euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Preliminary studies for metamaterial-based audio systems

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Abstract
Two of the key challenges in the design of professional audio systems are managing unwanted emissions and directivity control at low frequencies. Traditional solutions often comprise massive cabinets. The result is a static system, with limited freedom over the position of the listener for an optimal sound experience. In this paper, we introduce the use of acoustic metamaterials as design tools and present preliminary measurements where compact metasurfaces are used for both problems. In particular, with simulations and measurements, we show how a metamaterial enclosure can be used to shape backward and side emissions with a weight reduction of 60% compared to traditional systems. We also demonstrate, with measurements, how a system of compact acoustic lenses can be used to deliver personalized audio messages. The optimization of our devices could lead to headphone-less audio communication and to sound effects with a dynamic spatial component.

Keywords: acoustic metamaterials, metasurfaces, directivity control, loudspeaker systems, weight reduction.

1 Introduction

The development of loudspeaker systems is always a compromise between cost and performance [1]. Undesirable effects are often present at the lower end of the frequency range in which the individual transducer operates and are potentially more audible and visible in lower cost loudspeakers, which in most cases consist of sources coupled to cubic shaped cabinets. Equally noticeable is the presence of cabinet resonances, both internally and on the front panel, typically at frequencies below 1 kHz [2]. These result in tonal components and are typically damped with massive materials, used for the cabinet walls, or with absorbent materials inside the cabinet. Wadding, however, is most effective at high frequencies and should be placed in the sound path, whereas by necessity it is mounted on the cabinet walls, where its performance is further reduced. An additional solution, incorporated into the cabinet where necessary, would be highly desirable.
A solution can be offered by acoustic metasurfaces [3], which are metamaterials with a thickness less than the wavelength passing through them. In the past 10 years, metasurfaces have been successfully employed to obtain acoustic devices with an optical equivalent, such as lenses and absorbers, but with practical dimensions. Designed through computational modelling and micro-engineered into functional devices from classic materials – such as wood, glass or plastic – metasurfaces have ushered a new era for acoustic design. In this paper, we show how acoustic metasurfaces, shaped like a box (see Figure 1), can be used to increase the air volume within a cubic loudspeaker enclosure and thus reduce the overall weight of the system while optimising its performance.

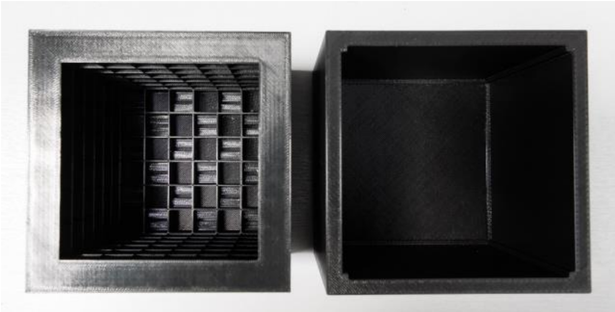

Figure 1 – (*left*) The metamaterial cabinet used in this study (“Aurora” cabinet) and (*right*) a cabinet of similar dimensions, but with smooth walls (“Smooth” cabinet).

Metasurfaces, however, are static: once the shape of the field is set, it cannot be changed, unless a hybrid system is used [4]. The frontier in the research of acoustic metamaterials moved then to the design of dynamic systems, with hybrid or mechanically implemented solutions [5]. These could offer the adaptable directivity that is extremely desirable in audio systems, both for domestic listeners and studio monitors, but seldom offered. In the second part of this paper, we will therefore show how a system of lenses, whose reciprocal position is varied mechanically, can allow the directivity to be controlled even for a commercial audio transducer.

2 Metasurface design

In 2017 Memoli *et al.* [6] demonstrated how metasurfaces can be assembled using only 16 prefabricated metamaterial bricks (see Figure 2, *left*), each of which encodes a specific delay that is imposed on the sound propagating through it. Similar geometries will be used in this work.
In the literature, the possibility of designing these bricks with a labyrinthine path has been exploited to maximize the transmitted sound [14]. A further optimization, performed on the thickness of the bricks, resulted in the realization of several metasurfaces (see bottom of Figure 2, *left*), each operating at different bandwidths [5].

