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A PROCEDURE FOR THE TOP GEOMETRY OPTIMIZATION OF THIN ACOUSTIC BARRIERS

R. Toledo*, Juan J. Aznárez, O. Maeso and D. Greiner

Instituto de Sistemas Inteligentes y Aplicaciones Numéricas en Ingeniería (SIANI)
Edificio Central del Parque Científico Tecnológico del Campus Universitario de Tafira
Universidad de Las Palmas de Gran Canaria, 35017, Spain
e-mail*: rayco.toledo102@alu.ulpgc.es - Web page: http://www.mmc.siani.es

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Abstract. This work aims at assessing the acoustic efficiency of different thin noise barrier models. These designs frequently feature complex profiles and their implementation in shape optimization processes may not always be easy in terms of determining their topological feasibility. A methodology to conduct the shape design optimization of thin cross section acoustic barriers by idealizing them as profiles with null boundary thickness is proposed (see Fig. 1). Such simplification of reality greatly facilitates the geometric definition of barrier profiles, having no major influence on the acoustic performance. According to previous work [5], the procedure presented herein is based on the maximization of the *insertion loss* of candidate profiles proposed by an evolutionary algorithm. As application, numerical simulations of the performance of two different top barrier configurations of practical interest (Fig. 1) are conducted by use of a 2D code based on the Boundary Element Method (BEM). The special nature of these sort of barriers makes necessary the implementation of a complementary formulation to the classical boundary element method. The inclusion of an additional BEM formulation (hyper-singular) combined with the classical one (singular) provides a compatible system of equations that allows the problem to be solved [9]. Results obtained show the usefulness, flexibility and versatility of the proposed procedure.

1 INTRODUCTION

The inclusion of sound barriers with the intention of breaking the line of sight between the traffic noise source and the intended protected area is a commonly used, effective strategy. Considerable research work and studies focused on sound diffraction around barriers have been carried out in the past two decades, specifically in the prediction of the performance and the development of more efficient designs. Among all of the different numerical methods available concerning the issue, the Boundary Element Method (BEM hereinafter) is one of the broadly present in the literature and has been extensively applied on the assessment of the acoustic performance of sound barriers by the authors of this work [1]. In particular to the concerning issue here presented, the combined used of BEM and evolutionary algorithms (EA) has been used for shape design optimization in outdoor acoustics problems. Duhamel [2] starts off with a rectangular volumetric structure built of equally-sized bricks to lead to the final optimized shapes with non-inner holes and fillings. Baulac et al. [3] assess the performance of T-shaped barriers with different series of wells covered with a reactive surface on the top. Greiner et al. [4, 5] conduct the study of a single- and a multi-objective design optimization of a Y-shaped noise barrier; the consideration of uncertainties in the optimum design has also been handled in [6]. Grubeša et al. [7] carry out a 3D optimization of both acoustic performance and economical feasibility of a noise barrier built from different modules with varying cross-sections. A more recent research, also covers the inclusion of an *innovization* procedure for multi-objective noise barrier optimum design in Deb et al. [8].

In this line, a procedure for the shape design optimization of noise barriers by coupling BEM with an EA is conducted in this work. Two-dimensional sound propagation problems concerning an infinite, coherent mono-frequency source of sound, placed parallel to an infinite noise barrier that stands on a flat plane (ground) of uniform admittance are studied. The sound propagation analysis is performed in the frequency domain. Expression of the fitness function to be maximized throughout the shape optimization process is written in terms of this response.

The proposed Dual BEM formulation is applied on the study of noise barriers featured with very thin boundaries, idealized as null boundary thickness-like models. This simplification of reality greatly facilitates the geometric definition of barrier profiles, having no major influence on the acoustic performance [9]. The special nature of these type of barriers makes every node of the discretization hold both the pressure and the flux value at each side of it, i.e., $2n$ unknowns per n nodes. The inclusion of an additional BEM formulation (hyper-singular) combined with the classical one (singular) provides a compatible system of equations that allows the problem to be solved. The coupling of an EA with the Dual BEM code allows to obtain interesting acoustic solutions avoiding the complexity associated with the geometric generation of volumetric structures. Fig. 1 shows the usefulness of representing complex volumetric structures as null boundary thickness-like models.

