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[3D Printed quadratic residue metadiffuser - design and measurements of an optimized deep-subwavelength sound diffuser]

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Abstract

It has been two years since the first publication of the novel concept of metadiffusers. Heavily based on critical coupling theory introduced in the case of perfect absorption in deep-subwavelength metamaterials, metadiffusers are presented in a similar fashion, i.e. slotted panels with thin slits, each one backed with a set of critically coupled Helmholtz resonators (HRs). Instead of focusing on absorptive and transmitting properties, metadiffusers emphasize on perfect or pseudo-perfect reflection of sound. Here a particular interest is given to the scattering patterns obtained by the customization of the metamaterial's geometry. The deep-subwavelength nature of the structure leads to dimensions 20 to 46 times smaller than the design wavelength, i.e. about 1/20th to 1/10th of the thickness of traditional designs. This presentation aims at introducing the physical aspects of sound propagation in and out of the metadiffuser, emphasizing on deep-subwavelength critical coupling, on the consequent strong dispersion relations and on the custom scattered fields. This theoretical overview will then be paired with numerical and experimental data of a 3D-printed quadratic residue metadiffuser (QRM). Finally, potential applications of such structures will be discussed in critical industry environments.

Keywords: metamaterials, sound diffusion, slow sound

1 INTRODUCTION

Sound diffusers are locally-reacting reflecting surfaces with a spatially dependent reflection coefficient designed to produce uniform scattering, i.e. the reflected waves by these surfaces are scattered in many different directions [1]. This means that diffusers tend to present a uniform Fourier transform magnitude 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 rigidly-backed slotted panels where each slit acts as a quarter wavelength resonator. The common approach for designing phase-grating diffusers is to implement an effective well depth sequence in function of the range of frequencies being targeted for optimal scattering. In traditonal means, this is done by using rigidly-backed slotted panels where each slit acts as a quarter-wavelength resonator (QWR). Therefore, Schröeder diffusers can easily become thick and heavy structures when designing for mid- to low frequencies of audio sound, e.g. the height or maximum well depth of a traditional Quadratic Residue Diffuser (QRD) is of the order of half the wavelength of the low cut-off design frequency; often being in the order of one or more meters.

In this work, we present an experimental validation of the concept of metadiffusers, i.e. deep-subwavelength acoustic diffusers based on slow sound acoustic metamaterials [3, 4, 5] dramatically reducing the effective thickness otherwise required by Schröeder diffusers. By tuning the geometry of the HRs and the thickness of the slits, the phase of the metamaterial's reflection coefficient can be tailored to that of usual diffusers with, however, extreme deep-subwavelength scales. We present herein the validation of a metadiffuser based on one presented in a previous work of some of the authors of the current abstract [1].

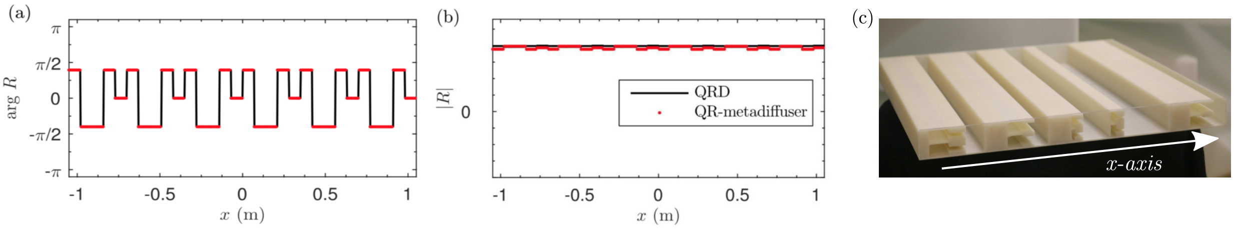

Figure 1. (a) Phase and (b) magnitude of the spatially-dependent reflection coefficient generated by six repetitions of a QRD (black line) and the QRM (red doted). (c) Picture the QRM (one period).