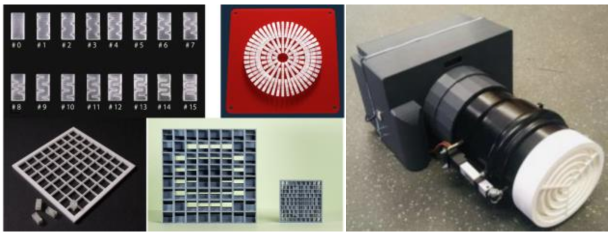

Figure 2 – (*left*) 3D printed metamaterial bricks in different assemblies. (*right*) Photograph of acoustic telescope with auto-zoom lens used in this study, designed to deliver sound to a target listener.

2.1 From a desired field to a phase distribution

Assigning a function to a metasurface means deciding what the acoustic pressure distribution will be after crossing it, both in terms of phase and sound intensity.
Li *et al.* [7] suggest approaching it as a backward propagation problem [12]: the desired far field is back-propagated in the vicinity of the metasurface itself and this provides the required phase/intensity distribution. The latter will then be encoded by specific unit cells on the incoming wavefront, until the desired accuracy is achieved (the bricks presented in [6], for example, allow 4-bit coding). More details for a generic field have been given in [4], while the discussion of how this approach can be used to design an absorber was addressed by Chisari *et al.* [8]. Here we will only discuss the case of a converging lens.

In optics, a diffractive lens is characterized by two quantities: its focal length (*f*) and its physical extent, i.e., how many unit cells it should contain. Once the desired *f* is set along the axis of the lens ($\hat{z}$), it is possible to obtain the phase distribution $\varphi(x, y)$ on the metasurface, which is assumed to be in the $z=0$ plane, by imposing that all contributions from the unit cells arrive in phase at the point (0, 0, *f*).
In order to realize the acoustic telescope (see Figure 2, *right*) we chose to design our lenses using a parabolic phase profile [9], given by:

$$\varphi(r)=\varphi_0-A^2\left(x^2+y^2\right) \quad (1)$$

where,

$\varphi(x, y)$ is the local phase, assigned to a unit cell [°]; A is a constant, related to the local curvature of the phase profile [m^{-2}]; λ_0 is the design wavelength [m]; and φ_0 is an arbitrary constant [°].

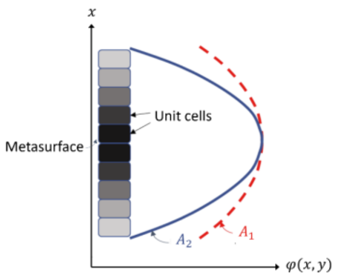

Figure 3 – Comparison of two different phase profiles, with A1<A2, highlighting how the unit cells encode the phase distribution $\varphi(x, y)$.

2.2 Unit Cell selection

Once $\varphi(x, y)$ is known, the designer must choose the appropriate unit cells in order to implement the metasurface. Many metamaterial geometries are available in the literature, but they all have one thing in common: the lower the frequency, the thicker the cell. As shown by Memoli *et al.* [6], one way to overcome this limitation is to use sub-harmonics of the design frequency.
In this work, we show a further step: we use cells that only have half of the thickness of the ones used in [6], replacing the other half with a reflecting wall. Like in Chisari *et al.* [8], we also consider cells that are made of two different units (a “doublet”), optimised for passive noise cancellation over larger bandwidths (see Figure 4, *left*). In practice, the reflected wave is in counterphase to the incident wave, ensuring its cancellation and resulting in high sound insulation. The numerical analysis which led to the metamaterial bricks used in this work will be treated elsewhere.

3 Numerical results

3.1 Frequency Domain analysis

The finite element analysis method (FEM) was employed to observe the acoustic insulation guaranteed by the metamaterial cabinet.

