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Towards Designing Pleasant Urban Soundscape: An Acoustic Metamaterial-Based Multi-Objective Psychoacoustic Analysis

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ABSTRACT*

Noise is a pervasive environmental concern with significant health impacts. Traditional noise mitigation techniques primarily focus on reducing noise levels, often overlooking the importance of human perception in shaping auditory experience. In contrast, the soundscape, an innovative emerging concept, addresses both noise levels and the perceptual aspects of noise but remains difficult to implement effectively. This study presents a novel multi-objective framework that integrates acoustic metamaterials (AMMs) with psychoacoustics to design harmonious urban areas, following the soundscape protocols. Leveraging real-time traffic noise data from an urban park, we investigate the simultaneous effects of positioning different numbers of AMMs on both psychoacoustic and propagated noise levels within the small-scale urban park area. Considering a single frequency (200 Hz), we establish a trade-off between noise levels (L_{Zeq}) and key psychoacoustics, such as sharpness (S), providing various alternative solutions. A solution envelope is observed between L_{Zeq} and S with extreme at #2 AMMs yield ~59.11 dB and 1.17 acum and #9 AMMs achieve ~47.90 dB and 1.26 acum while #6 AMMs offer a balanced solution at ~54.54 dB and 1.21 acum. This approach enables decision-makers to choose between different competing solutions, enhancing the practical viability of soundscape interventions in designing pleasant urban environments.

Keywords: *Traffic noise reduction, Soundscape, Acoustic Metamaterials, Urban Areas, Psychoacoustics, Multi-objective optimization.*

1. INTRODUCTION

Noise pollution has become a significant environmental concern, negatively affecting public health, well-being, and overall quality of life. According to the European Environment Agency, environmental noise is the second most significant concern, affecting over 106 million people in the EU [1], causing severe health impacts and posing challenges to net zero, making it crucial to address this challenging issue. Traditional noise mitigation strategies primarily focus on reducing sound pressure levels (SPL) but often neglect the perceptual and psychological aspects of noise. However, recent research highlights the limitation of such approaches, calling for more human-centric solutions [2]. Soundscape, which defines the acoustic environment as perceived by humans within a specific context, offers a promising approach to traditional noise control by shifting the focus from mere SPL reduction to investigating human perception of sound and creating acoustically pleasant environments [3]. According to ISO/TS 12913-2 (2018) [4], psychoacoustic metrics are reported as key parameters for

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soundscape assessments, which characterize the acoustic environment. Attributes such as loudness, roughness, and sharpness play a crucial role in human auditory perception. Specifically, psychoacoustics describes and quantifies the psychological aspects of auditory perception through different sensory experiences [5]. Roughness describes the sensation caused by fast temporal modulations (ranging from 15 to 300 Hz) in sound, which influences the perceived texture and annoyance of an auditory experience. Sharpness measures the high-frequency content of a sound; a greater proportion of high frequencies results in a 'sharper' perception. Previous studies indicated that reducing loudness (N_5), roughness (R), and sharpness (S) enhances the auditory experience in urban environments [6]. However, most noise reduction studies have solely focused on mitigating noise intensity, with limited consideration of psychoacoustics. Thus, there is a growing need for innovative approaches that not only target noise intensity but also aim to create a favorable and pleasant environment for passersby, all while being sustainable and adhering to noise regulations.

Acoustic metamaterials (AMMs) have emerged as a promising tool for sound manipulation, offering tunable sound mitigation solutions, though they have been primarily applied in indoor environments [7,8]. In general, AMMs are specially engineered structures that can uniquely manipulate the sound field with unprecedented characteristics as opposed to conventional methods. In our recent work, we have, for the first time, demonstrated the effect of AMMs on modulating outdoor urban noise and its impact on psychoacoustics [9]. Initially, this problem was approached with a single objective of minimizing SPL. However, it does not capture realistic complexities, and challenges remain in measuring psychoacoustics with AMM configuration strategies, especially when analyzing perceptual sound quality. A key difficulty lies in understanding the trade-off between noise levels and the psychoacoustics of the low- and high-frequency components of the sound field, as reducing low-frequency noise levels may unintentionally alter or compromise the high-frequency components such as sharpness, thereby complicating the task of creating and improving overall acoustic comfort.

However, to realistically build urban space, it is essential to consider the simultaneous investigation of both low- and high-frequency components of the sound field. Given the proven ability of AMMs in designing the urban soundscape, we have utilized the effects of AMMs in this work to not only suppress the sound pressure level (SPL) (L_{Zeq}) value but also to identify sharpness (S) levels simultaneously. We streamlined this psychoacoustic analysis by proposing a novel multi-objective AMM-based psychoacoustic analysis framework to approximate the effects of different AMM layouts on traffic noise. A recent soundscape study [10] reported a negative correlation between roughness and soundscape pleasantness, prompting us to target the reduction of low-frequency traffic noise and select 200 Hz for optimization. Using real-time traffic noise data from an urban park, we investigate how different AMM placements influence noise fields at 200 Hz and key psychoacoustics components of the sound field.

