approach utilizes the idea of coupled HRs, when the neck of one HR is attached to a cavity of another HR. The simulations reveal that a coupled HR has two low-frequency absorption peaks. The frequencies of the peaks are sensitive to the mutual arrangement of the HR cavities. Optimizing the geometry and eigenfrequencies of several detuned coupled HRs, one can achieve quasi-perfect sound absorption at different frequency ranges. Below, after the description of the employed numerical model, we illustrate the advantages of the proposed approaches by several examples.

2. NUMERICAL MODELS AND METHODS

Let us study the absorption of air-borne sound by thin rigidly-backed panels with periodic sets of cylindrical cavities of depth L arranged in a rectangular lattice and loaded by N HRs. The surface of a panel is assumed to coincide with Oxy place, and the lattice pitches are a_x and a_y along the x and y directions, respectively. The kth HR ($k = 1, \ldots, N$) is formed by a cylindrical cavity of radius $R_c^{(k)}$ and length $L_c^{(k)}$ attached to the panel cavity by a cylindrical neck of radius $R_n^{(k)}$ and length $L_n^{(k)}$. At the analyzed frequencies, the wavelength of incident sound waves is always larger than $\max_k \left\{L_n^k + L_c^k\right\}$, so that the panel cavities loaded by the HRs behave as asymmetric Fabry-Perót cavities with N point-like resonant scatterers [6, 7].

Due to the structural periodicity, the analysis is restricted to a representative building block, containing a single cavity, with Bloch-type boundary conditions for pressure at the faces normal to x and y axes. The air outside and inside the block is represented by a three-dimensional finite-element fine-meshed model in COMSOL Multiphysics with the parameters listed in Ref. [8]. The visco-thermal losses in the cavities and the HRs are taken into account by means of effective material parameters [6, 8]. At the boundaries between the air domains and solid parts of the panel, sound-hard boundary conditions are applied. For normally incident sound, the absorption coefficient is estimated as $\alpha = 1 - |R|^2$, where the magnitude of the complex-valued reflection coefficient R is calculated in a standard way by evaluating acoustic pressure at two aquisition points.

3. RESULTS AND DISCUSSION

3.3.1. HRs sharing the spatial location

We consider a building block with six detuned HRs arranged on a rigidly-backed tube of radius $R_t = 7$ mm and length $L = 9$ cm at a center-to-center distance $a = L/6$ (Fig. 1a). The HR parameters are $R_n = 2.5$ mm, $R_r = 5$ mm, $L_{HR} = L_r + L_n^{(k)} = 11.92$ cm for all HRs, and $L_n^{(1)} = 5$ mm, $L_n^{(2)} = 10$ mm, $L_n^{(3)} = 15$ mm, $L_n^{(4)} = 25$ mm, $L_n^{(5)} = 35$ mm, $L_n^{(6)} = 45$ mm for each single HR when numbered from the open end of the tube.

The absorption coefficient α for the panel composed of these blocks exhibits six peaks

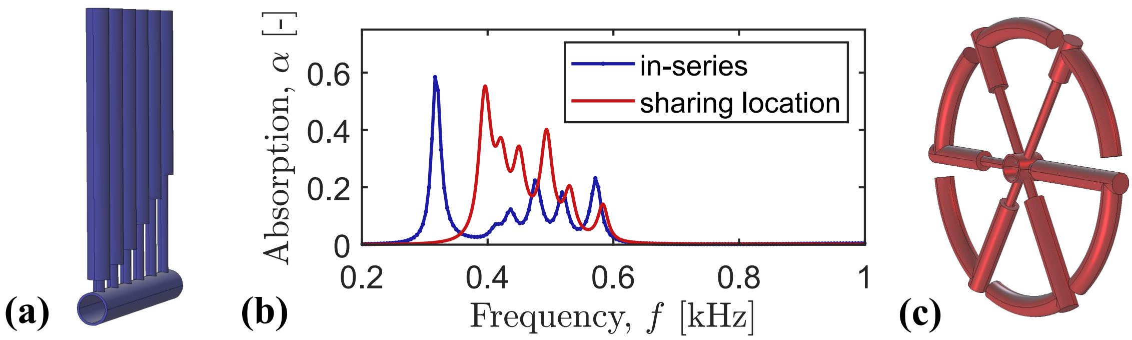

Figure 1: (a) Six detuned cylindrical HRs arranged in-series on a rigidly-backed tube. The sound waves impinge the visible end of the tube. (b) Absorption coefficient of the panel with periodically perforated cavities with six HRs arranged either in-series (the blue curve) or sharing the spatial location (the red curve). (c) Six detuned coiled HRs sharing the spatial location on a rigidly-backed tube.

