Proceedings of the

ICA 2019 AND EAA EUROREGIO

23rd International Congress on Acoustics, integrating 4th EAA Euroregio 2019

9 - 13 September 2019, Aachen, Germany

ISSN 2226-7808 and 2415-1599
ISBN 978-3-939296-15-7

PROCEEDINGS of the
23rd International Congress on Acoustics
9 to 13 September 2019 in Aachen, Germany

Perfect acoustic absorption in deep sub-wavelength structures for the ventilation problems with degenerate resonators

Vicente Romero García[1], Noé Jiménez[2], Olivier Richoux[1], Georgios Theocharis[1], Jean Philippe Groby[1] and Vincent Pagneux[1]

(1)Laboratoire d'Acoustique de l'Université du Mans, UMR CNRS 6613, Le Mans, France
(2)Instituto de Instrumentación para Imagen Molecular, Consejo Superior de Investigaciones Científicas, Universitat Politècnica de València, València, Spain

Abstract

In this work we report a mechanisms providing symmetric perfect acoustic absorption by sub-wavelength structures in the ventilation problem. While in the problem of reflection the mechanism consists in critically coupling a single resonance independently of its nature, the problem of transmission becomes more complicated and a degenerate resonator with symmetric and antisymmetric resonances should be designed with both resonances critically coupled. The system analyzed in this work is made by a panel with a periodic distribution of slits, the upper wall of which are loaded by Helmholtz Resonators. The propagation in the slit is highly dispersive due to the presence of the resonators, producing a slow sound propagation before the resonance, and down shifting it to low frequencies. By controlling the geometry of the resonator, the visco-thermal losses can be tuned in order to compensate the leakage of the system and fulfill the critical coupling condition so activating the perfect absorption of sound. In the case of transmission, a double slit is needed, one acting as symmetric and the other one as antisymmetric resonators.

Keywords: Acoustic metamaterials, Acoustic metasurfaces, Perfect absorption

The ability to perfectly absorb an incoming wave field by a sub-wavelength material is advantageous for several applications in wave physics. This challenge requires to solve a complex problem: reducing the geometric dimensions of the structure while increasing the density of states at low frequencies and finding the good conditions to match the impedance to the background medium. A successful approach for increasing the density of states at low frequencies with reduced dimensions is the use of metamaterials. Recently, several possibilities based on these systems made of open lossy resonant building blocks have been proposed to design sound absorbing structures which can present simultaneously sub-wavelength dimensions and strong acoustic absorption [1, 2]. Among them, Helmholtz resonators (HRs) have been shown as potential candidates to solve the problem due to the tunable possibilities they offer [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

These open resonant lossy systems, at the resonant frequency, are characterized by both the leakage rate of energy (i.e., the coupling of the resonant elements with the propagating medium) and the intrinsic losses of the resonator. The interaction of an incoming wave with this lossy resonant structure, in particular, the impedance matching with the background field, can be achieved when the energy leakage perfectly compensates the inherent losses. This is known as the critical coupling condition, allowing the energy to be trap around the resonant elements and generating a maximum of energy absorption. In the case of reflecting system (one port systems), either symmetric or antisymmetric resonances that are critically coupled can be used to obtain perfect absorption of energy by a perfect trapping of energy around the resonators. In the case of transmission systems, degenerate critically coupled resonators with symmetric and antisymmetric resonances or systems with broken symmetry can be used to perfectly absorb the incoming energy. In this work we report the possibility to create degenerate resonators.

This methodology has been shown as an efficient tool to design broadband acoustic absorbers in the low frequency range. In our case, fine tuning of the losses [11, 12] and of the geometric characteristics [13, 14] of the sub-wavelength resonators leads to the crossing of the complex zeros of the eigenvalues of the scattering matrix with the real axis which signifies the perfect absorption condition. This methodology has been also used to design efficient broadband absorbers in the low frequency regime.

Let us consider a two-port, one-dimensional and reciprocal scattering process. The relation between the amplitudes of the incoming (a, d), and outcoming (b, c) waves, on both sides of the scatterer Σ, is given by

$$\begin{pmatrix} c \\ b \end{pmatrix} = \mathbf{S}(f)\begin{pmatrix} a \\ d \end{pmatrix} = \begin{pmatrix} T & R^{+} \\ R^{-} & T \end{pmatrix}\begin{pmatrix} a \\ d \end{pmatrix}, \qquad (1)$$

where $\mathbf{S}(f)$ is the scattering matrix (S-matrix), f is the incident wave frequency, T is the complex transmission coefficient, R^{-} and R^{+} are the complex reflection coefficients for left $(-)$ and right $(+)$ incidence, respectively. In this work, the time dependence convention of the harmonic regime is $e^{-i\omega t}$, and it will be omitted in the following. The eigenvalues of the $\mathbf{S}$-matrix are expressed as $\lambda_{1,2} = T \pm [R^{-}R^{+}]^{1/2}$ and the eigenvectors of the system are $\mathbf{v_1} = (v_{11}, v_{12}) = \left(R^{+}, -\sqrt{R^{+}R^{-}}\right)$ and $\mathbf{v_2} = (v_{21}, v_{22}) = \left(\sqrt{R^{+}R^{-}}, R^{+}\right)$. Therefore, the ratio of the eigenvector components v_{1i} and v_{2i} is $v_{2i}/v_{1i} = (-1)^{i}(R^{-}/R^{+})^{1/2}$. A zero eigenvalue of the $\mathbf{S}$-matrix corresponds to the case in which the incident waves can be completely absorbed ($b = c = 0$). This, called coherent perfect absorption (CPA) [**?**], happens when $T = \pm[R^{-}R^{+}]^{1/2}$ and the incident waves a, d correspond to the relevant eigenvector.