2. METHOD

2.1 Data collection

The data collection involved GPS-tracked short-term acoustic measurements to assess the traffic noise field under unoccupied conditions (i.e., without humans) and a soundscape assessment under occupied conditions (i.e., with humans) to capture the perceived noise.

Real-time traffic noise was recorded in a 20m × 30m churchyard (urban park) in Bloomsbury, London, using a 5m × 5m grid system. Across this area, 71 validated binaural recordings were obtained after excluding non-traffic sounds. Additionally, a soundscape survey, following the ISO/TS 12913-2:2018 Soundscape Indices Protocol, collected 62 responses, assessing the perceived affective qualities of the sound environment in the churchyard.

2.2 Multi-objective AMM-based psychoacoustic analysis

In general, AMM structures are formed by arranging the repeating unit cells or elements in a pattern with spatial resolution '$\partial\lambda$' ($0 < \partial < 1$ and wavelength (λ)) to achieve the required functionality. Using the phase retrieval, Wirtinger flow method [6], the holographic sound field is propagated back and forth to train the AMM structures and determine the phase and intensity values at the target location. Interested readers can refer to References [6] and [8] for more details. We utilize this mechanism to compute the noise field within the urban space by creating acoustic hologram images of the interacting complex traffic noise field for each AMM structure layout (numbers and position), which are then propagated to the desired locations to reflect the noise in the urban space.

To evaluate the impact of AMMs on psychoacoustic perception, we developed a streamlined batch-processing pipeline integrating audio filtering and psychoacoustic analysis with holographic propagation of AMM-based noise levels. Initially, we use Soundscapy [11] to process the collected sound recordings from 71 locations, computing the L_{Zeq}, N_5, and S on binaural traffic noise recordings and verifying the stereo format. Then, for the determined AMM layout, we compute the sound attenuation by evaluating the difference between the noise levels of holographic-propagated AMM-based noise and the psychoacoustic metrics. We then use these precomputed attenuation levels and targeted frequency of 200 Hz to apply a customized notch filter using the *scipy.signal.iirnotch* function from the SciPy library [12]. This filtering step approximates the 200 Hz noise field as a broadband frequency range (20 Hz -20 kHz). The filtered recordings were then reanalyzed using the same psychoacoustic metrics. To investigate the effects of different numbers of AMM structures positioned at the boundary of urban space, a binary variable-based multi-objective framework is developed in this work. To determine the AMM layout at the boundary of the urban area, we first divide the boundary into grid spaces, where each grid point corresponds to a potential location where AMMs can be placed. A binary variable, which can take the values 0 or 1, is assigned to each grid point, indicating the presence or absence of AMMs at these locations. We employ a widely used multi-objective genetic algorithm [13] to determine the optimal layout of AMMs, while simultaneously minimizing propagated SPL and S. As a result, a non-dominated Pareto front will be obtained, providing decision-makers with ample choices to select the desired solution and assess the impact of each AMM configuration on perceptual sound quality.

3. RESULTS

3.1 Validation of the proposed framework

To validate the proposed AMM-based psychoacoustic analysis framework, we compared the noise levels and psychoacoustic outputs of different AMM number cases with the widely recognized ArtemiS SUITE 12.9 psychoacoustic workflow. Using the 2×2×λ/2 m² as AMM structures size (λ at 200 Hz) and layout configurations with #9, #7, and #5 AMMs, respectively, we calculated SPL and psychoacoustic indicators for each measurement point (total 71) within the churchyard. **Fig 1** shows the comparison plots of psychoacoustics and noise levels with two approaches. Our results showed strong agreement between the AMM-based analysis framework and the ArtemiS SUITE 12.9 analysis, confirming the reliability of the proposed framework. The observed R^2 values of 0.988 for L_{Zeq}, 0.982 for N_5, 0.976 for S, and 0.964 for R, indicates the high accuracy of the proposed framework across all selected AMM layouts (#5, #7, and #9). This validates the capability of the proposed AMM-based psychoacoustic analysis framework to approximate the effects of AMM structures on the 200 Hz noise field.

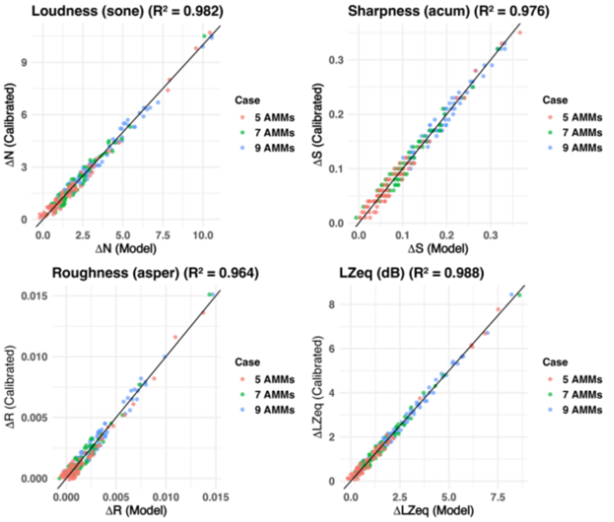

Fig 1. Validation of the proposed AMM-based psychoacoustic analysis framework *(represented at x-axis)* with the ArtemiS SUITE 12.9 workflow (*represented at y-axis*) for different AMM layouts (#9, #7, and #5).