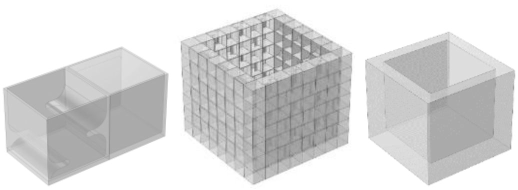

Figure 4 – (*left*) Geometry of the unit cell constituting the metamaterial cabinet. (*centre*) Complete geometry of the Aurora cabinet. (*right*) Complete geometry of the Smooth cabinet. The two cabinets have similar dimensions.

In the simulations, the performance of a metamaterial cabinet of the Aurora type was compared with a Smooth cabinet of similar dimensions (both $21\times21\times21$ cm, see Figure 4). The main difference between the two designs is in their walls: while both cabinets have a wall thickness of 25 mm, the Smooth cabinet is whole, while the Aurora cabinet is patterned so that there is only 1 mm of PLA between the inside and the outside.
The FEM analysis was run using the commercial software COMSOL Multiphysics, and in particular the Acoustic Pressure Module (to simulate acoustic propagation) and the Solid Mechanics Module, to simulate fluid-structure interactions. A study was conducted in the frequency domain, from 500 Hz to 5000 Hz, with an interval of 1/12th octaves.
In order to simulate an infinite domain for the air outside the cabinets, a PML (Perfectly Matched Layer) was assigned to an air box surrounding each cabinet, to mimic an open and non-reflecting infinite domain. In the frequency domain analysis, the PML imposes a complex-valued coordinate transformation to the selected layer which effectively makes it absorbing at a maintained wave impedance, and thus eliminating reflections.
To model a sound source with directivity in the range 500 Hz-5000 Hz, we employed a dipole point source with a reference power equal to 3 W. The source was positioned at the centre of the open face of each cabinet. Each cabinet was then closed with a 2.5 cm thick hardwood board, in order to simulate the surface supporting the source used in the experiments (see later). The air inside the cabinet, beyond it and in the PML is characterised by a density and a speed of sound at room temperature and the sound propagation neglects non-linearities. Acrylic plastic was assigned to the cabinets and the rigid wall boundary condition was assigned on the internal walls and on the face closing the Aurora cabinet. Thermo-viscous losses have not been taken into account in this study.
The mesh size where sound propagation occurs is determined according to the FEM criterion, where at least five nodes are used to simulate a wavelength in air. Thus, a maximum element size is assigned as a sixth of the minimum study wavelength.
Due to the computational weight of the numerical model of the entire Aurora cabinet, it was decided to exploit the C_4 symmetry of the cabinet. Therefore, only a quarter of each cabinet was used, and symmetry boundary conditions have been assigned to its rigid walls and to the air inside and outside it. The entire geometry of the cabinet was later used for the numerical analysis of the eigenmodes, which will be discussed in the next section.
In order to observe the acoustic insulation provided by the metamaterial cabinet, when compared with the Smooth cabinet, we observed the rear sound pressure level for the two configurations, at the same distance of 0.15 m. As can be seen in Figure 5, the FEM analysis predicted a good sound insulation from both the Aurora cabinet and the Smooth one. However, the Smooth cabinet insulation performances are mainly due to the fact that its walls are more massive, as will be more clearly explained later in this work. A more thorough investigation on the Aurora cabinet, discussed in next section, was run to evaluate the effect of internal cabinet resonances on its overall sound insulation.

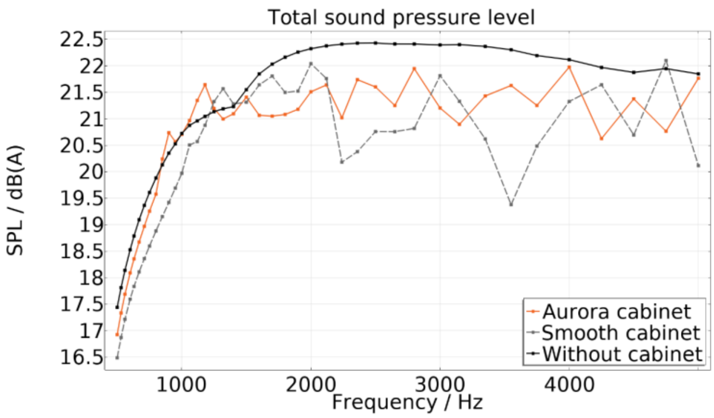

Figure 5 – Rear total sound pressure level measured at 0.15 m; two configurations compared: (orange) Aurora cabinet (1 mm effective walls), (grey) Smooth cabinet (25 mm walls), (black) Without cabinet.