2 Problem definition

Fig. 2 represents the general configuration of the model under study. It deals with a two-dimensional model concerning an infinite, coherent mono-frequency source of sound, parallel to an infinite thin cross-section noise barrier placed on a ground with uniform admittance. Both the ground and the barrier boundary feature a perfectly reflecting surface ($\beta_g = \beta_b = 0$). A trapezoidal section holds the area for feasible profiles, defined by

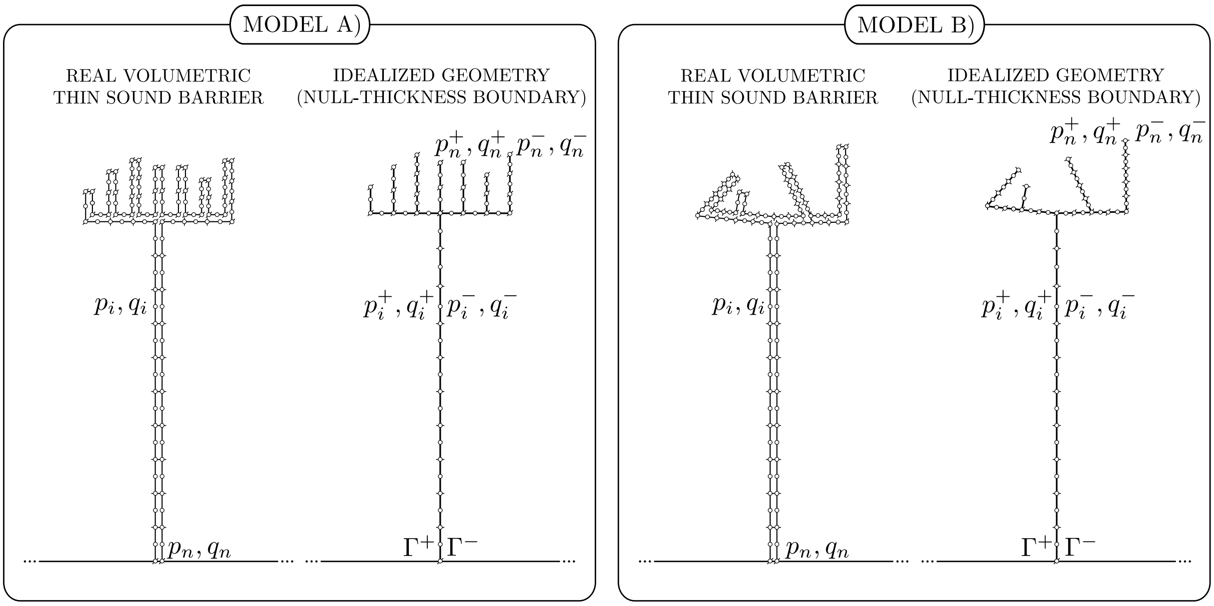

Figure 1: Convenience of representing real volumetric structures as idealized geometries featuring null-thickness boundaries. Left, example of model A) boundary discretization. Right, example of model B) boundary discretization.

the limited barrier projection to the ground, that is $\mathrm{d_p} = 1.0\,\mathrm{m}$, and the maximum effective height to be achieved, that is $\mathrm{h_{eff}} = 3.0\,\mathrm{m}$ at the median of the rectangle trapezium.

Just one receiver in the shadow region is considered. Both the noise source and the receiver are located at $\mathrm{h_s} = \mathrm{h_r} = 1.5\,\mathrm{m}$ over the ground and are $\mathrm{d_s} = \mathrm{d_r} = 2.5\,\mathrm{m}$ away from the horizontal projection of the barrier, respectively.

