ACOUSTIC CONDITIONS IN ORCHESTRA PITS: ARE METADIFFUSERS A POTENTIAL SOLUTION?

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1 INTRODUCTION

Rising concerns about public health and safety have progressively induced a change in control of noise regulations, specifically on those applicable to the work environment. These directives have been developed to protect employees from harmful side effects of their working conditions, firstly targeting high noise levels generated by heavy machinery in industry.

Nowadays, noise control regulations are widely effective and applicable to nearly all working environments, including institutions dedicated to the arts, such as opera houses. To the latter, directives on noise control are of major concern as opera performances tend to generate very high sound levels, especially in the area of the orchestra pit – the sunken space between stage and audience. In such context, management faces a difficult task conforming to noise regulations as they must balance the sometimes competing demands to (i) dutifully protect their employees – musicians and others – from any harmful 'sounds' or 'noise' that might be generated, and (ii) deliver world-class operatic art for the public, where noise regulations might compromise the culture of the art form.

'Sound' and 'noise' are two terms of intense interest when dealing with control of noise regulations in the entertainment sector. Indeed, noise is generally described as 'unwanted' sound, judged as unpleasant, whereas music is considered most of the time as a 'desirable' and pleasant sound; leading to a debate on the pertinence of *noise* regulations within the *musical* arts. Such debate has recently been discussed in the High Court in London, where the court favoured an orchestral viola player who claimed to have suffered noise induced hearing loss during a rehearsal of Wagner's Valkyrie[1]; the major argument being that the opera house exceeded industry-wide standards on noise control, viz. daily L_{AE} > 85 dBA. Such a case has no precedent in UK history, raising concerns for other opera houses and music spaces on how to enforce noise regulations without affecting the performances' nature. This leads to the question of whether *noise* control regulations should apply to all industries, regardless of the type of *sound* they generate.

2 PIT ACOUSTICS

2.1 Loudness in pits

Despite the debate on sonic terminology and current jurisdiction, it is true that orchestra pits are generally known to represent difficult performing environments for musicians, as the overall loudness may be overwhelming and hence affecting the musicians' hearing and performance capacities. It is not surprising to find in such environments levels reaching 130 dBC_{peak} when playing in *fortissimo*. In previous studies, Brockt[2] outlined weekly and annual exposure levels of typical orchestra musicians of 85 to 95 dBA, expecting higher levels for pit musicians. Levels this high set a challenging scenario where control of sound levels must be achieved without compromising the performing environment of the opera art form.

Whilst audiences may generally be satisfied by the overall orchestral sound level, musicians in the pit often complain about the loudness of such environment. This is likely due to the geometric nature and material properties of the pit's boundaries, as well as the close proximity of each musician. Indeed, orchestra pits are of a relatively small size when considering typical orchestral dimensions, consisting of a deep, narrow cavity, placed between the stage and the audience area. This peculiar placement was instated to reduce the sounds coming from the orchestra to the audience in order to prioritize the singers' voices, as well as visually hiding it for aesthetic purposes. This however introduced difficult playing conditions for musicians, as the pit encloses a group of sound sources, resulting in a greater sound intensity within the enclosure as many strong reflections build-up within a limited space due to the acoustically hard boundaries of the pit, a phenomenon otherwise mitigated in more 'open' configurations.

Such a gain of sound energy is commonly termed as acoustic Strength (G) or Loudness, depending on either a quantitative or a qualitative description, respectively. The more sound reflections accompanying the direct sound, the stronger the acoustic Strength or Loudness. For this reason, acoustic absorption, by the reduction of reflected energy, is frequently considered as being the most efficient way to reduce the level of acoustic Strength. However, it is unlikely to be practical, artistically and technically, to significantly reduce the sound energy radiated by a full orchestra, as this would affect the nature of the performance, reducing drastically the sound emitted to the audience and to the stage.

Another aspect to consider is also about the perception of loudness from a musician's point of view. In musical acoustics, the loudness of sounds reaching musicians within specific time windows helps to increase or decrease parameters relating to performance conditions. It has been demonstrated[3,4] that early reflections arriving at musicians' ears were responsible for the sensation of 'ensemble' playing while late reflections from the auditorium were a good descriptor of 'support' sensation; the former allows musicians to hear themselves while performing and the latter gives them an acoustic feedback from the hall, both sensations helping them to adjust their performing levels. This shows that acoustic diffusion, dispersing sounds in both time and space, is a potential tool for controlling the amount of sound energy reaching the musicians' ears within these particular time frames. This balance between 'ensemble' and 'support' parameters, easing musical performing conditions, could also help decrease the perceived level of loudness as musicians should receive a more distributed sound energy instead of many strong specular reflections. This also limits the amount of acoustic absorption that can be applied to orchestra pits.