3.2 AMM impacts on SPL and Psychoacoustics

Fig 2 depicts the non-dominated Pareto front obtained after solving the multi-objective noise-psychoacoustic problem to minimize noise pressure levels and high-frequency sharpness values. Here, only sharpness is considered to represent the psychoacoustic component of the

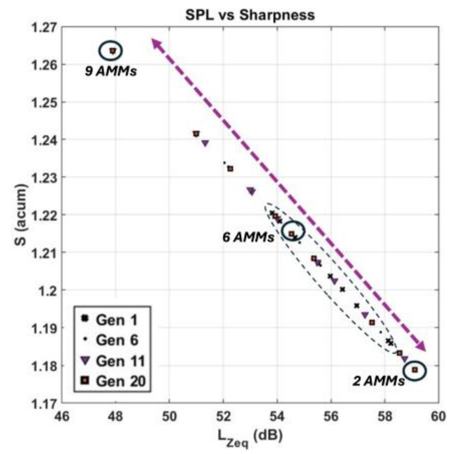

Figure 2: Pareto plot between SPL L_{Zeq} (dB) and Sharpness S (acum) components of the sound field. Here, the solution evolved from a narrow range to a wide range, resulting in many alternative solutions.

sound field, as other loudness and roughness properties vary linearly with the noise levels, showing no conflicting properties. With only a small number of variables involved, the computation converges in 20 generations (with a population size of 20), achieving the final trade-off solutions, where each Pareto point solution corresponds to a different AMM layout. As the solution converges, the Pareto front evolved from the narrow range to a wide range of solutions. It is observed that with a small number of AMMs (#2), where the noise is allowed to propagate freely inside the urban space, corresponds to high noise levels (~59.11 dB) with low sharpness (~1.17 acum) values. These sharpness levels are generally perceived as acceptable; however, with the corresponding high noise levels, the degree of annoyance will be higher [1]. On the other hand, with the large number of AMMs, the noise levels are observed to be lower (~47.90 dB), but they correspond to high sharpness (~1.26 acum), which increases the likelihood of having high-frequency components that can be perceived as harsher and more unpleasant. However, when we select the balance solution with the #6 AMMs layout, the noise levels and sharpness are recorded as ~54.54 dB and 1.21 acum, respectively, which is perceived as somewhat acceptable, with a low degree of annoyance. This left the decision maker with a choice of solutions and determined a balanced solution that can be perceived as less annoying, with a low degree of annoyance. Moreover, in comparison to a single-objective framework [8], the proposed approach offers a wide range of solutions with improved sharpness and noise values.

4. DISCUSSION

The proposed AMM-based multi-objective psychoacoustic analysis framework shows strong potential in reducing L_{Zeq} at 200 Hz while maintaining S within a perceptual threshold. While this study optimized for L_{Zeq} and S, incorporating other psychoacoustics such as 'R' can further enhance the framework. Dealing with reductions in low-frequency SPL can also influence 'R' along with 'S', explicitly incorporating it as an optimization objective would enable more holistic soundscape tuning and offer a more accurate reflection of perceptual outcomes.

In the current framework, the multi-objective optimization considered only the AMMs layout (numbers and position) along the churchyard boundary. However, incorporating the spatial distribution of AMMs within the churchyard could provide additional information, as it will not only influence the traffic noise field but also consider non-acoustic factors that are essential for creating a pleasant soundscape, as emphasized in ISO/AWI TS 16755-1 [14]. Thus, expanding the framework to optimize both the quantity and spatial configuration of AMMs could better balance noise control with the perception of the sound environment.

5. CONCLUSION

The study proposes a novel, multi-objective psychoacoustic analysis framework integrating AMMs trained on a single frequency (200Hz) to optimize soundscape perception within a small-scale urban park. The framework's reliability is validated against the ArtemiS SUITE 12.9 workflow, showing strong agreement with prior results (R^2>0.96 for L_{Zeq}, N_5, S) [9],confirming its capability to approximate psychoacoustic effects of AMM deployments at 200 Hz. As a result, a trade-off solution is observed with extremes at #2 AMM layout yielding high SPL with low sharpness (~59.11 dB, 1.17 acum) and #9 AMM minimizing SPL at the cost of higher sharpness (~47.90 dB, 1.26 acum), while the solution with #6 AMM achieves a balanced profile (~54.54 dB, 1.21 acum). These results demonstrate the framework's capability to approximate perceptual effects and support diverse, informed design choices. Future work will extend the optimization to include AMM spatial distributions and additional psychoacoustic parameters to achieve a pleasant urban soundscape.

6. ACKNOWLEDGMENTS

XF and PM contributed equally to this work and are recognized as joint first authors. The authors gratefully acknowledge partial funding support from the UCL Architecture Research Fund 2022/23, the ERC Advance Grant (787413), and the RAEng (CIET 18/19).

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