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. Whereas phase grating diffusers are based on quarter wavelength resonators (wells) – with well depths given by $L_n = s_n \lambda_0 / 2N$, where λ_0 is the design wavelength – the metadiffusers' ability to create impedance changes across their surface is achieved by coupled deep-subwavelength resonance between the slits and the HRs, which takes into account the thermo-visous losses happening when sound propagates in very narrow regions. By making a parametric design of such strategy, allowing the geometry of the slits and HRs to change and using genetic algorithms, it is then possible for a metadiffuser to mimick the spatially-dependent reflection coefficient $R(x)$ of a given surface whilst conserving a minimal thickness. Thus, let be a classical QRD with $N = 5$ and total thickness of $L = 27.4$ cm with side $Nd = 35$ cm to be designed for a low cut-off frequency of 500 Hz. The resulting reflection coefficient of the QRD could then be mimicked by a metadiffuser structure, as shown in Figs. 1 (a,b).

As illustrated, perfect agreement is found between the reflection coefficients of the QRM and the target QRD phase. The picture of the designed metadifuser structure is shown in Fig. 1 (c), with a deep sub-wavelength thickness of $L = 2$ cm.

3 EXPERIMENTAL SET-UP

The QRM was experimentally tested in the anechoic chamber of the Laboratoire d'Acoustique de l'Université du Mans (LAUM). The metasurface was excited by a maximum length sequence (MLS) radiated by a source placed at 2 m from it at 0° incidence (normal). The structure was placed on a turning table covering all azimutal angles. The scattering pressure field, p_s, was 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 was then 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 QRM and an equivalent rigid panel of the same dimensions. Figure 2 shows the experimental results for the evaluated QRM (red lines) as well as for the rigid panel (blue lines). In both cases the experimental scattered field, $p_s(\theta)$ across the x-axis is plotted for two different frequencies. The first one at 700 Hz, where the QRM behaves as a rigid panel would, i.e. even spreading of sound due to the diffraction of the finite surface sample. The second frequency, at 1500 Hz, shows however the even spreading of the acoustic energy in all the directions produced by the QRM whereas the flat surface acts in a more directive fashion.

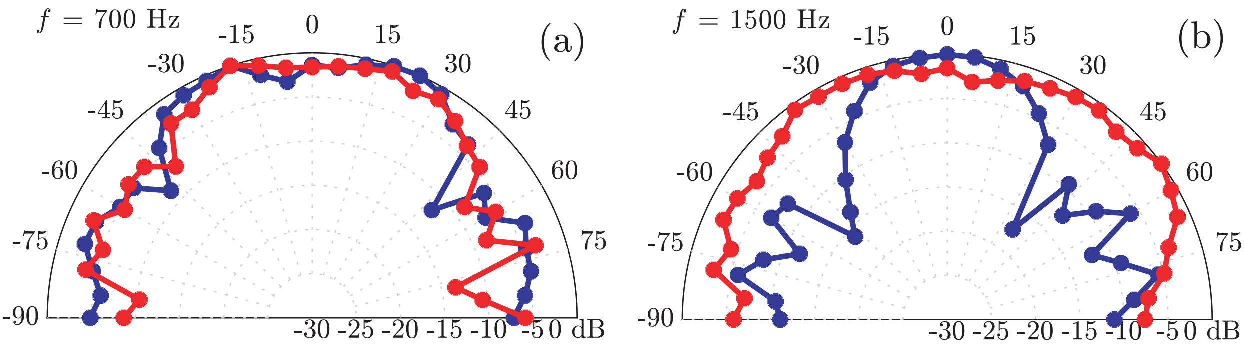

Figure 2. Experimental polar plots of the scattered acoustic field, $p_s(\theta)$, for (a) 700 Hz and (b) 1500 Hz. Experimental evaluation of the far field of a flat square rigid panel (blue line) and the QRM (red line) of dimensions $35 \times 35 \times 2$ cm^3.

5 CONCLUSION

The concept of metadiffuser – as a deep subwavelength locally reacting surface with tailored acoustic scattering – was experimentally validated, thus demonstrating the potential of metadiffusers to be used in critical listening environments. Due to their deep-subwavelength nature, the thickness of the panels can be strongly reduced; by 11 times in the case herein presented. 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 acoustic solutions using less resources. Moreover, the proposed designs have the potential to meet the aesthetic requirements that are mandatory for modern auditoria design.

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