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# OPTIMISING METASURFACE RETRIEVAL BY HILL DESCENDING

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## 1. ABSTRACT

Delivering a uniform acoustic experience in a space is a well-known challenge. Today, this is achieved stacking many digitally controlled wavefront shape loudspeakers. However, since the directivity of each speaker varies with the frequency, the sound waves do not mate consistently, resulting in a non-uniform sound pressure level, changing with both the frequency and the position of the listener. Here we show how this can be addressed using acoustic metasurfaces, capable of locally manipulating both phase and intensity of a sound wave in a small footprint by changing their geometrical parameters. When coupled at the outlet of a sound source, they could create meta-filters, passively embedding part of the required signal processing, creating sound homogeneity or providing sound effects. The question is: given a desired wavefront, how can the parameters be tuned efficiently? In this study, a method for retrieving an acoustic metasurface through the hill descending algorithm is presented. The algorithm is tested on a simple optimization problem, searching for the best metamaterials combination providing a desired coverage in a reflection-free listening area. Input data are retrieved by finite-element modelling a simplified sound system in a reflection-free venue. Further research is required to validate this method toward multi-objective optimisation.

**Keywords:** *acoustic metamaterials, hill climbing, passive signal processing, metasurface design.*

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## 2. INTRODUCTION

Considering a simple listening area, a traditional line array loudspeaker system is typically characterized by a narrow coverage[1]. The resulting sound pressure level (SPL) is not uniform in the venue, generally higher in the direction of main beam, and decreases gradually off-axis, while changing with the listener distance and narrowing with the increased reproduced frequency. Especially in the near field, signals will not be in phase with each other, creating destructive interference[2]. This is more prominent at mid-high frequencies, due to the shorter wavelengths. As the array length increases, a fixed frequency will get more directional. Also, as the wavelength decreases for a given array length, the beam-width gets tighter[3,4]. However, for a straight line array, there is a very slight position where the frequency response of the system is just right, which is far too small to cover a reasonable size audience. The next step in enhancing the use of a line array reported in literature was to curve it, normally at the bottom[3]. This provides the small secondary lobe benefits of a line array, while widening the main on-axis lobe to a more practical beam-width, but resulting in a more cumbersome system. Metamaterial-based solutions are proving to be viable alternatives to the products commonly used to control the directivity and to reduce the unwanted sound emissions in loudspeaker systems[5-7], resulting in a lighter and more compact system as a first benefit. Acoustic metasurfaces are made up of sub-wavelength structures, capable of locally manipulating both phase and intensity of an impinging sound wave in a small footprint. Metasurfaces designed combining analytical and numerical procedures have shown efficient passive sound control over a wide frequency range and in very little space[8,9]. Assembled in meta-filters or acoustic lenses they could cooperate with digital processing of the signal to obtain a desired coverage of a listening area. Traditionally, the design of acoustic metamaterials (MMT) depends upon physics-inspired methods[9-11] and is guided by human knowledge such as, physical insights obtained through studying basic systems, experience gained from past practices, and intuitive reasoning. The initial design often tested using simulations must then come up against the manufacturing limits and the real-world application requirements[12]. To approach the design objective, changes to a handful of parameters and re-evaluation by simulations must be repeated on an iterative basis. Although this method has had a lot of successes, it is becoming increasingly computation-expensive and time-consuming as the complexity of acoustic metamaterial design grows[13]. An alternative approach is to use inverse design methods for this task. Instead of using physical principles for the initial guess, the intended acoustic functionalities are obtained through optimisation in the search space defined by MMT parameters, by seeking a solution that optimises an objective function. This can be achieved via gradient free methods, including hill-climbing algorithms (as employed here) and evolutionary algorithms, gradient based methods that include topology optimization[14] or level set method or adjoint methods. In this study, an acoustic metasurface is retrieved, by hill descending algorithm. As proof-of-principle, a simple optimization problem is built, searching for the best configuration of metamaterials, which provide a desired horizontal coverage in a listening area.