A similar numerical analysis in the frequency domain was performed to study the sound radiation of the metamaterial cabinet when coupled with a generic tweeter. This study was also conducted in the frequency range from 500 Hz to 5000 Hz, with an interval of 1/12th octave, and a dipole was used as source. In this simulation, the loudspeaker system was positioned inside an air-filled sphere, and only the latter was surrounded by an external PML layer. Simulations were repeated using alternatively the Aurora cabinet and the Smooth cabinet, and assessing the radiation emitted at a distance of 1 m by the two loudspeaker systems (Figure 6).

A comparison of the directivity graphs in Figure 6 shows that although no significant change in directivity at lower frequencies can be observed, a major change of the systems directivity in the horizontal plane occurs at 1900 Hz (black dashed line in Fig. 6). So around this frequency we will investigate in more detail what influence the metamaterial cabinet walls have on this behaviour.

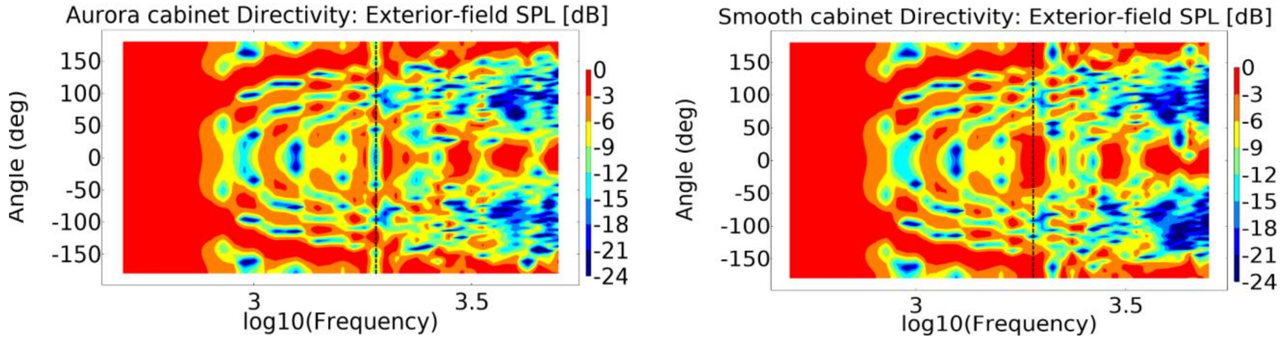

Figure 6 – Directivity graphs of the loudspeaker systems realized with (*left*) Aurora cabinet and (*right*) Smooth cabinet. The black dashed line in both graphs highlights directivity at 1900 Hz.

3.2 Eigenmodes analysis

As anticipated in the previous section, we observed some key differences in the response of the two cabinets in the range 1000 Hz to 3000 Hz. One potential reason for this behaviour is the presence of unwanted resonances in the Aurora cabinet. Just like in a more classical cabinet, its dimensions could in fact introduce resonances not related to its metamaterial geometry, both in the vertical and horizontal planes. An eigenfrequency analysis was used solves for the eigenfrequencies and the shape of the eigenmodes.

To perform this study, the PML was neglected and a static acoustical pressure value of 0 Pa was assigned in correspondence of the open face of the Aurora cabinet. The first 50 eigenfrequencies were then computed.