2.2 Previous solutions

The issue of acoustic loudness in orchestra pits has rarely been studied over the last 40 years when compared to other fields of investigation in auditoria. The majority of such research aimed to gather information or state the ongoing issues arising from these difficult performing environments; mainly focusing on hearing loss due to dangerous sound levels and a few dealing with the pure physical interactions between sound and the enclosure's boundaries.

Despite the novelty of this research field, a few solutions were tried in order to mitigate acoustic levels in orchestra pits. E.L. Harkness[5] conducted in 1984 one of the first acoustic studies on pit acoustics, where orchestral groups, i.e. woodwinds, brass, strings, etc., were separated by acoustically absorbing and/or diffusing barriers that would help control acoustic loudness. The results were considered convenient from an acoustic viewpoint but it appears that musicians very much disliked this proposed configuration as it would break their musical balance and 'ensemble feeling' while playing in the pit. In 1985, G.M. Naylor[6] and R.K. Mackenzie[7] completed a complimentary study and decided to implement an electroacoustic reinforcement system in the pit that would adapt feedback levels to specific orchestra groups. Unfortunately, this approach had to be rejected due to artistic reasons following feedback from orchestra directors and musicians. Further works consisted in either (i) increasing the pit area over the first audience rows or stage, (ii) adding diffusion to scatter sound with built-in diffusers in the walls or (iii) adding critical absorption for controlling low-frequency standing waves[8-11]. All those solutions did work to differing degrees, yet each one had its own set of drawbacks preventing it from being widely implemented, e.g. the cost and questionable benefits of extending the pit; the time, cost and expertise of construction work for adding built-in diffusers; and size of low-frequency treatments.

2.3 Treatment constraints

Controlling acoustical aspects of orchestra pits, such as attenuating troublesome frequencies or enhancing the spatial and temporal distribution of sounds, may not only enhance musical performing conditions while reducing the perceived loudness of sounds being generated, but could eventually lead to a reduction of the quantitative sound levels experienced by a matter of a few decibels. Such initiatives usually take the form of targeted low-to-medium-frequency sound absorption for controlling standing wave phenomena and acoustic diffusion for a broad distribution of sound across the performing space and into the auditorium; both being applied to the pit's boundaries. Yet, spaces such as orchestra pits have a very limited free space, making the latter approaches impractical, as absorptive and diffusive structures can be quite cumbersome for such applications.

Therefore, this issue opens the way to multiple research enquiries, one being about the miniaturization of acoustically diffusive and/or absorptive structures that could fit within the tight space available in existing orchestra pits, i.e. an approximate 10 cm limit.

3 METADIFFUSERS

3.1 Theory

Standard treatments for acoustic absorption and diffusion usually work on a 1:1 (full) wavelength scale, i.e. the optimal dimensions of the treatments for a specific set of frequencies are proportional in a 1:1 ratio to the respective wavelengths. For frequencies between 50 Hz and 12 kHz, wavelengths lie in the range of 6.8 m to 2.8 cm, an impractical scale for low to medium frequency treatments in orchestra pits. Therefore, a 'subwavelength' sized acoustic treatment[12] would be more convenient, as this would allow targeting lower frequencies than conventional designs, but retaining minimal treatment depth.

Materials achieving this subwavelength performance, affecting longer wavelengths than what the material's dimension would genuinely allow, fall under the vast category of metamaterials, i.e. materials that obtain their extraordinary physical properties (e.g. non-ordinary refraction, diffusion and absorption) from their structure rather than from their chemical composition. A proper definition of metamaterials could be termed as a 'class of structured composites whose wave functionalities arise as the collective manifestations of its locally resonant constituent units'[13]. Due to the resonating nature of the constituents, the resonant frequency can thus be orders of magnitude higher than the physical dimension of the resonating unit. As such, a basic example of an acoustic metamaterial could simply consist of an array of Helmholtz resonators (HRs), achieving subwavelength features due to their quarter-wavelength resonance.