## 3. METHOD

Previous literature demonstrates that sound fields with high spatial resolution can be created from a discrete set of 16 phase-delay metamaterial labyrinthine structures[15], with a constant amplitude. The metasurface here described has 10 labyrinthine structures. For the sake of simplicity, the method here presented exploits the metasurface symmetry with respect to its central axis. Therefore, the problem variables are the phases of the 5 acoustic MMTs, also called bricks, as described by Memoli et *al*.[10]. Each brick can take 8 possible phase values, resulting in a 5D space search problem. Phase delays are associated with indices, to which correspond values ranging from 0 to 7/4π [rad], in steps of π/4. Assuming that only a symmetrical distribution of delays is possible, and thus limiting the search of a desired pressure distribution on-axis with respect to the sound source, the number of possible combinations is reduced to $8^5$. This input space is retrieved by finite-element modelling, using COMSOL Multiphysics software package. The 2D numerical model concerns a metasurface, placed at the center of the right boundary of a reflection-free listening area (100x100 cm), where a desired pressure distribution is aimed to be obtained by hill descending. The sound system is not modelled and no MMT geometry is explicitly represented here, for practical reasons. In fact, previous literature[9] allows to determine the geometrical parameters a 2D MMT brick needs to have, once the desired wavefront amplitude and phase at its outlet are known. In this work, the sound wavefront propagation in air is modelled as a planewave, emitted by the MMTs. Together, they determine the total wavefront emitted by the acoustic metastructure. The metasurface (2x20 cm) consists of sound transmission bricks, represented with 10 air squares ($brick_x$=$brick_y$= 2 cm), each of which will impose a precise phase delay on the emitted wavefront. Pressure Acoustic, Frequency Domain interface computes the pressure variations for the propagation in air of acoustic waves at quiescent background conditions. Perfectly Matched Layers 20 cm thick are added to the external boundaries, to absorb all outgoing wave energy. Sound Hard Boundary is assigned to all the external boundaries of the metastructure components and thus, the normal component of the acceleration results zero. A Background Pressure Field is assigned to each MMT brick, with unitary Pressure Amplitude, negative *y* wave direction and an initial nil phase. The calculation is performed by considering a minimum element size mesh equal to 1/5th of the shortest wavelength studied. The study is conducted for a single frequency $f_1$= 2k [Hz] and it provides, in approximately 30 minutes, the search space needed for the algorithm to work. Data are exported from COMSOL to MATLAB in a single spreadsheet, containing bidimensional space coordinates and the root mean square value of total acoustic pressure ($p_{rms}$), evaluated on a 2500 points regular grid (N) in the listening area or region of interest (ROI), for all the $8^5$ configurations. The hill climbing algorithm used here is a local search method, often employed when the gradient of the objective function is unknown. It is an iterative algorithm which starts with an arbitrary solution, then attempts to find a better solution by making incrementally changing (i.e. mutating) the solution. If the change produces a better result, another incremental change is made to the new solution, and so on until no further improvements can be found. Thus, an objective function (or Score) to be minimised is defined (Eq.(1)), for every brick configuration.

$$\sum_{i=1}^{N} \frac{\left| p_{rmsROI} - \frac{\sum_{i=1}^{N} \left(p_{rmsROI}\right)_i}{N} \right|_i}{N} \quad (1)$$

Then, we modified the objective function (Eq. (2)) reducing the ROI to M points:

$$\sum_{i=1}^{M} \frac{p_{rms\,i}}{M} \quad (2)$$

A mutation function is performed by the algorithm, starting with a random MMT brick, selecting a random phase value for the selected brick and then replacing the current value with a newly generated one. The algorithm was run for a fixed number of 100 iterations which was sufficient for convergence for the objective functions used here.

## 4. RESULTS

For the proof-of-principle to work, a simple case is chosen, retrieving the metamaterial bricks needed to obtain acoustic pressure uniformity in the target listening area. In Figure 1a, the score over time is shown, whose behaviour indicates the error always decreases and reaches convergence.

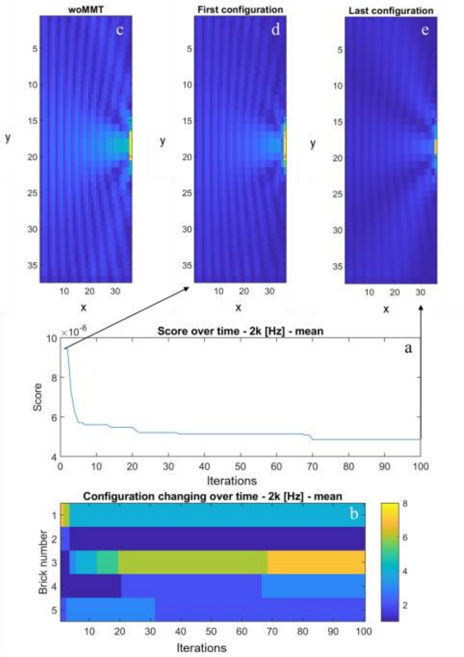


Figure 1 – a) Score over time; b) Configuration changing over time; c, d, e) Listening area $p_{rms}$ woMMT, 1st and last configuration found.

