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Acoustical topology optimization for Zwicker's loudness model – Application to noise barriers

Junghwan Kook [a], Kunmo Koo [a], Jaeyub Hyun [a], Jakob S. Jensen [b], Semyung Wang [a,*]

[a] School of Mechatronics, Gwangju Institute of Science and Technology, 261 Cheomdan-gwagiro, Buk-gu, Gwangju 500-712, Republic of Korea
[b] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, Building 404, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

Traditionally, the objective of design optimization of an acoustic system is to reduce physical acoustic properties, i.e., sound pressure and power. However, since these parameters are not sufficient to present the relation of physical sound stimulus with human perceptual judgment, physical acoustic properties may not represent adequate parameters for optimizing acoustic devices. In this paper, we first present a design method for acoustical topology optimization by considering human's subjective conception of sound. To consider human hearing characteristics, Zwicker's loudness is calculated according to DIN45631 (ISO 532B). The main objective of this work is to minimize the main specific loudness of a target critical band rate by optimizing the distribution of the reflecting material in a design domain. The Helmholtz equation is used to model acoustic wave propagation and, it is solved using the finite element method. The sensitivity of the main specific loudness is calculated using the adjoint variable method and the chain rule. To demonstrate the effectiveness of the proposed method, various examples of noise barriers are presented with different source and receiver locations. The results obtained, using the optimized noise barriers that consider Zwicker's loudness, are compared with the results for straight and T-shaped barriers. The results are also compared with topology optimization using 1/3-octave band level as an objective function. The optimized noise barrier using the proposed method shows the best result with respect to a human's hearing sensation.

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1. Introduction

The effect of noise on human emotion ranges from negligible, through annoyance and anger, to psychologically disruptive. Noise can also exert economic factors by decreasing worker efficiency, affecting turnover, decreasing property value, and so forth. Traditionally, a reduction of noise can be obtained by minimizing sound pressure or sound power. Thus, the objective of design optimization of an acoustic system is to reduce physical acoustic properties, i.e., sound pressure and power. However, not all sound pressures are equally loud because the human ear does not respond equally to all frequencies. That is to say, these parameters are not sufficient to present the relation of physical sound stimulus with human perceptual judgment. In other words, for the purpose of noise reduction considering the human subjective feelings on the sound, physical acoustic properties may not represent adequate parameters for designing acoustic devices.

For this purpose, psycho-acousticians developed sound quality metrics that are the primary psychological correlation of physical strength (i.e., loudness, sharpness and roughness) that will be considered in this work. Among these metrics, loudness is the most important parameter because it indicates how much louder (or softer) a sound is perceived relative to a standard sound. For loudness measurements, the study of the A-weighted sound pressure level (SPL) began with the work of a set of equal-loudness contours by Fletcher and Munson [1]. In most laboratories and in the research field, the A-weighted SPL has been used as a valid indicator of the perceived magnitude of noise. However, many people complained that the predicted loudness results using the A-weighted SPL were not matched with subjective annoyance. Hellman and Zwicker [2] proved that a decrease in the A-weighted SPL can result in a corresponding increase in loudness and annoyance. To overcome the problems of the A-weighted SPL, research about mathematical modeling of sound perception considering human hearing characteristics was performed by Fastl and Zwicker [3] using the objective SPL. The Zwicker's loudness model has been broadly used for a valid annoyance metric because of its graphical representation, and it was also adopted as a standard metric in ISO 532B (International Organization for Standardization) [4].

In recent years, environmental noise (e.g., highway noise and aircraft noise) has received more attention. To reduce noise in the vicinity of roads and residential areas, noise barriers are a useful tool. A noise barrier (also called a sound wall, sound barrier,

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* Corresponding author. Tel.: +82 62 970 2390; fax: +82 62 970 2384.
E-mail address: smwang@gist.ac.kr (S. Wang).

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or acoustical barrier) is an exterior structure designed to protect sensitive land from noise pollution. The design of efficient noise barriers that are able to protect human emotions from noise pollution is an important task in environmental noise protection. It is well known that the position and the geometry of the barrier (mainly its height) are important parameters to estimate the efficiency of the barrier. However, for aesthetic reasons (e.g., blocking scenic vistas), or practical reasons (e.g., cost of design, construction, and maintenance), it is often not suitable to build very high barriers. Therefore, it is necessary to redesign barriers to improve their performance for a given height constraint.

Several studies have been carried out in the last two decades which focused on the prediction of performance and the development of more efficient designs of noise barriers. Hothersall et al. [5,6] calculated the performance of various noise barriers using a two-dimensional (2D) boundary element method (BEM). They studied a range of barrier forms including straight, circular, Y and T shapes as well as different surfaces. Crombie and Hothersall [7] performed numerical calculations and considered scale models of multiple noise barriers and found that multiple barriers provide a significant improvement over single barriers. Ishizuka and Fujiwara [8] also did other studies comparing various barriers in a large range of shapes. Duhamel [9] proposed a shape optimization method for the design of noise barriers by coupling a BEM with a genetic algorithm optimization. Greiner et al. [10] carried out a study of optimal design of Y shape barriers using evolutionary algorithms and the BEM. Mun and Cho [11] suggested a method focused on minimizing the barrier dimensions as well as satisfying the target sound pressure levels using a simulated annealing algorithm. In these earlier studies, the authors proposed different barrier shapes and showed their efficiency in decreasing sound pressure by numerical calculations. However, these approaches suffer from a lack of a systematic method to obtain a good conceptual design and there has been no study aimed at designing noise barriers that consider the human subjective perceptions of sound.

