Deep Sub-wavelength Materials for Controlling Sound Diffusion: Experimental Validation of Metadiffusers

E. Ballestero[1], N. Jiménez[2], J.-P. Groby[2], S. Dance[1] and V. Romero-García[2*],

[1]London South Bank University, Department of The Built Environment,
90 London Road, London, SE16LN, United Kingdom.
[2]Consejo Superior de Investigaciones Científicas (CSIC), Universitat Politècnica de València,
Camino de Vera S/N, 46085, València, Spain.
[3]Laboratoire d'Acoustique de l'Université du Mans, LAUM - UMR 6613 CNRS, Le Mans Université,
Avenue Olivier Messiaen, 72085 LE MANS CEDEX 9, France.
*corresponding author, E-mail: vicente.romero@univ-lemans.fr

Abstract

This work reports the experimental validation of a deep-subwavelength material for sound diffusion called metadiffuser. Metadiffusers are rigidly backed slotted panels, with each slit being loaded by an array of Helmholtz resonators (HRs) introducing strong dispersion in the slits and slow sound conditions. Therefore, the effective thickness of the panel is dramatically reduced introducing its quarter wavelength resonance in the deep-subwavelength regime. By tuning the geometry of the metamaterial, the reflection coefficient profile can be tailored to obtain a custom reflection phase. In this work we validate in particular a metadiffuser based on a quadratic residue sequence, producing a uniform scattering function, so the reflecting waves are dispersed in many different directions by the subwavelength metadiffuser of thickness $\lambda_0/34$ (where λ_0 is the wavelength of the design frequency).

1. Introduction

Sound diffusers are locally-reacting reflecting surfaces with spatially dependent reflection coefficient designed to produce uniform scattering, i.e., the reflected waves by these surfaces are dispersed in many different directions [1]. Therefore, diffusers present a uniform far field magnitude, i.e. a uniform magnitude Fourier transform of its spatially dependent reflection coefficient distribution. The generation of spatially dependent reflecting surfaces is commonly achieved by using phase grating diffusers, also known as Schröeder's diffusers [2], that are rigid-backed slotted panels where each slit acts as a quarter wavelength resonator. However, Schröeder diffusers are limited by their depths, which becomes large at low design frequencies. This results in thick and heavy panels, limiting the use of phase grating diffusers for low-frequencies where the wavelength of sound in air is of the order of several meters.

In this work, we present the experimental validation of the concept of metadiffusers which are deep-subwavelength thickness diffusers based on slow sound acoustic metamaterials [3, 4, 5] to dramatically reduce the thickness of Schr´oeder diffusers. By tuning the geometry of the HRs and the thickness of the slits, the phase of the reflection coefficients can be tailored to those of usual diffusers but with extremely deep subwavelength structures. We present the validation of a metadiffuser based on the one presented in a previous work of some of the authors of the current abstract [1].

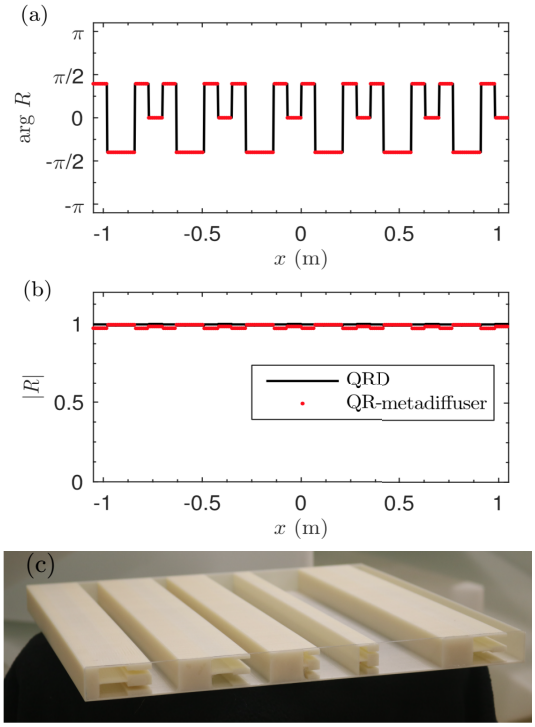


Figure 1: (a) Phase and (b) magnitude of the spatially-dependent reflection coefficient of a QRD (black line) and the QR-metadiffuser (red doted). Picture the analyzed metadiffuser (b).

2. Design of metadiffusers

A quadratic residue diffuser (QRD) is made from a numerical sequence given by $s_n = n^2 \mathrm{mod} N$, where mod

is the least non-negative remainder of the prime number N. If the phase grating diffuser is based on quarter wavelength resonators (wells), the depth of the wells is given by $L_n = s_n\lambda_0/2N$, where λ_0 is the design wavelength. A classical QRD with $N = 5$ and total thickness of $L = 27.4$ cm with side $Nd = 35$ cm could be designed for a frequency of 500 Hz. The resulting reflection coefficient could be mimicked by a metadiffuser structure as shown in Figs. 1(a,b). Perfect agreement is found between the reflection coefficients of the meta-QRD and the target phase. The picture of the designed metadifuser is shown in Fig. 1(c), with a deep sub-wavelength thickness of $L = 2$ cm.

