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ABSTRACTS

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Multiobjective optimization of very thin noise barriers

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1. Introduction - Using multi-objective (MO) optimization gives rise to a more comprehensive design scenario by providing a set of trade-off optimal solutions, popularly known as Pareto-optimal solutions. Due to the multiplicity in solutions, these problems are proposed to be solved suitably using evolutionary algorithms (EA's), which are relatively new but very powerful techniques used to find solutions to many real-world search and optimization problems [1-9].

The approach of this work is based on the evolutionary multi-objective optimization (EMO) of very thin noise barrier models with improved performance, whose designs were previously studied in [10] by means of single-objective optimization framework for idealized single-wire barrier models. One of the criterions involves maximization of the noise attenuation efficiency, while the remaining one deals with the minimization of the amount of material used in manufacturing the barrier as representative of the its total length. This work deals with optimization problems performed by the combined use of a MO genetic algorithm (MOGA) and a code that implements a dual boundary element (BE) formulation for the assessment of very thin road barriers idealized as single-wire configurations. The MOGA software used in this study applies an own implementation of the NSGA-II [11] algorithm, one of the references in the EMO field. In this sense, results here presented are a step forward in the direction marked by previous works developed within the SIANI institute [12-14].

Two-dimensional sound propagation hypotheses are considered, i.e., an infinite, coherent mono-frequency source of sound and a noise barrier with no geometric variation that stands on a flat plane (ground) of uniform admittance. The problem is performed in the frequency domain with the usual assumptions (Helmholtz equation): the medium (air) is modeled as homogeneous, elastic and isotropic with no viscosity, under small disturbances and initially at rest with no wind effects. Expression of the objective function to be maximized throughout the shape optimization process is written in terms of this response.

2. Methodology – When dealing with very thin bodies numerical integration problems, involving quasi-singular points, may appear affecting to the barrier performance. The idealization of such boundaries as non-thickness elements not only solves the problem but also contributes to ease their geometric representation. With this aim, the singular boundary integral equation (SBIE) and the hyper-singular boundary integral equation (HBIE) are applied separately [15, 16]. Image 1 facilitates comprehension. The boundaries at both sides of the idealized bodies are represented by the discretization, with disparate values of acoustic pressure and flux. The application of the classic formulation of the method, based on the SBIE applied at both sides of null-width elements, yields a singular system of equations that does not allow the solution of the problem to be obtained. However, the use of both the SBIE and the HBIE leads to a dual BE formulation that offers a proper solution to address this issue.

Image 1(a) represents an idealization of a generic thin body to be solved by the dual BE formulation. After a discretization process, each node holds the values of pressure and flux with respect to the boundary normal (p^+, q^+, p^-, q^-hereinafter). The strategy used to isolate the singularity of the method in this type of domains can be seen in Image 1(b) [17, 18]. Thus, the BE expression for these boundaries can be written as follows:

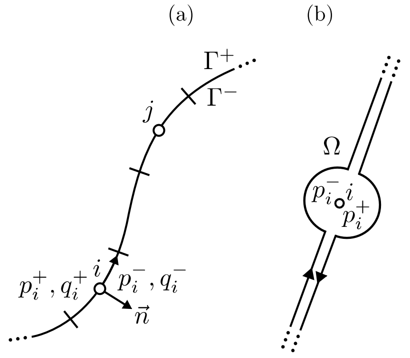

Image 1. (a) Geometric idealization as single-wire configuration of a barrier featuring a very thin section. (b) Strategy used to avoid the singularity around the collocation point in the dual approach for the treatment of elements idealized as null-thickness type

$$0.5(p_i^+ + p_i^-) + \sum_{j=1}^{N}\left(H_j^+ p_j^+ + H_j^- p_j^-\right) = \sum_{j=1}^{N}\left(G_j^+ q_j^+ + G_j^- q_j^-\right) + G_0(k,r) \qquad (1)$$

The hyper-singular expression concerning these types of geometries is then obtained:

$$0.5\left(\frac{\partial p_i^+}{\partial n_i^+} + \frac{\partial p_i^-}{\partial n_i^+}\right) + \sum_{j=1}^{N}\left(M_j^+ p_j^+ + M_j^- p_j^-\right) = \sum_{j=1}^{N}\left(L_j^+ q_j^+ + L_j^- q_j^-\right) + \frac{\partial G_0(k,r)}{\partial n_i} \qquad (2)$$

being N the overall nodes number of the discretization over the boundary, G_0 the fundamental solution concerning the external noise source and H, G the integration cores of the SBIE and M, L the integration cores of the HBIE (involving just the variables of the problem along the barrier boundary in both cases).