Metamaterials can be useful in manipulating acoustic waves in non-conventional ways, as they can affect the constitutive parameters of the wave equation (mass density, 'ρ', and bulk modulus, 'β', as seen in Eq.1) and make them take unusual values when considering 'effective' medium characteristics (e.g. negative, zero or near divergent values). Such values thus imply acoustic wave features not usually associated with 'ordinary' composites.

$$\nabla^2 P - \frac{\rho}{\beta}\frac{\partial^2 P}{\partial t^2} = 0 \qquad \text{(Eq.1)}$$

The concept of metadiffusers (see Figure 1) was recently presented by Jimenez et al.[14] in July 2017, who developed a metamaterial-inspired sound diffuser working on a deep-subwavelength regime. These designs reproduced either Primary Root Diffusion (PRD), Quadratic Root Diffusion (QRD) schemes or even Perfect Absorption (PA) by critical impedance coupling between the metadiffusers' slits and the exterior medium. Generally, such metasurfaces are considered as a rigid panel of finite length with a set of N thin slits, with the aim of modifying the dispersion relations inside each slit by loading one of their boundaries with a set of HRs. The sound propagation in the slits becomes strongly dispersive due to viscous losses, drastically reducing the speed of sound, c_p.

As each slit behaves as a deep-subwavelength resonator, the effective depth of the slits can be substantially decreased according to $L = c_p/4f$, with c_p potentially reaching values lesser than 200 m/s. Based on this mechanism, the dispersion relations inside each slit can be modified by tuning the geometry of the HRs as well as the thickness of the slits, hence allowing the frequency-dependent phase of the reflection coefficient to be tailored. Furthermore, the magnitude of the reflection coefficient can also be tuned by adapting the thermo-viscous losses – inherent in the HRs and in the narrow slits – inside the metadiffusers and thus generating perfect absorption conditions for the desired frequencies, thus potentially changing the behaviour of the metasurface from perfect reflector to perfect absorber.

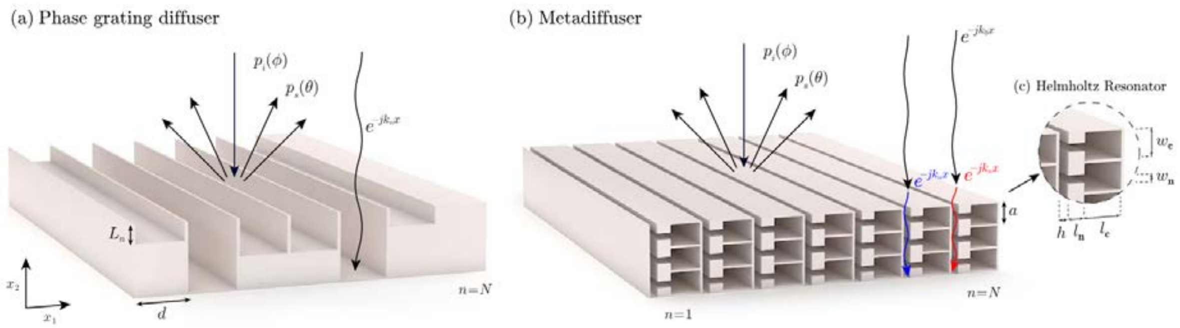

Figure 1: (a) Scheme of a QRD Schroeder diffuser composed by N = 7 wells or quarter wavelength resonators. (b) Metadiffuser composed of N = 7 subwavelength slits, each of them loaded by M = 3 Helmholtz resonators. (c) Detail of a slit of the metadiffuser showing the geometrical parameters of the cavity of a HR (w_c and l_c) and its neck (w_n and l_n). (After Jimenez et al.[14])

3.2 Broadband optimal metadiffusers

Various metadiffuser designs were proposed by Jimenez et al., successfully reproducing the reflection features of PRDs and QRDs for single frequencies. However, in order to provide a useful solution for room acoustic applications, the diffusion obtained by such metasurfaces must be broad in frequency. Thus, Jimenez et al. ultimately proposed a broadband metadiffuser with a maximum normalized diffusion coefficient in the optimal frequency range of f_{low} = 250 Hz to f_{high} = 2000 Hz. The geometry of the latter was obtained through an optimization procedure using a genetic algorithm. This resulted in a metadiffuser with a set of *N* = 11 slits separated by *d* = 12 cm, a constrained thickness of the panel *L* = 3 cm, and variable resonator dimensions for each slit. The optimized metadiffuser dimensions are shown in Figure 2 along with comparative far field polar responses of different diffusing surfaces.