70 are the iterations for the algorithm to find a solution which minimise the error (135s), but it not necessarily is the global optimal one. Fig. 1b represents the change of the brick configurations over time. Y-axis indicates the index associated to each brick, and colors are associated to a phase value between the 8 possible ones. Comparing the pressure distribution without the use of metamaterials (woMMT), the 1st and the last configurations found by the optimization algorithm (Fig. 1c-e), field uniformity can be evaluated. To quantify this effect, the SPL difference between the last configuration (wMMT) of bricks and the one woMMT, is shown in Figure 2a. Histograms show the distributions of SPLs without metamaterials and with the best bricks combination found by the algorithm (Fig. 2b,c). Having validated this search method, we modified the objective function to Eq. (2), obtaining a '*hole*' having dimensions 1/3rd of the metasurface width and placed at its outlet. In this case, the algorithm minimises the mean SPL within the rectangle where the hole is desired (Fig. 3c).

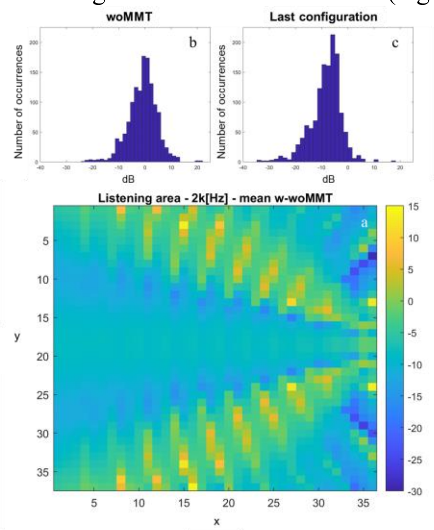


Figure 2 – a) Listening area dB difference w-woMMT; b, c) Histograms with n° of occurrences of a SPL woMMT and for the last configuration found.

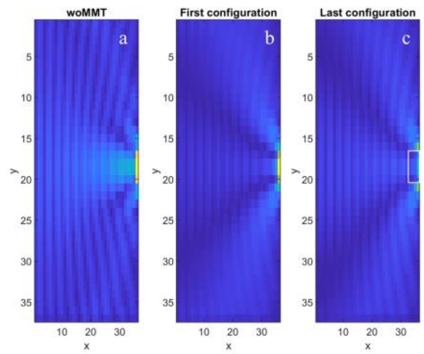


Figure 3 – a, b, c) Listening area ($f_1$) $p_{rms}$ woMMT, 1st and last configuration found.

An average -10 dB reduction (Fig. 4a) is obtained where the '*hole*' is expected, confirming the metasurface found by the algorithm contributes to generate the desired sound shape.

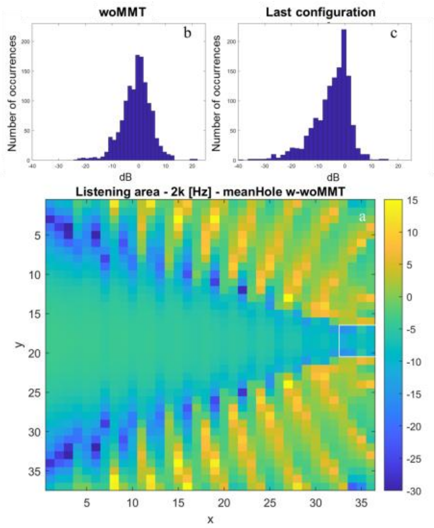


Figure 4 – a) Listening area dB difference w-woMMT; b, c) Histograms with n° of occurrences of a SPL woMMT and for the last configuration found.

## 5. CONCLUSION

In this work, we use hill climbing to retrieve the metamaterial bricks required to build up a metasurface, aiming to distribute sound more uniformly in a target listening area with respect to a sound distribution without metamaterials. As this is only proof-of-principle, the method is applied to a simplified case consisting of a single frequency. It can be concluded that the wavefront uniformity has increased compared to what would be obtained without metamaterials, at the cost of having shifted the levels towards lower values. The method confirmed its validity also having modified the objective function, using a metamaterial to create a '*hole*' of relative "quietness" in the listening area, which could be beneficial for audiodiverse listeners. We found an average difference of 6 dB between the '*hole*' and the rest of the listening area. Future studies will explore ways to enhance this "contrast". The results here showed demonstrate this method could be applied in order to obtain more complex sound shapes such as, multiple soundless '*holes*' or controlled distance sound propagation. In future work, we expect to design lenses, diffractors and other tools to create special effects for sound. This simplified procedure allows to drastically reduce the time required to design acoustic metasurfaces. Further modelling of the sound source and additional research are required in order to enhance solutions and to validate this method toward multi-objective optimisation.

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