By operating conveniently in Eq. (1) and Eq. (2), the following matrix system is obtained for the proper assessment of noise barrier configurations idealized as bodies with null section:

$$\begin{bmatrix} 0.5\mathbf{I}^* + \mathbf{H} + ik\beta\mathbf{G} \\ ik\beta(0.5\mathbf{I}^* + \mathbf{L}) + \mathbf{M} \end{bmatrix} \cdot \{\mathbf{P}\} = \begin{Bmatrix} \mathbf{G_0} \\ \dfrac{\partial \mathbf{G_0}}{\partial n_i} \end{Bmatrix} \qquad (3)$$

Once the variables on the barrier boundary are known, the acoustic pressure values at any internal point (receiver position) can be easily obtained, as usual, by applying the standard BE formulation:

$$p^i = G_0(k,r) - \sum_{j=1}^{N}\left(h_j + ik\beta g_j\right) p_j \qquad (4)$$

Further details concerning dual BEM formulation for very thin bodies can be consulted in [10].

Image 2 represents the general configuration of the study. It deals with a source of sound placed on a ground with a perfectly reflecting surface ($\beta_g = 0$) at $\mathrm{d_s} = 9.5$ m from the feasible region, parallel to an infinite thin cross-section noise barrier. A trapezoidal section holds the area for feasible profiles, defined by the limited barrier projection to the ground, that is $\mathrm{d_p} = 1.0$ m, and the maximum effective height to be achieved, that is

$h_{eff} = 3.0$ m at the median of the rectangle trapezium.

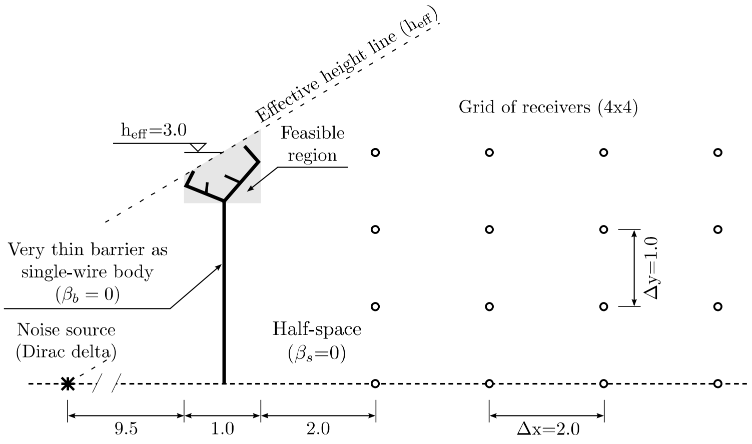

Image 2. Bi-dimensional configuration for the MO optimization of the topological barrier design under study. Dimensions expressed in meters

A grid of 4x4 receivers is considered. The first line of receivers lays on the ground and the remaining ones are placed at different heights, vertically separated by $\Delta y = 1.0$ m. A horizontal distance of $\Delta x = 2.0$ m among them is considered. The nearest receivers to the side limit of the feasible region are $d_r = 2.0$ m away. The proximity of the receivers to the barrier is motivated by the fact that the barrier performance in near regions is more affected by the shape design rather than by the effective height, as occurs in non-near regions.

The determination of the shielding efficiency of a barrier is well defined by means of the insertion loss coefficient (IL) that in the harmonic problem, for every frequency from the analyzed noise source, is defined as usual:

$$IL_i = -20 \cdot \log_{10}\left(\frac{P_B}{P_{HS}}\right) \text{ [dB]} \qquad (5)$$

on every frequency of the band spectrum. As can be seen, this coefficient represents the difference of sound pressure levels at the receiver points in the situation with (P_B) and without (P_{HS}) considering the barrier.

With the purpose of conducting an optimization process where the excitation is represented by a noise source pulsing at every frequency of the band spectrum, the efficiency of the barrier for a specific receiver can be written in terms of the broadband insertion loss (IL_{total}):

$$IL_{total} = -10 \cdot \log_{10}\left(\frac{\sum_{i=1}^{NF} 10^{\left(A_i - \frac{IL_i}{10}\right)}}{\sum_{i=1}^{NF} 10^{\frac{A_i}{10}}}\right) \text{ [dB(A)]} \qquad (6)$$

being NF the studied spectrum number of frequencies (in the analyses conducted here, NF = 14), A_i the spectrum A-weighted noise level and IL_i the insertion loss value for sources pulsing at every frequency of the spectrum, according to Eq. (5).