If the scatterer Σ is mirror symmetric, $R^{+} = R^{-} \equiv R$ and the problem can be reduced to two uncoupled sub-problems by choosing incident waves that are symmetric or antisymmetric with the reflection coefficients $R_s = R + T$ and $R_a = R - T$. In particular, the reflection and transmission coefficients of the initial problem can be expressed as $R = (R_s + R_a)/2$, and $T = (R_s - R_a)/2$ while the eigenvalues of the $\mathbf{S}$-matrix can be written as $\lambda_1 = R_s$ and $\lambda_2 = -R_a$. For an one-sided incident wave, the absorption coefficient defined as $\alpha = 1 - |R|^2 - |T|^2$ becomes $\alpha = (\alpha_s + \alpha_a)/2$, where $\alpha_s \equiv 1 - |R_s|^2$ and $\alpha_a \equiv 1 - |R_a|^2$. Achieving $\alpha(f_{max}) = 1$ at a frequency f_{max}, is equivalent to getting simultaneously the minima of the reflection coefficients of the two sub-problems, i.e., $R_a(f_{max}) = R_s(f_{max}) = 0$ $[\alpha_s(f_{max}) = \alpha_a(f_{max}) = 1]$. This has been achieved in Ref. [**?**] for a mirror symmetric slab through intensive numerical calculations.

In this talk we analyze the perfect absorption in ventilation problems by using mirror symmetric scatterers made by a panel with a periodic distribution of slits, the upper wall of which are loaded by Helmholtz Resonators. The propagation in the slit is highly dispersive due to the presence of the resonators, producing a slow sound propagation before the resonance, and down shifting it to low frequencies. By controlling the geometry of the resonator, the visco-thermal losses can be tuned in order to compensate the leakage of the system and fulfill the critical coupling condition so activating the perfect absorption of sound. In the case of transmission, a double slit is needed, one acting as symmetric and the other one as antisymmetric resonators.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the ANR-RGC META- Room (ANR-18-CE08-0021) project and the project HYPERMETA funded under the program E?toiles Montantes of the Région Pays de la Loire. This article is based upon work from COST (European Cooperation in Science and Technology) Action DENORMS CA15125, supported by COST (European Cooperation in Science and Technology).

REFERENCES

[1] V. Romero-García, G. Theocharis, O. Richoux, A. Merkel, V. Tournat, and V. Pagneux. Perfect and broadband acoustic absorption by critically coupled sub-wavelength resonators. *Scientific Reports*, 6:19519 EP –, 01 2016.

[2] N. Jiménez, W. Huang, V. Romero-García, V. Pagneux, and J.-P. Groby. Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption. *Applied Physics Letters*, 109(12):121902, 2016.

[3] V. Romero-García, G. Theocharis, O. Richoux, and V. Pagneux. Use of complex frequency plane to design broadband and sub-wavelength absorbers. *The Journal of the Acoustical Society of America*, 139(6):3395–3403, 2016.

[4] A. Merkel, G. Theocharis, O. Richoux, V. Romero-García, and V. Pagneux. Control of acoustic absorption in one-dimensional scattering by resonant scatterers. *Applied Physics Letters*, 107(24):244102, 2015.

[5] Noé Jiménez, Vicent Romero-García, Vincent Pagneux, and Jean-Philippe Groby. Quasiperfect absorption by subwavelength acoustic panels in transmission using accumulation of resonances due to slow sound. *Phys. Rev. B*, 95:014205, Jan 2017.

[6] Noé Jiménez, Vicent Romero-García, Vincent Pagneux, and Jean-Philippe Groby. Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems. *Scientific Reports*, 7(1):13595, 2017.

[7] N Jiménez, V Romero-García, J Groby Perfect absorption of sound by rigidly-backed high-porous materials. *Acta Acustica united with Acustica*, 104(3):396–409, 2018.

[8] J.-P. Groby, W. Huang, A. Lardeau, and Y. Aurégan. The use of slow waves to design simple sound absorbing materials. *Journal of Applied Physics*, 117(12):124903, 2015.

[9] J.-P. Groby, R. Pommier, and Y. Aurégan. Use of slow sound to design perfect and broadband passive sound absorbing materials. *The Journal of the Acoustical Society of America*, 139(4):1660–1671, 2016.

[10] V. Achilleos, O. Richoux, and G. Theocharis. Coherent perfect absorption induced by the nonlinearity of a helmholtz resonator. *The Journal of the Acoustical Society of America*, 140(1):EL94–EL100, 2016.

[11] Michael R Stinson. The propagation of plane sound waves in narrow and wide circular tubes, and generalization to uniform tubes of arbitrary cross-sectional shape. *J. Acoust. Soc. Am.*, 89(2):550–558, 1991.

[12] C. Zwikker and C.W. Kosten. *Sound absorbing materials*. Elsevier Publishing Company, Inc., Amsterdam, 1949.

[13] Vincent Dubos, J Kergomard, A Khettabi, J-P Dalmont, DH Keefe, and CJ Nederveen. Theory of sound propagation in a duct with a branched tube using modal decomposition. *Acta Acustica united with Acustica*, 85(2):153–169, 1999.

[14] J Kergomard and A Garcia. Simple discontinuities in acoustic waveguides at low frequencies: critical analysis and formulae. *J. Sound Vib.*, 114(3):465–479, 1987.

[15] A. Santillan and S. I. Bozhevolnyi. Acoustic transparency and slow sound using detuned acoustic resonators. *Phys. Rev. B*, 84:064394, 2011.