3. Experimental set-up

The metadiffuser is experimentally tested in the anechoic chamber of the Laboratoire d'Acoustique de l'Université du Mans (LAUM). The metadiffuser is excited by a maximum length sequence (MLS) radiated from a source placed at 2 m from it at 90° of incidence. The metadiffuser is placed on a turning table covering all the azimutal angles. The scattering pressure field, p_s, is evaluated in the polar angles, along a semi-circumference of 1 m radius centered in the center of the metadiffuser. Therefore all the scattering directions can be captured by the experimental set-up. The scattering field is obtained by Fourier transforming the impulse response of the system after windowing it in the corresponding time period in order to remove the direct sound from the source.

4. Results

We evaluated a single repetition of the meta-QRD and an equivalent rigid panel with the same dimensions. Figure 2 shows the experimental results for the evaluated meta-QRD (in red lines) and for the rigid panel (in blue lines). In both case the experimental scattered field, $p_s(\theta)$ is plotted. Two different frequencies are evaluated. The first one at 700 Hz, where the meta-QRD behaves as a rigid panel. The second frequency, at 1500 Hz, shows the spreading of the acoustic energy in all the directions produced by the meta-QRD.

5. Conclusion

The concept of metadiffuser as a design of deep subwavelength locally reacting surfaces with tailored acoustic scattering was experimentally validated, demonstrating the potential of the metadiffusers to be used in critical listening environments. Due to their deep-subwavelength nature, the thickness of the panels can be strongly reduced. In the context of smart building design and sustainability, metadiffusers can be used to save space and to produce lightweight materials, improving the performance of the acoustic solutions using less resources. Moreover, the proposed designs have the potential to meet the aesthetic requirements that are mandatory for modern auditoria design.

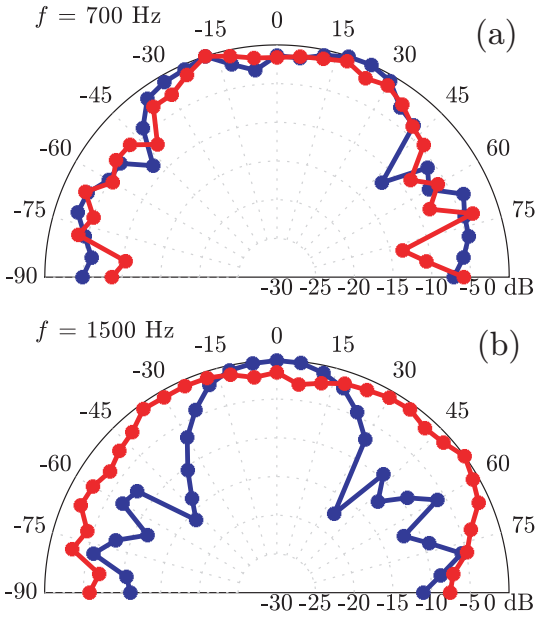


Figure 2: Experimental polar plots of the scattered acoustic field, $p_s(\theta)$, for (a) 700 Hz and (b) 1500 Hz. Blue line (Red line) represents the experimental evaluation of the far field of a flat square rigid panel (meta-QRD) of dimensions 35×35 cm^2.

6. Acknowledgement

The authors gratefully acknowledge the ANR project METARoom and the project HYPERMETA funded under the program Étoiles 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, supportedby COST (European Cooperation in Science and Technology).

References

[1] N. Jiménez, T. J. Cox, V. Romero-García and J.-P. Groby, Metadi users: Deep-subwavelength sound diffusers, *Sci. Rep.*, 7, 5389, 2017.

[2] Schr´oder, M. R. Diffuse sound reflection by maximum length sequences. *Jour. Acous. Soc. Am.*, 57, 149-150 (1975).

[3] Groby, J.-P., Huang, W., Lardeau, A. and Aurégan, Y. The use of slow waves to design simple sound absorbing materials, *J. Appl. Phys.*, 117, 124903 (2015).

[4] V. Romero-Garcá, G. Theocharis, O. Richoux, and V. Pagneux, Use of complex frequency plane to design broadband and sub-wavelength absorbers. *Jour. Acous. Soc. Am.*, 139, 3395-3403 (2016).

[5] N. Jiménez, W. Huang, V. Romero-García, V. Pagneux, and J.-P. Groby, Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption. *Appl. Phys. Lett.*, 109, 121902 (2016).