In all the studies performed in this paper, the noise source is characterized by using the UNE-EN 1793 [19] normalized traffic noise spectrum for third-octave band center frequencies, ranging from 100 to 2,000 Hz, the same used by the Spanish Technical Building Code (CTE) [20].

Following [12, 21], a simple procedure to mathematically represent the geometry of barriers is proposed. The design points of the screen model are defined in a systematic, simple way in a reference domain as a previous step to the barrier profile generation in the real space. In short, the transformed domain holds the set of design variables of the model under study, denoted by (ξ_i, η_i), and represents the rectangular search space for the GA (see left part of Image 3). Every (ξ_i, η_i), point in the transformed domain has its image (x_i, y_i) in the Cartesian space, which is the real domain where the barrier operates.

In this paper $h_{eff} = 3.0$ m is proposed. This value and the maximum barrier projection to the ground dp have been chosen according to the geometric dimensions of the barriers studied herein and present in the bibliography. Both latter parameters define the feasible region by generating a trapezoidal search space in the Cartesian barrier domain (see right part of Image 3). Its final dimensions are dependent, logically, of the placement of the noise source (d_s).

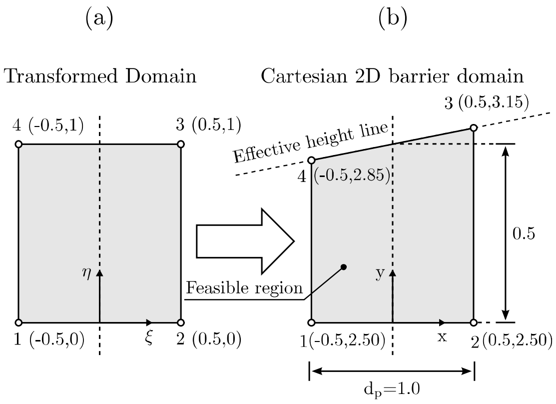

Image 3. Bi-dimensional coordinate systems. Dimensions expressed in meters

Image 4 shows the model under study. It deals with an evolution of the broadly studied Y-shaped design, by adding two branches at each arm of such design. Two of the branches are born from the ending points of the main arms (points 1 and 6) while the remaining ones do it from the middle. The design variables responsible for the inclination of the main arms are constrained to vertical movements (η_1 and η_6) through the left- and right-side limits of the feasible region. The barrier model stands on a vertical, fix bar of 2.5 m height placed on the median of the feasible region.

The geometry feasibility of the model is constrained to both the condition of non-cut-off points among boundaries and the fact that points from 2 to 5 are always in the upper region enclosed by the main arms in the search domain.

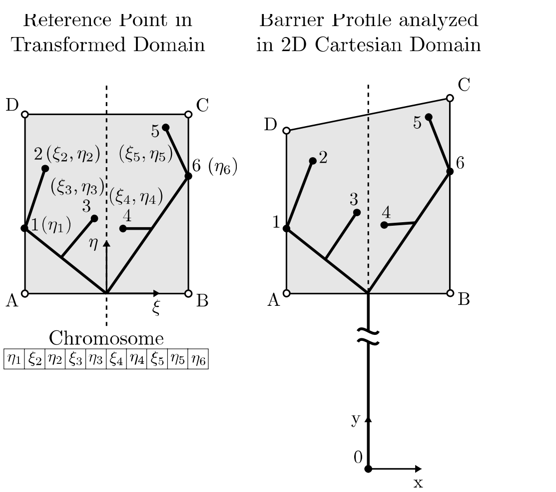

Image 4. Model under study. Y-variant-shaped barrier with six design points

The study here presented deals with a uniform crossover operator applied on a population size of 100 individuals. The considered mutation rate is $1/n_{ch}$, where n_{ch} is the chromosome length ($n_{ch} = 8xn$, with n being the overall number of the design variables -of 8 bits precision each-). Codification of such design variables was carried out with the Standard Reflected Gray Code, as in [22]. The stopping criterion is met after 20,000 objective functions evaluations. One of the aims of the multi-objective optimization presented in this work is the search of barrier designs with ever-increasing screening performance (maximization of the shielding efficiency). This criterion has been the basis of shape optimizations presented so far and can be properly determined, as is well known, by the broadband insertion loss. Its representation in terms of the objective function can be expressed as follows:

$$OF_1 = \frac{\sum_{j=1}^{NR} IL_{total_j}}{NR} \; [dB(A)] \qquad (7)$$

being IL_{total_j} the broad band IL -see Eq. (6)- for each receiver and NR the total number of receivers considered in the study.