at frequencies below 1 kHz, which are uniformly distributed between 316 Hz and 521 Hz (the blue curve in Fig. 1b). The overall absorption in this frequency range is below 0.2, expect the first peak with $\alpha = 0.58$. To increase α, we propose rotating the HRs by 60° and moving them towards the air domain, so that they have an identical z coordinate. The length of the tube can thus be reduced to $L/6$.

The simulations show that after these manipulatons, the panel absorption is increased up to 200% at certain frequencies and exceeds 0.2 at the first five peaks and frequencies between them, resulting thus in a broadband absorption (Fig. 1b). The explanation to this can be found from the analysis of the pressure distribution at the peaks, revealing that each HRs sharing the spatial location contributes to the wave absorption at every peak, in contrast to the "in-series" placement when one or several HRs remain unexcited at the HR resonant frequencies (see Ref. [8] for more details). The absorption can be improved further by adjusting the cavity resonance $f_t = c_0/4L$ (with c_0 indicating the speed of sound) to the frequency of the sixth peak [6, 8]. Note that in order to minimize the panel lateral sizes, we coil the HR cavities (Fig. 2c) that does not influence the frequencies of the absorption peaks. Finally, the panel absortion can be maximized by optimizing the HR geometries with the aim to satisfy the critical coupling conditions [6, 7].

3.3.2. Coupled HRs

To illustrate the absorption efficiency of a panel with coupled HRs, we design the latter by partitioning the HR cavities by supplementary necks. This approach allows comparing directly the performance of coupled HRs with their individual counterparts.

For instance, a tube ($L_t = 2$ cm, $R_t = 7$ mm) loaded by a single HR with parameters $L_{r1} = 12$ cm, $R_{r1} = 7.4$ mm, $L_{n1} = 5$ mm, $R_{n1} = 6.75$ mm is characterized by a single absorption peak $\alpha_1 = 0.983$ at $f_1 = 589$ Hz below 1.7 kHz. When the HR cavity is partitioned into two equal parts by a neck of length $L_{n2} = 1$ mm and radius $R_{n2} = 2.75$ mm, the system has already two peaks $\alpha_1 = 0.951$ and $\alpha_2 = 0.885$ at $f_1 = 553$ Hz and $f_2 = 1557$ Hz, respectively. Thus, the increase of the HR length by L_{n2} (less than 0.8% of the total HR length in the considered case) provides an additional absorption peak with a high value of α at low frequencies, while, importantly, the frequency and absorption at the first peak remain almost unchanged. This feature enables

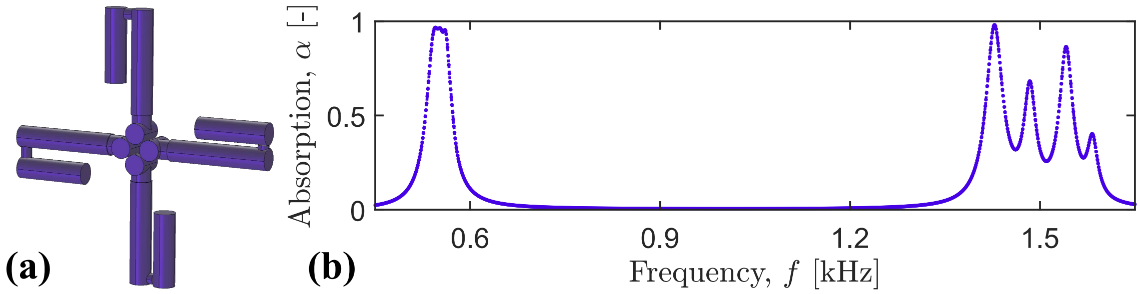

Figure 2: (a) The building block with four rigidly-backed tubes loaded by coupled HRs. The HRs have identical parameters except the length of the supplementary neck. (b) Absorption coefficient of the panel composed of the blocks shown in (a).

to design panels of compact sizes capable of absorbing sound at wide frequency ranges.

