# Solving a Hard Multi-Objective Problem - Optimization of Noise Absorbing Metamaterials

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## 要旨

多くの設計・目的パラメターがある複雑なデバイスの設計において，エンジニアや研究者が制約条件を克服し複数の目的パラメターを最適化するデバイスのデザインセット，即ち設計パラメターのセットを見つける事を可能にするソフトウェアのツールボックスを開発しました。このツールボックスを用い，実際に複数の周波数領域で高い音響透過抑制を可能にする音響メタマテリアルのデザインを試みました。音響メタマテリアルは従来の質量法則に従う遮音材料に比して軽量な代替材料であり，自動車や航空など多くの産業で活用されることが期待されています。

## Abstract

A multi-objective optimization toolbox, which enables the engineer and researcher to navigate complex design and performance landscapes and find the optimum set of designs, has been developed. This toolbox can be applied in various disciplines, e.g. optimization of materials formulation or processing. In this study, the toolbox was used to design acoustic metamaterials with high sound transmission loss at multiple frequencies. These metamaterials can be light-weight alternatives to conventional mass-loaded acoustic insulating materials and could find many industrial applications, such as in the automotive or aviation industries.

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## 1 Introduction

In the search and design process for a new material or component, researchers and engineers are faced with the task to pick the right ingredients or parameters in order to obtain the optimal performance of the new material or design. With the availability of increasing amounts of data, the demand for improved performance in various fields and increasingly complex designs, this task can overwhelm the researcher. A traditional approach based on the researcher's intuition or based on a simple visualization of the relationship between one or two design parameters and the performance might not yield the optimal design. In addition, various performance goals might contradict each other. For instance, a car engine should be optimized for maximum fuel mileage, maximum power, minimum emissions and maximum reliability (Fig. 1). The number of parameters in designing an engine, such as displacement, number of cylinders, type of fuel is almost endless. The relationships between the large number of parameters (design space) and the performance space (e.g. fuel mileage, power output) are often complex and the parameters are interdependent. This makes it difficult to find the optimal design. In fact, with multiple performance goals (objectives) and an unknown weighting between objectives (e.g., how much horsepower is the customer willing to sacrifice for a 5 % gain in fuel mileage), there is no single optimal design that satisfies all objectives. Instead, there are multiple conflicting optimal designs which lie on the Pareto front (Fig. 3). The definition of the design set lying on the Pareto front (the Pareto set) is that there are no designs that offer improved performance in all performance directions. Those offering improved performance in one direction (e.g. engine power) have worse performance in another direction (e.g. fuel mileage).

These types of optimization problems are called multi-objective optimizations and are encountered in various disciplines, for instance formulation of polymer materials (e.g. type and ratio of ingredients vs. strength and cost), materials processing (e.g. temperature and time vs. strength and throughput), or component design (e.g. wall thickness and material type vs. stiffness and weight) [1]. In order to navigate these complex problems and to accelerate the discovery of optimal designs, we conducted an open innovation research project with the Computational Fabrication group under Professor Matusik at Massachusetts Institute of Technology, Computer Science and Artificial Intelligence Laboratory and developed a toolbox that enables the engineer to easily tackle difficult optimization problems (Fig. 2). This optimization toolbox was applied to the design of acoustic metamaterials using both simulations and experiments. These acoustic metamaterials offer outstanding noise attenuation at certain frequencies without the heavy weight of conventional acoustic insulating materials. Furthermore, acoustic metamaterials can be tailored to deliver optimal performance for a given use case [2].

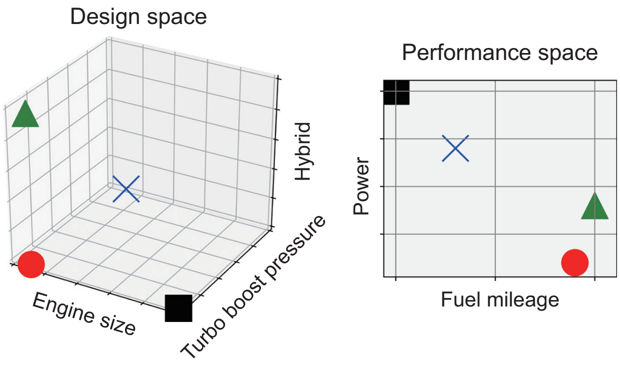

Fig. 1 Illustration of design space and performance space, exemplified on a combustion engine vehicle. The four symbols represent different engine designs.