In this study, a design method based on acoustical topology optimization to minimize Zwicker's loudness is proposed. Topology optimization is based on free distribution of material in a design domain and, hence, it does not restrict the final design topology to resemble the initial design shape. The method was originally developed for use in structural mechanics with the aim of obtaining the stiffest possible structures with a restricted amount of material [12] but has now been extended to a multitude of design problems in structural mechanics as well as in optics, magnetics, and fluids [13–16]. Topology optimization has also been successfully applied in acoustics. Lee et al. [17] applied topology optimization to minimize the radiation and scattering of sound from thin body using genetic algorithms. Wadbro and Berggren [18] presented a method for topology optimization of an acoustic horn with the aim of radiating sound as efficiently as possible. Yoon et al. [19] proposed a formulation for topology optimization of acoustic–structural interaction problems. Dühring et al. [20] demonstrated that topology optimization can be applied effectively to acoustic design either to reduce noise in certain part of a room or to design noise barriers. Lee and Kim [21] presented a method for acoustical topology optimization to maximize acoustical attenuation performance of a muffler. However, the papers written above are entirely based on reducing the objective sound pressure.

Recently, Koo and Wang [22] presented the sizing design sensitivity analysis of Zwicker's loudness and sizing optimization for a structural–acoustic semi-coupled model. (They are the second and fifth author of this paper, respectively.) To the authors' best knowledge this paper is the first to consider the importance of Zwicker's loudness as an objective function for acoustical topology optimization.

This paper is organized as follows. In Section 2, we describe the acoustic model governed by the Helmholtz equation and associated boundary conditions for noise barrier problems. The model is discretized and solved via the finite element method. Design variables and material interpolation functions are introduced for an acoustical topology optimization problem. In Section 3, we outline the Zwicker's loudness model and introduce the main specific loudness as an objective function. The topology optimization problem is stated with the main specific loudness as the objective function in Section 4. The design sensitivity analysis needed for the optimization algorithm is described in detail in this section. In Section 5, the results obtained by using the proposed method are compared with the results of using alternative objective functions considering the value of 1/3-octave band as well as with the standard straight and T-shape noise barriers. To estimate the influence of the source and receiver positions, different numerical examples are presented in this section. Finally, conclusions are given in Section 6.

2. Acoustical topology optimization of noise barriers

The task of topology optimization is to find the optimized distribution of material in a chosen design domain for which the objective function is optimized. The basic principle in the material distribution for topology optimization is to model the presence of the material with design variables (material indicator) that govern the distribution of the material in the design domain. The design variable is assigned to each finite element (or nodal point) used to discretize a design domain and the material properties of each element are allowed to vary continuously as an interpolated function of the design variable. In acoustical topology optimization, the task is to find the optimal distribution of the reflecting material (rigid body) in the design domain. In this paper, we employ acoustical topology optimization to design noise barriers with minimum Zwicker's loudness by optimizing the distribution of the reflecting material in a chosen design domain. Details of design variables and material interpolation functions for acoustical topology optimization will be given later.

The model problem that we considered is illustrated in Fig. 1(a). Here, a straight noise barrier that will be used as an initial design for the optimization procedure is presented. The aim is to distribute solid material in a designated design domain around the initial noise barrier (Fig. 1(b)) in order to minimize Zwicker's loudness. The setup of the optimization problem is similar to [20], where noise barriers were designed using topology optimization considering minimization of the average of the squared sound pressure amplitude in the objective domain. The only difference is the design domain Ω_{d}, which is 0.2 m × 2 m on both sides of the straight barrier (0.1 m × 2 m), and the sound source with a radius of 0.1 m is placed at ground level 5 m in front of the barrier. The objective is to reduce Zwicker's loudness at the receiver position Ω_{r}, that has been chosen to be a circle with coordinates 9.25 m, 1.25 m in direction of X and Y separately and a radius of 0.35 m.

It should be noted that, since the frequency of interest spans a wide range of frequency for the objective functions, the distribution of the sound pressure amplitude becomes more complex and the design to minimize the objective functions naturally becomes complicated and included gray-scales in the optimal topology, which lead to difficulties in demonstrating the effectiveness of the proposed method and in the manufacturing process. However, with the chosen design domain, we can obtain physically reasonable designs that are useful to thoroughly confirm the applicability of the proposed method. From a practical point of view, we also can obtain sufficiently efficient noise barriers simply by installing appendages to the existing noise barriers (i.e. straight barriers or

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