Results generated in Figure 2 were obtained by computational simulations using the Transfer Matrix Method (TMM) and the Finite Element Method (FEM) in COMSOL Multiphysics 5.2™. It can be seen that the maximum normalized diffusion coefficient of the broadband metadiffuser stands out when compared to both a 3 cm and 56 cm thick QRD, with values between 0.4 and 0.7 in the frequency range of 300 Hz to 2000 Hz. With respect to the 56 cm deep QRD, the broadband 3 cm metadiffuser shows a deep-subwavelength behaviour as low frequencies between 250 to 500 Hz are being affected by the metasurface, a behaviour not accounted in the case of the traditional 56 cm QRD. Above those frequencies, the diffusion provided by the 3 cm metadiffuser shows to be similar to that provided by its 56 cm equivalent. This shows the great potential of metadiffusers, as the geometry required to disperse sound in a broad frequency range has been reduced by a factor of almost 1/20th of the conventional designs, affecting even lower frequencies.

This significant change in dimension for diffusing surfaces holds great potential for spaces with limited geometry, such as orchestra pits; as such metasurfaces can fit within the ridiculous limit of 3 to 4 cm! Nonetheless, it should be reminded that these results are theoretical, with a certain degree of accuracy that should hold true in practice, but have yet to be proven.

3.3 Prototyping of a broadband metadiffuser

Even though expected results of the broadband metadiffuser are very promising, this acoustic behaviour needs to be verified experimentally. To this end, a 1:1 scale prototype of the broadband metadiffuser was constructed.