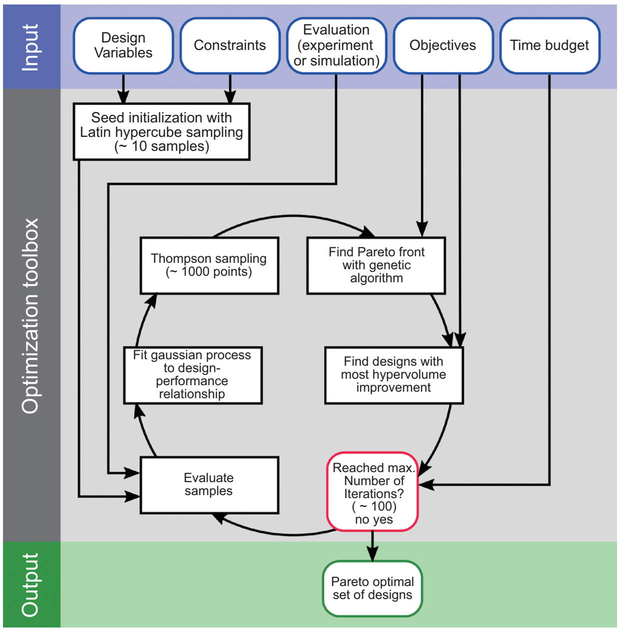

Fig. 2 Flow chart of optimization toolbox.

## 2 Acoustic Metamaterials

Metamaterials are artificial materials whose properties are determined by their engineered structures, not by the properties of the constituent materials. Metamaterials are designed to manipulate waves, e.g. electromagnetic waves (e.g. light, radio signal) or acoustic waves (e.g. sound, ultrasound). They can be designed to bend, focus, reflect or absorb waves. Acoustic metamaterials manipulate sound waves and typically use membranes or resonators. We have used the optimization toolbox to design an acoustic metamaterial that can attenuate road noise emanating from a tire, based on a starting material found in the literature [3]. It is light weight and can be installed in car wheel wells or in other locations in the vehicle. It consists of a honeycomb structure with membranes and can be 3D-printed. It is lighter than conventional mass-loaded acoustic insulating materials. Compared to conventional fabrication technologies (e.g. extrusion, injection molding), 3D-printing enables complex designs without penalizing cost or manufacturability and thus represents an excellent use case for optimization over a large design space. With multi-material 3D-printing, as applied in this project, the design space is enlarged even further.

A typical tire road noise spectrum has two maxima at 800 Hz and 1600 Hz [4]. For that reason, we chose to optimize the design for two objectives: Maximize the sound transmission loss at 800 Hz and 1600 Hz. We started with a simple metamaterial with a honeycomb-membrane structure based on the state of the art (Fig. 4) and computed its performance using COMSOL Multiphysics simulation. We then performed a sensitivity analysis in order to identify design parameters which have the most effect on the performance (e.g. cell size, cell thickness, membrane stiffness). We optimized these parameters in order to obtain optimal performance for the road noise use case described above.

We connected the optimization toolbox to the COMSOL simulation software. In an iterative cycle, the optimization tool, based on the previous designs and their performances, proposes designs that likely offer improved performance, and the simulation software validates the performance of the proposed designs. More precisely, the optimization tool uses Gaussian processes in order to model the relationship between the design space and each objective. Then, Thompson sampling efficient multi- objective optimization (TSEMO) algorithm is used to determine the designs that most likely yield improved performance for each objective [5]. Thompson sampling considers the probability distribution of performances for each design. Lastly, a genetic algorithm picks the designs that yields the most overall improvement after combining all objectives. These designs are then proposed to the simulation software. After validation of the design by the simulation software (or by experiment), this cycle is repeated about 200 times, depending on the complexity of the design and the cost to evaluate the performance. Finally, a Pareto set of about 10 designs is obtained and the engineer can decide which of those designs is best for the given application. A comparison between TSEMO-guided performance optimization and random search shows that almost all points on the approximate Pareto front were found by TSEMO search and only few by random search (Fig. 3).

After finding the optimal designs in the simple design space, we allowed the simulation to explore more complex designs beyond regular hexagonal honeycombs. This led to even better performance. Fig. 5 shows the performance of various designs. Designs optimized for a single objective (either 800 Hz or 1600 Hz) typically yield poor performance at the other frequency. Simple design search approaches, which only optimize one design parameter while keeping all others constant, also show poor performance. Similarly, reducing the complexity by limiting the design to regular hexagons only, showed suboptimal performance. In contrast, using the new toolbox with multi-objective optimization yielded designs that perform well at both objectives.