In the harmonious problem, for every frequency from the analyzed noise source, the efficiency of the barrier design under study is given in terms of the *insertion loss* (IL), defined as usual:

$$\mathrm{IL} = -20 \cdot \log_{10}\left(\frac{\mathrm{P_B}}{\mathrm{P_{HS}}}\right)[\mathrm{dB}] \tag{1}$$

on every frequency of the band spectrum, and represents the difference of sound pressure levels at the receiver point in the situation with ($\mathrm{P_B}$) and without ($\mathrm{P_{HS}}$) 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 can be written as:

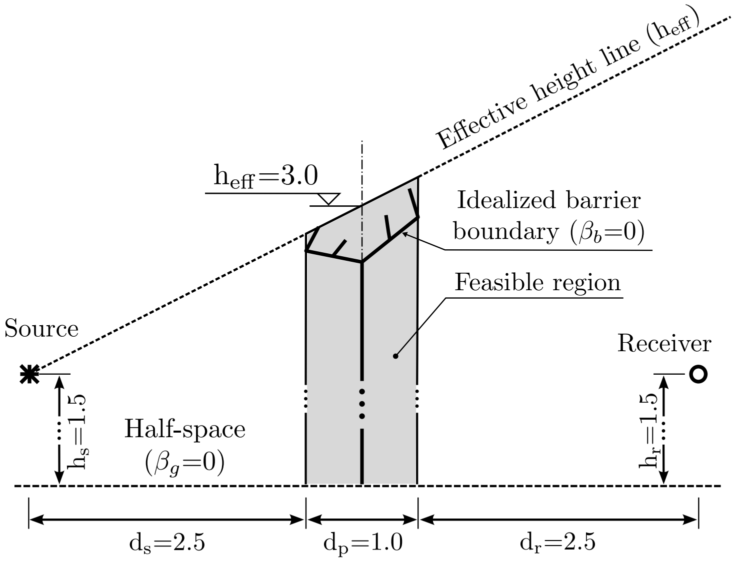

Figure 2: Bi-dimensional configuration to be used in the optimization process of thin noise barriers. Distances and dimensions expressed in [m].

$$\overline{\mathrm{IL}} = -10 \cdot \log_{10} \left(\frac{\sum_{\mathrm{i}=1}^{\mathrm{NF}} 10^{(\mathrm{A_i} - \mathrm{IL_i})/10}}{\sum_{\mathrm{i}=1}^{\mathrm{NF}} 10^{\mathrm{A_i}/10}} \right) \text{[dBA]} \tag{2}$$

being NF the studied spectrum number of frequencies, here NF = 18, $\mathrm{A_i}$ the A-weighted sound pressure level and $\mathrm{IL_i}$ the insertion loss value for sources pulsing at every frequency of the spectrum, according to (1). In this work, the noise source has been characterized by using the ISO 717.2 [10] normalized traffic noise spectrum for third-octave band center frequencies, ranging from 100 to 5 000 Hz.

Concerning the estimator taken into account along the shape optimization process, it is worth noting that it is based on the overall IL mean value for the considered receiver point:

$$\mathrm{FF} = \max\left(\overline{\mathrm{IL}}\right) \tag{3}$$

This value corresponds to the so called *fitness function* (FF) to be maximized, according to the proper terminology used in the field of evolutionary algorithms.

3 Shape optimization

Shape design optimization is carried out by the combined use of an evolutionary algorithm and a code that implements a Dual BEM formulation.A further description of the methodology here presented concerning the acoustic performance of thin barriers can be consulted in [9, 11]. The evolutionary algorithm software used in this work applies the GAlib package [12]. This library is a collection of C++ genetic algorithm (GA) components from which it is possible to quickly construct GA's to attack a wide variety of problems.