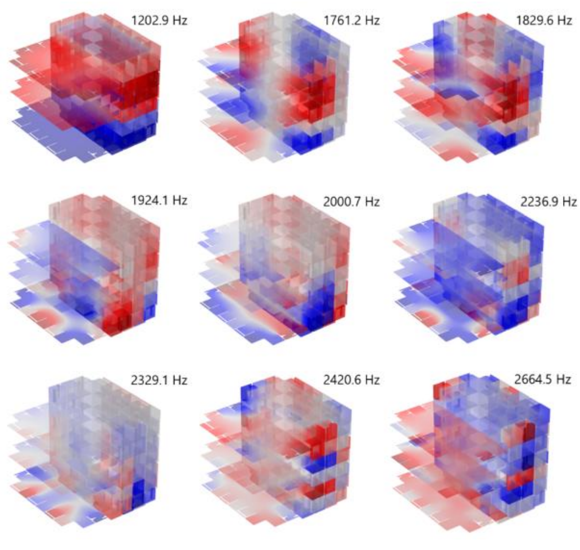

Figure 7 – Some of the eigenmodes of the Aurora cabinet.

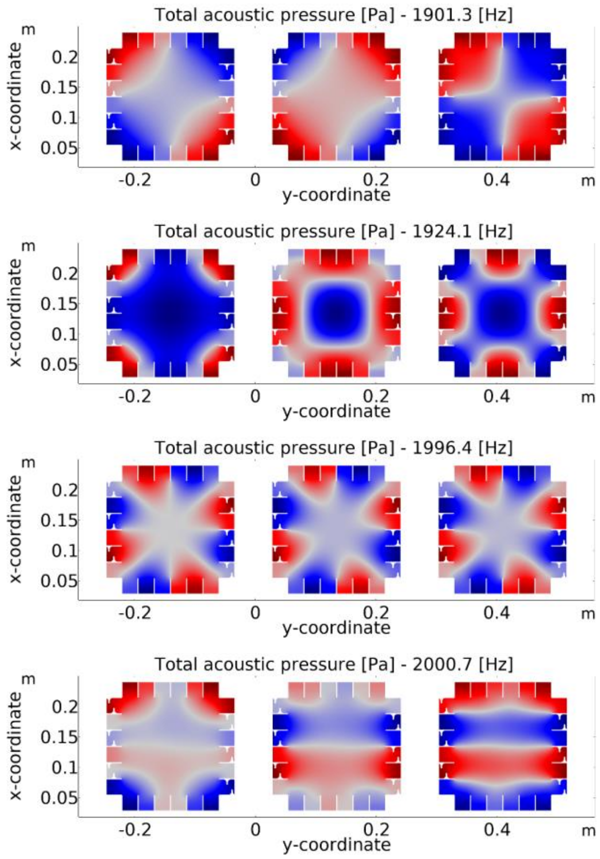

Figure 8 – Total acoustic pressure field top, middle and bottom cut planes placed inside the Aurora cabinet, eigenfrequencies equal to 1901.3 Hz, 1924.1 Hz, 1996.4 Hz and 2000.7 Hz.

Figure 7 shows that the region between 1000 Hz and 3000 Hz is modal dense, with some of the internal eigenmodes of the standing waves inside the cabinet highlighted. A more detailed analysis of these modes can be found in Figure 8, which shows the pressure field obtained on three evaluation planes placed at different heights of the metamaterial cabinet around the frequency of 2000 Hz i.e. where one of the resonant behaviours of the system response was noted in the simulations.

Looking at the graphs in Figure 8, sound pressure minima and cancellations generated by the geometry of the metamaterial cabinet are evident. If one of these modes is excited by the source, the acoustic energy transforms into vibrations of the structure. Thus, vibration of the cabinet due to reaction forces of the electrodynamic transducer occurs. One solution to avoid this effect would require changing the dimensions of the cabinet in such a way that the vertical and horizontal axial modes due to the side walls do not coincide with those due to the top and bottom walls. Thus, reducing the total power in the antinodes of the resonant mode.