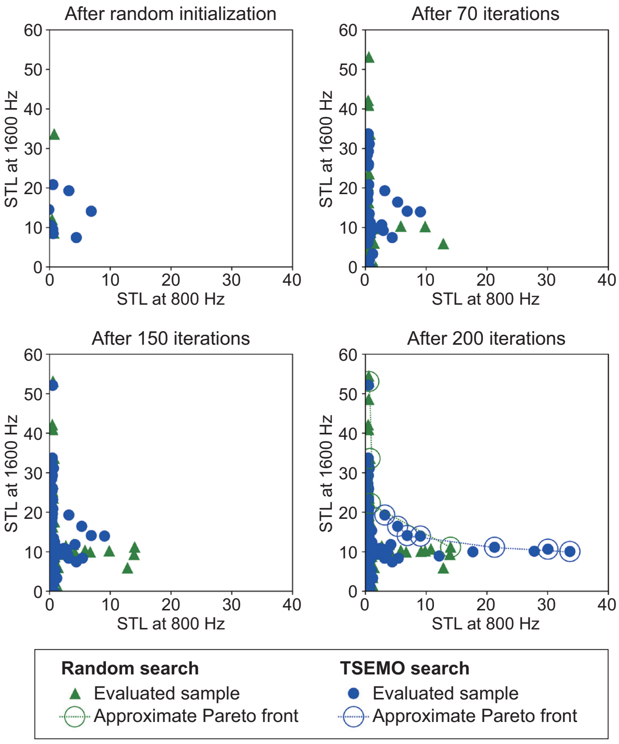

Fig. 3 Optimization of an acoustic metamaterial with the optimization toolbox. The performance space after various iterations is shown, comparing TSEMO optimization with random search. The approximate Pareto front is indicated by circles in the last graph. STL = sound transmission loss.

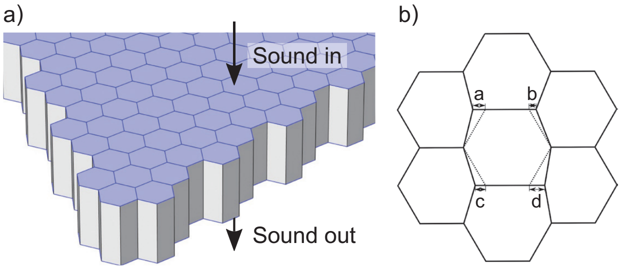

Fig. 4 Sketch of the acoustic metamaterials. a) Perspective projection of the material with regular hexagons. Blue indicates elastic membranes, grey indicates rigid cell walls. b) Honeycomb structure with regular periodic unit cells consisting of seven irregular hexagon cells. *a*, *b*, *c*, *d* are design parameters.

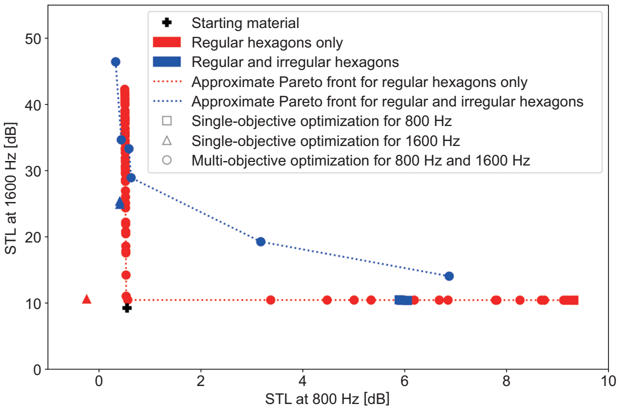

Fig. 5 Sound transmission loss (STL) performances of various optimized acoustic metamaterials, compared to the starting material. Better performance can be achieved with more complex designs.

## 3 Conclusion

An optimization toolbox that allows the researcher and engineer to find optimal solutions to complex problems has been developed as a part of the open innovation collaborative research project between Konica Minolta Laboratory USA, Research Division and Massachusetts Institute of Technology, Computer Science and Artificial Intelligence Laboratory. We successfully applied this tool to 3D-printed acoustic metamaterials. This multi-objective optimization process will accelerate the design process in various disciplines, such as single-material and multi-material 3D-printing, materials formulation and materials processing.

## References

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