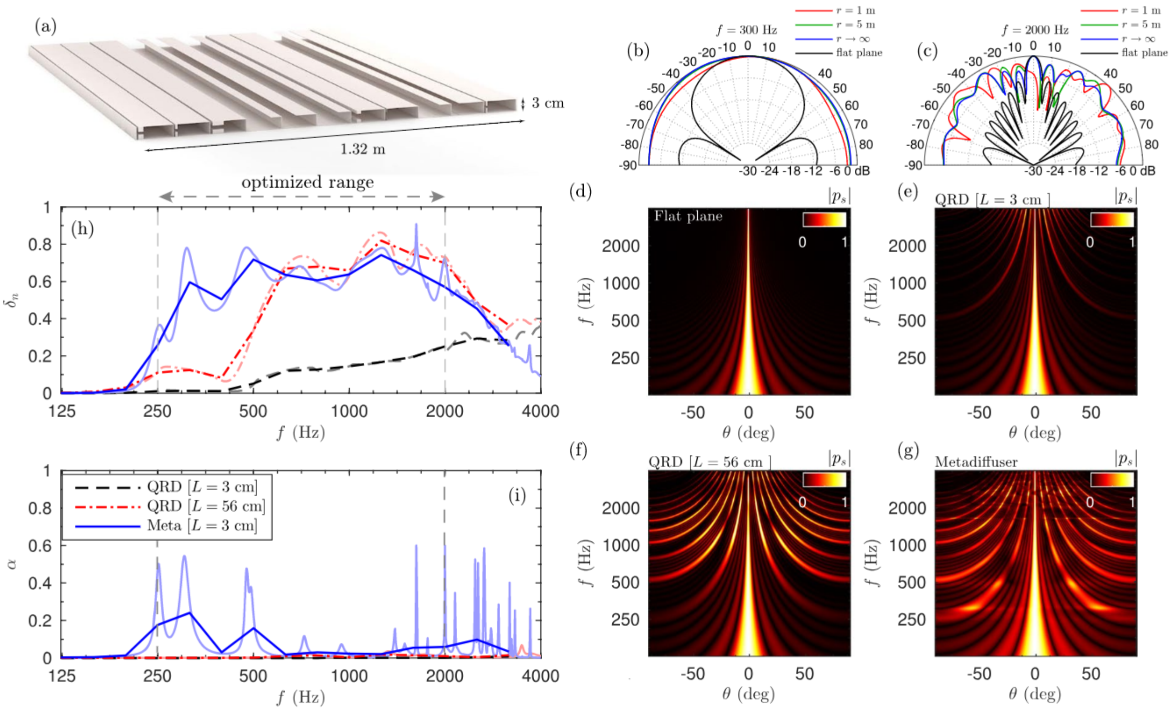

Figure 2: (a) Visualization of the broadband metadiffuser design. (b - c) Near and far field polar responses of the metadiffuser and a flat plane as function of distance for 300 Hz (b) and 2 kHz (c). (d – g) Frequency dependent far field polar responses for a reference flat plane with the same width than the metadiffuser, a thick QRD with a design frequency of 250 Hz (L_{QRD} = 56 cm), a thin QRD with the same thickness than the metadiffuser ($L_{QRD,thin}$ = 3 cm) and the optimized metadiffuser. Down right: Normalized diffusion and absorption coefficients of the different surfaces being compared. (After Jimenez et al.[14])

The prototype was built using 3 mm thick acrylic sheets that were laser-cut and welded together over an MDF board covered by a PVC sheet using a plastic solvent. The thickness of the material being used should be as thin as possible but still be rigid enough so that the panels do not start oscillating freely, which could affect low frequency behaviour of the metasurface. The necks of the different HRs were built using balsa wood sticks in order to minimize the weight being applied to the endpoint of each subwavelength slit. A picture of the physical prototype is shown in Figure 3 with dimensions given in Figure 2.

4 SCATTERING MEASUREMENT

4.1 Measurement method

The scattering characteristics of the broadband metadiffuser prototype were measured according to the standard AES-4id-2001[15] (r2007). Due to environmental difficulties around the measurement period, the test had to be quite limited with respect to the angular resolution of the sample's characteristics. As illustrated in Figure 3, the spatial sampling for measuring the scattered sound of the metasurface was set to 30°, at ± 60° around the normal axis; instead of a minimum of 5° recommended in the standard. Still, this 30° sampling should allow to verify to some extent the scattering behaviour of the broadband metadiffuser. The measurements were conducted by producing an impulse through a loudspeaker at specific angular positions, each at a time and equidistant to the centre of the measured surface by a distance d_2. The scattered sound field is then recorded using a series of microphones surrounding the sample at the same angular positions, but at a closer distance to the source, d_1. This procedure allows the observation of the amount of scattering of the incident sound at particular angles.

The scattered sound field of the incident pulse being measured at each microphone is analysed in both time and frequency domains, being ultimately described in terms of third-octave band levels per angular position with respect to a specific incidence of sound. This results in polar plots representing the amount of sound energy being scattered by the surface for each angular incidence. The reflected pulses, as well as the respective scattered levels in third octave bands are illustrated in Figure 4.

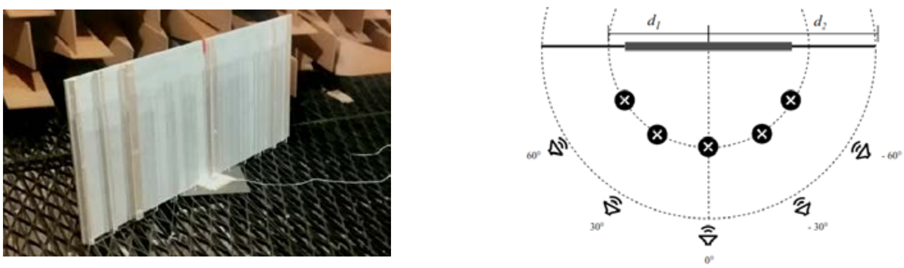

Figure 3: (Left) Picture of the scattering measurement of the broadband metadiffuser; (Right) Diagram of the measurement layout displaying source ( ) and receiver ( ) positions around the test surface at specific angular positions from the geometric centre of the surface, where d_1 and d_2 are 1.5 m and 3 m, respectively.

4.2 Measurement analysis

The impulse responses presented in Figure 4 demonstrate the difference between a flat surface and the broadband metadiffuser. Specular reflections over the flat surface in (a) are quite strong in the opposite incident angle – presently at 0° – with low temporal dispersion, i.e. the reflected IRs are strongly correlated to the incident sound. In (b), however, one can see that the incident sound is much more dispersed in both space and time, with a lack of strong specular reflections and high dispersive features at grazing reflections (± 60°). This difference in the reflected IRs demonstrates the ability of the broadband metasurface to effectively diffuse sounds.