Additionally, the minimization of the amount of material used in manufacturing the barrier profile is intended. This second objective can be expressed in terms of the sum of the boundary lengths, as follows:

$$OF_2 = \sum_{k=1}^{NB} L_k = \sum_{k=1}^{NB} \sqrt{\left(x_k^f - x_k^i\right)^2 + \left(y_k^f - y_k^i\right)^2} \; [m] \qquad (8)$$

with L_k being the length of each boundary and NB the overall number of boundaries of the considered barrier.

3. Results and discussions – Following, results concerning multi-objective optimization of such model are shown. Image 5 collects the results after the multi-objective optimization. The upper graph shows the non-dominated front solutions of the MO optimization. Some of these solutions are labeled from 1 to 7 and represented within a grey box by their objective functions: the overall shielding efficiency considering all receiver points (OF_1) and the total length of the barrier (OF_2). The corresponding geometric representation of these solutions is shown at the bottom of such graph.

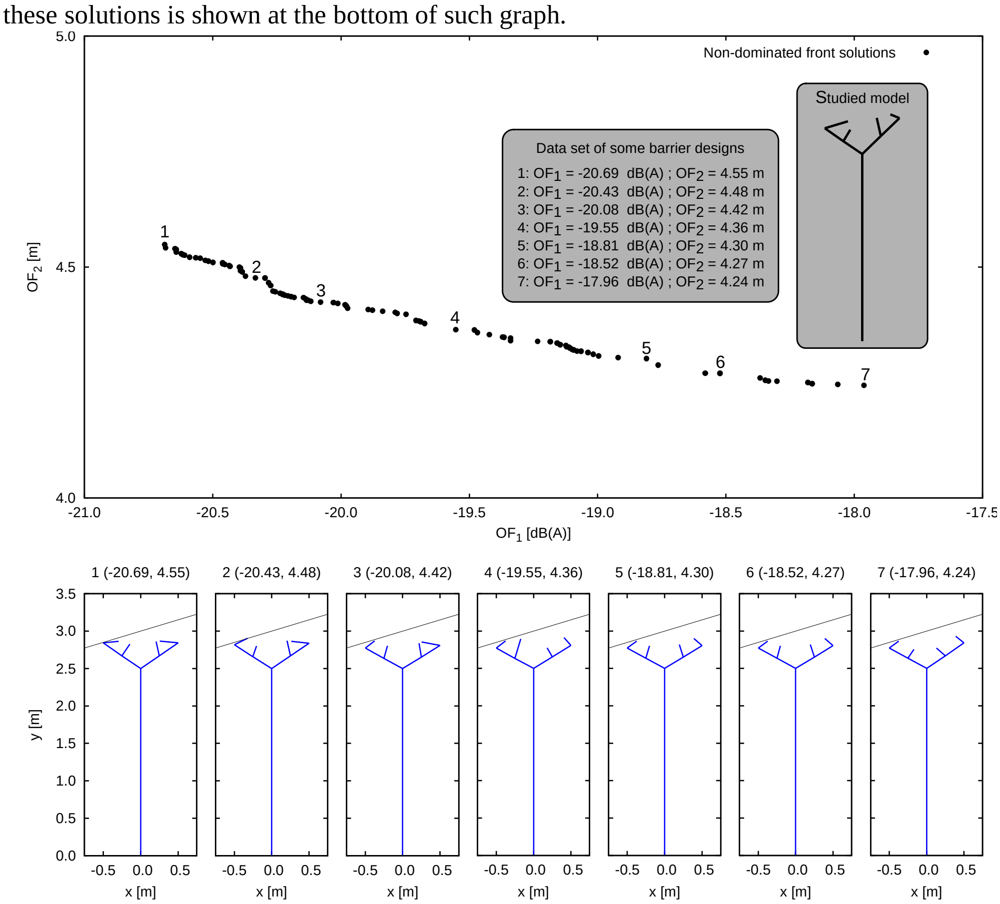

Image 5. Non-dominated solutions of MO optimization for the presented model.

According to the disclosed results, the multi-objective optimization has performed well to find, generally speaking, a wide and uniformly spread-out Pareto-optimal front (non-dominated solutions) for the presented barrier model. This is illustrated by the geometric diversity of noise barriers depicted in Image 5.

4. Conclusions – Results derived of the multi-objective optimization of a very thin noise barrier with perfectly rigid surface were presented. Based on a barrier model introduced and studied in a previous work by the authors under single-objective optimization [10], numerical multi-objective analyses were conducted in the pursuit of both the maximization of the shielding efficiency and the minimization of the overall length of the barrier and, therefore, the manufacturing material needed. An optimal set of designs was obtained along a wide and uniformly spread-out Pareto front.

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