The performed numerical analysis reveals that f_2 and α_2 depend on the length and the radius of the supplementary neck, as well as the mutual location of the coupled HR cavities. By properly choosing these parameters, one can tune the absorption peaks to desired frequencies and absorption values.

As an example, we consider a building block with four tubes loaded by coupled HRs. The tube and HR geometries are the same as described above, and the center-to-center distance between the tubes is R_t. The only difference between the HRs is the length of the supplementary neck, namely, $L_{n2}^{(1)} = 2$ mm, $L_{n2}^{(2)} = 3$ mm, $L_{n2}^{(3)} = 5$ mm, $L_{n2}^{(4)} = 7$ mm (Fig. 2a). A panel composed of these blocks is characterized by a broadband quasi-perfect ($\geq 95\%$) absorption between 542 and 562 Hz and an additional broadband absorption range between 1400Hz and 1590Hz with $\alpha \geq 27\%$ (Fig. 2b). Obviously, it is possible to further optimize the panel geometry with the aim to extend the absorption frequencies or improve the absoprtion value. However, this example already reveals that a system with coupled HRs can efficiently attenuate low-frequency sound at several frequency ranges by preserving compact structural sizes.

4. CONCLUSIONS

In this work, we proposed to extend the sound absorption in rigidly-backed panels by allowing internal HRs to share the spatial location or empoying the concept of coupled HRs. These design approaches are especially suitable for applications with severe restrictions on the structural thickness. In order to minimize the lateral dimensions of the panels, we suggest coiling the HR cavities or wave propagation paths [3,9]. We hope that the proposed approaches will be of use for the development of novel designs of sound absorbers, possibly in combination with other wave attenuation mechanisms [10], and their future practical implementation.

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6. REFERENCES

[1] S.A. Cummer, J. Christensen, and A. Alu. Controlling sound with acoustic metamaterials. *Nat. Rev. Mater.*, 1(3):16001, 2016.

[2] B. Liang, J.-C. Cheng, and C.-W. Qui. Wavefront manipulation by acoustic metasurfaces: from physics and applications. *Nanophotonics*, 7(6):1–15, 2018.

[3] A.O. Krushynska, F. Bosia, M. Miniaci, and N.M. Pugno. Spider web-structured labyrinthine acoustic metamaterials for low-frequency sound control. *New J. Phys.*, 19:105001, 2017.

[4] B. Cheng, H. Hou, and N. Gao. An acoustic metasurface with simultaneous phase modulation and energy attenuation. *Mod. Phys. Lett. B*, 32(23):1850276, 2018.

[5] A. Bozhko, J. Sanchez-Dehesa, F. Cervera, and A. Krokhin. Redirection and splitting of sound waves by a periodic chain of thin perforated cylindrical shells. *Phys. Rev. Appl.*, 7(6):064034, 2017.

[6] N. Jiménez, V. Romero-García, V. Pagneux, and J.P. Groby. Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems. *Sci. Rep.*, 7:13595, 2017.

[7] J.P. Groby, R. Pommier, and Y. Aurégan. Use of slow sound to design perfect and broadband passive sound absorbing materials. *J. Acoust. Soc. Am.*, 139:1660–1667, 2016.

[8] A.O. Krushynska. Between science and art: thin sound absorbers inspired by Slavic ornaments. *Front. Mater.*, 2019.

[9] A.O. Krushynska, F. Bosia, and N.M. Pugno. Labyrinthine acoustic metamaterials with space-coiling channels for low-frequency sound control. *Acta Acust. united Ac.*, 104:200–210, 2018.

[10] N. Gao, Z. Wei, H. Hou, and A.O. Krushynska. Design and experimental investigation of V-folded beams with acoustic black hole indentations. *J. Acoust. Soc. Amer.*, 145(1):EL79–EL83, 2019.