Regarding the scattering values presented in the polar responses in Figure 4, they can be seen to have strange and non-symmetric variations, which could be due to the low spatial sampling around the test surface, with lower energy values certainly corresponding to particular dips in the lobes of the polar response due to destructive interferences. These variations could be clarified in further measurements with a greater spatial sampling of the angular space around the test sample. Nonetheless, such values still help to illustrate the pattern difference between a flat surface and the broadband metadiffuser, i.e. specular reflections can be easily seen in the context of a flat surface whereas reflected sound from the broadband metadiffuser appears to be more distributed over the angular space. Even if the set of sound pressure levels of each polar response is quite variable, the autocorrelation derived from them for obtaining the directional diffusion coefficient should hold a more representative average value of all the scattered levels at each reflected angle. The autocorrelation diffusion coefficient of the surface shown in Figure 4 is calculated by applying Eq.2[16], where L_i are the set of sound pressure levels in decibels in a polar response, n is the number of receivers and ψ is the angle of incidence.

$$d_{\psi} = \frac{\left(\sum_{i=1}^{n} 10^{L_i/10}\right)^2 - \sum_{i=1}^{n}\left(10^{L_i/10}\right)^2}{(n-1)\sum_{i=1}^{n}\left(10^{L_i/10}\right)^2} \qquad \text{(Eq.2)}$$

Comparing the results of the autocorrelation diffusion coefficients presented in Figure 4.e, clear differences between the two surfaces can be observed. The broadband metadiffuser prototype demonstrates much better diffuse features over the frequency range of 450 Hz to 2 kHz, with values between 0.35 and 0.8. This shows that the 3 cm broadband metadiffuser indeed affects frequencies much higher than its own dimension, corroborating to some extent the computational predictions.