4 Experimental results

The experimental campaign was conducted at Contralto Audio's laboratories. The aim was to study the acoustic response of two prototype devices: (1) the system obtained coupling the previously described Aurora cabinet to a commercial tweeter and (2) the adjustable system obtained coupling the metamaterial loudspeaker to an auto-zoom lens.

4.1 Metamaterial enclosure

As for the simulations, for these measurements we used two different cabinets (Figure 1): both were closed on five sides and made of PLA with a commercial printer (F170 Stratasys). Due to limitations of the 3D printer,

however, both cabinets were reduced to dimensions of 15×15×15 cm. In addition, while the Aurora-type box maintained a wall thickness of 1 mm, the Smooth box was realised with a wall thickness of 7.5 mm. We will refer to these two cabinets respectively as "Cabinet A" (for "Aurora") and "Cabinet S" (for "Smooth").
First, we used a single microphone positioned at 100 mm from each cabinet to measure their sound insulation. Each cabinet was placed on a shelf thus enclosing a low-cost commercial sound source. Cabinet S gave us a 6 dB reduction between 500 Hz and 6000 Hz. The back of this cabinet was then reinforced with a wooden plate (2.5 cm thick, density 800 kg/m3), for a total weight of 1.6 kg and a 20 dB reduction in the frequency band of interest. "Cabinet A" showed the same reduction of 20 dB between 500 Hz and 6 kHz for a weight of 600 g and a material thickness of 1 mm.
We then built a prototype metamaterial loudspeaker system using three different configurations: coupling a source in cabinet S, in S with a wooden board and in A. The sound source was mounted on a wooden board and assembled to the cabinets with a spring clamp. Measurements were carried out (with CLIO) using a logarithmic sinusoidal sweep and placing the system on a rotating base, in order to observe its horizontal polar in the different configurations. Two microphones (Earthworks M30) were placed respectively at 1 m and 2 m from the system.

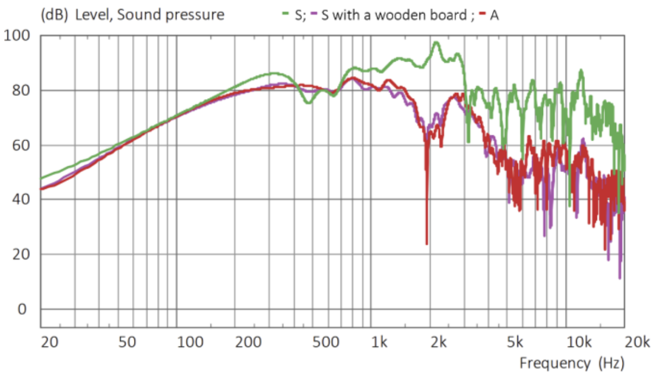

Figure 9 – Frequency response of the back of the system (-180°), measured at 1 m. Three configurations compared.

Figure 9 shows the frequency response of the back of the systems, measured at 1 m from the source. It can be seen that the A cabinet produces the same performance as the reinforced S cabinet, but using less mass. Around 1.9 kHz there is a strong loss of acoustic energy, probably due to the cooperation of the metamaterial cabinet's vibrational modes, resulting in a cancellation which is not observed in the case of the Smooth cabinet.

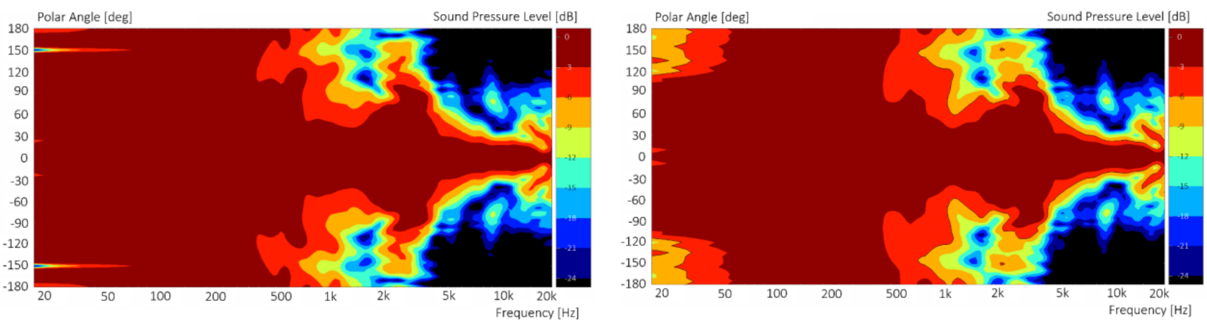

Figure 10 – Directivity graphs of the two loudspeaker systems. (*left*) cabinet S with a wooden board and (*right*) cabinet A (VACS Viewer).