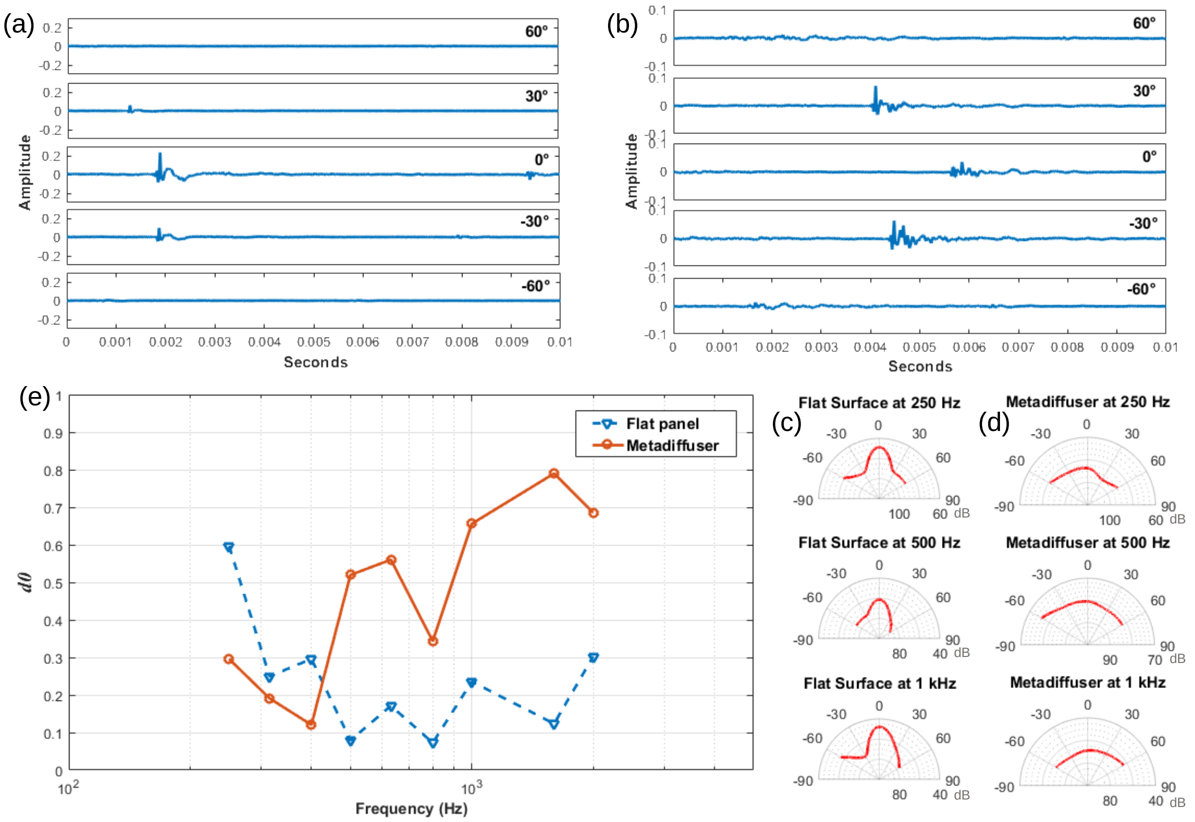

Figure 4: (a) Reflected IRs over a flat surface at normal incidence. (b) Reflected IRs over the broadband metadiffusers prototype. (c – d) Polar responses of scattered levels of a flat surface (c) and the metadiffusers prototype (d). (e) Autocorrelation diffusion coefficients (Eq.2) of both the flat surface and the metadiffuser prototype.

Of course, the presented curves may exhibit variations as they depend on the autocorrelation of the few scattered sound levels. Again, such curves could be clarified with a better spatial sampling of the test surface. The subfigure (e) presents, however, three major artefacts: (i) the apparent worse acoustical diffusion in low frequencies (f < 400 Hz) than that of a flat panel, (ii) the dip in the diffusion coefficient at 800 Hz, and (iii) the slightly high diffusion values around 1.6 kHz, where 0.7 is usually considered as the maximum diffusion a surface can provide[16]. After discussions with N. Jimenez and V. Romero-Garcia, some defaults in the prototyping of the broadband metadiffusers where outlined, explaining the plausible origin of such artefacts.

4.3 Prototyping errors & design considerations

The first conceptual error made for the broadband metadiffuser prototype was in the length and terminations of the panel. For the prototype, the panel was assumed to behave in a 2D fashion and was thus reduced in length (or height) for more convenience in manufacturing. The terminations of the panel were also left ‘open’, as shown in Figure 2. However, it was made clear that the broadband metadiffuser actually needed all its height, with closed terminations, so that the slits could affect low frequencies more effectively (like a HR). This explains the absence of diffusion in the lower frequency bands. The unusual diffusion behaviour in those bands, worse than that of a flat panel, could be explained by the measurement uncertainties generated by poor spatial sampling of the scattered sound levels and/or destructive interferences. Furthermore, the dip in the diffusion coefficient around 800 Hz could be explained by the reduced height of the panel (0.55 m instead of 1.3 m), as it corresponds to the respective wavelengths of this frequency band, i.e. $\lambda_{800Hz} \approx 0.5$ m. Finally, the slightly high diffusion values (ca. d = 0.8 at 1.6 kHz) could be due to measurement uncertainty, as mentioned previously.

5 DISCUSSION & FURTHER WORK

Even though some mistakes were made for the prototyping of the broadband metadiffusers, it can be seen that there is actually an important difference between the acoustic behaviour of a flat panel and the one of the broadband metadiffuser, with an average difference of 0.3 to 0.4 in diffusion coefficients for a thickness increase of just 3 cm. These results are an early proof of concept that metadiffusers are likely to behave as predicted. In such case, they could hold great promise for spaces such as orchestra pits as they could easily fit within the tight space available, with a relatively low cost of manufacturing and visual adaptability to any kind of artistic constraints (e.g. colour/contrast). The tailoring capabilities of such deep-subwavelength surfaces could also prove to be very useful for absorbing low frequencies, thus controlling any standing wave phenomena or reducing the energy of certain incident sounds, all within a few centimetres.

The work presented herein is at its early stages and still ongoing. More detailed measurements will further be conducted in order to explore the manufacture and acoustic behaviour of these diffusers (e.g. better scattered spatial sampling, analysis for all sound incidences, temporal dispersion analysis, intensity probing in the slits and HRs, effects on pit acoustics through computer simulations, etc.). Hopefully, this study will help to tailor the quantity and quality of sound absorption and diffusion needed in orchestra pits, leading to better performing conditions for musicians and adherence to noise control regulations.

6 ACKNOWLEDGEMENTS

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