The effectiveness of the Aurora cabinet ("A" in Fig. 10) is confirmed by the response as a function of the angle on the horizontal plane (Fig. 10). The graphs are normalised with respect to the maximum level value for each frequency, as was done in the numerical analysis. It can be observed that, with the same frontal emission, in the case of A there are less low-frequency back-emissions.

The graph in Figure 11 represents the on-axis response measured at 1 m. It can be clearly seen that the metamaterial cabinet guarantees the same performance as a traditional massive enclosure when coupled with the same sound source. Moreover, it can be noticed the previously discussed resonant behaviour around 2 kHz.

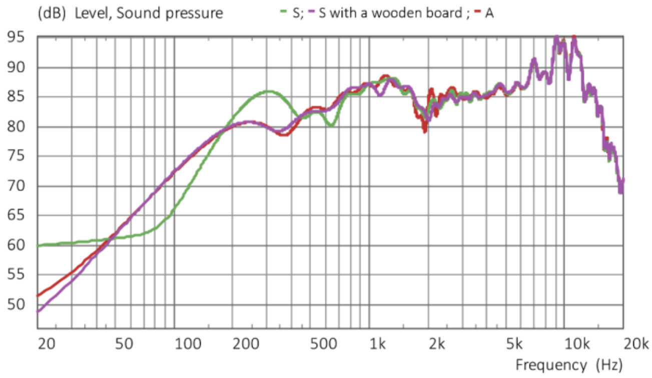

Figure 11 – Frequency response of the front of the system, measured at 1 m. Three configurations compared.

4.2 Acoustic telescope with auto-zoom objective

Ours (Figure 2, *right*) is a Keplerian telescope for sound [5], whose objective consists of two converging lenses, positioned at a variable distance d, capable of focusing on a moving target listener [10].

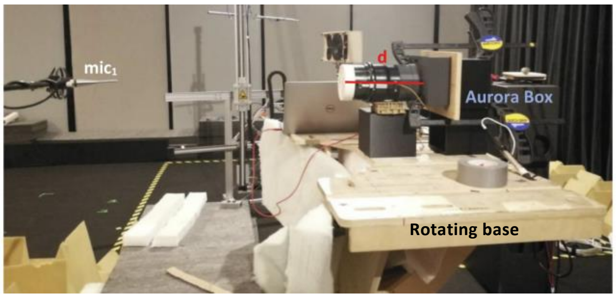

Figure 12 – Experimental set-up. Acoustic telescope with Aurora cabinet (A) + twitter.

For this study, we used two convex lenses for sound having the same focal length (f = 53 mm) which we mounted in front of the source system + cabinet A. Measuring on axis at 1 m and 2 m distance from the second lens (Figure 12) we focused the sound on the first microphone and then on the second. Figure 13 shows the response of the system, measured as above. The directivity increased (comparison with Fig. 10), consistently from 1.5 kHz onwards. Numerous peaks and valleys are observed in the response, probably due to the physical presence of the auto-zoom objective, and at some frequencies the decay is greater than expected at doubling distance.

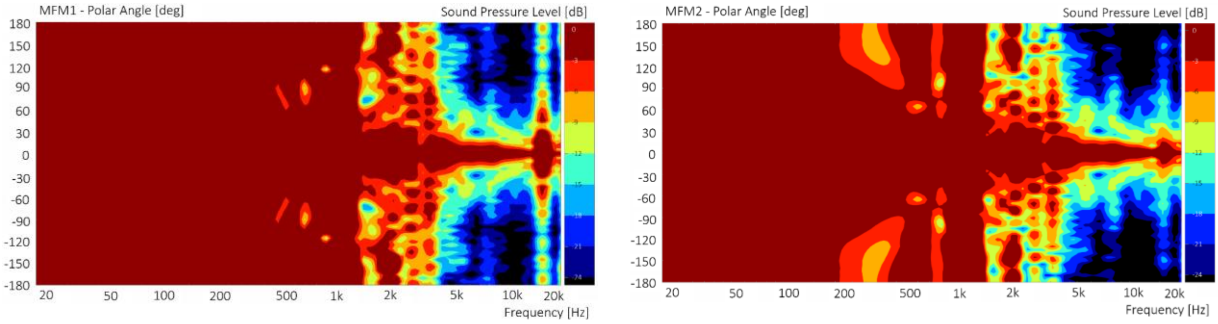

Figure 13 – Directivity graphs of the acoustic telescope. Focus at (*left*) 1 m and (*right*) 2 m.

5 Applications

Centuries of development in the field of optics have provided us passive devices such as lenses or mirrors to enrich the immersivity of the audience with light effects, but there is nothing similar for sound.
Possible applications of the systems described above include the reception (or emission) of a signal exclusively for a single person in the crowd. Other applications concern acoustic displays (e.g. a group of people dancing and following a specific acoustic focus in a discotheque) or the reproduction of music with a dynamic spatial component.
Proof of concept that a metamaterial telescope can be used to follow a moving source in the field of view has been shown by Rajguru *et al.* [15]. In the future, similar systems could be used to deliver sound effects to multiple users having the same immersive experience, without a headset.
In the near future, we also expect to improve the audio reproduction performance of low-cost loudspeaker systems or ceiling and in-wall speakers. The latter are often directly mounted into the wall because frequently there is no space for a cabinet to be coupled to them. Reducing the size of the cabinet by exploiting and optimising the geometry of the metasurfaces that make up the enclosure can be highly desirable.

6 Limitations and future developments

In this work we have shown that it is possible to reduce the weight of a loudspeaker system by 60% by using a metamaterial cabinet and that this allows us to shape backward and side emissions of a system without deteriorating its acoustical performances. This was done both by numerical analysis and by experimentally testing the system in its different configurations. The source used to perform the comparative analysis presented in this study has a major influence on the results, both in simulations and experiments. In fact, depending on the frequency reproduced, the vibrating transducer components can also play a key role in the system emission. A more accurate validation of the conclusions will therefore require a complete numerical vibroacoustic analysis of the source. In parallel, measurements with different transducers will give us insights into the potential effects.
Numerical analysis was employed to investigate the resonant behaviours observed in the simulated response, highlighting that a more accurate spectroscopy of the system is required, as these resonances may “colour” the emission of the system.
Finally, in this study we used two metasurfaces, arranged in a telescope, to control the directivity of audio systems. In the experimental measurements, directivity control at low frequencies was observed which was not investigated in the numerical analysis and which probably also depends on the type of source used.
Our study is set in a context, where acoustic lenses and metamaterial systems [11,12,13] are used in professional audio. Optimisation of the prototype devices described above could lead to a personalised form of audio communication, but it will be very important to carry out experiments in the telephony band in order to demonstrate that the intelligibility is guaranteed.
The key limitation of metamaterials, in fact, is still their bandwidth of operation. While in optics one octave in frequency is sufficient to cover the visible spectrum, metasurfaces cannot currently transmit the 11 octaves that make up our audible range. As many studies are showing, however, the bandwidth of a metasurface is as much a design parameter as its spatial footprint: acoustic metamaterials auto-zoom lens, incorporating lenses that can focus a basic melody, are not far away.

Acknowledgements

This work has been done in collaboration with the University of Sussex, which acknowledges funding through UKRI grant EP/S001832/1. LC would like to thank all the other members of the Aurora project team for the useful discussions.

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