In this paper, for a good equilibrium between exploration and exploitation a steady-state genetic algorithm is used replacing the two worst individuals (in terms of their fitness function) at each generation, with a population size of 100 individuals. A single-point crossover operator is used in this study, with a crossover rate of 0.9. The considered mutation rate is $1/\mathrm{n_{ch}}$, where $\mathrm{n_{ch}}$ is the chromosome length ($\mathrm{n_{ch}} = 8\mathrm{xn}$, being n the overall number of the design variables -of 8 bits precision each-). Five independent runs of the optimization process are considered for each model. The stopping criterion condition is met for 20 000 evaluations of the fitness function.

Following [4, 5], 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 $(\xi_i,\ \eta_i)$, and represents the rectangular search space for the GA (see left part of Fig. 3). Every $(\xi_i,\ \eta_i)$ point in the transformed domain has its image $(\mathrm{x_i},\ \mathrm{y_i})$ in the Cartesian space, that is the real domain where the barrier operates.

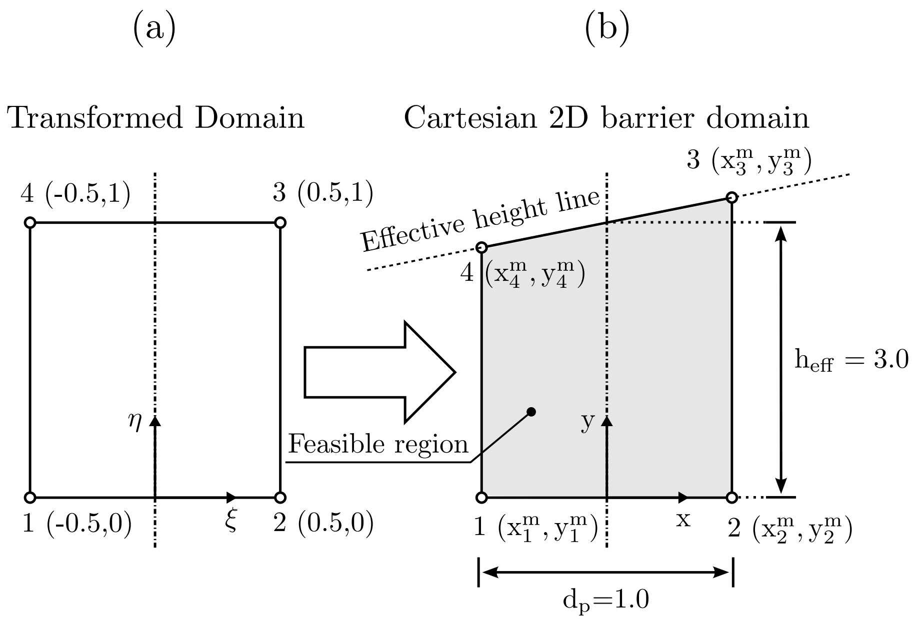

Figure 3: Bi-dimensional coordinate systems. Dimensions expressed in [m].

The transformation of Fig. 3 can be expressed as follows:

$$\begin{Bmatrix} \mathrm{x_i} \\ \mathrm{y_i} \end{Bmatrix} = \gamma_1 \begin{Bmatrix} \mathrm{x_1^m} \\ \mathrm{y_1^m} \end{Bmatrix} + \gamma_2 \begin{Bmatrix} \mathrm{x_2^m} \\ \mathrm{y_2^m} \end{Bmatrix} + \gamma_3 \begin{Bmatrix} \mathrm{x_3^m} \\ \mathrm{y_3^m} \end{Bmatrix} + \gamma_4 \begin{Bmatrix} \mathrm{x_4^m} \\ \mathrm{y_4^m} \end{Bmatrix} \tag{4}$$

where:

$$\gamma_1 = \left(\frac{1}{2} - \xi\right)\left(1 - \eta\right) \; ; \; \gamma_2 = \left(\frac{1}{2} + \xi\right)\left(1 - \eta\right) \; ; \; \gamma_3 = \eta\left(\frac{1}{2} + \xi\right) \; ; \; \gamma_4 = \eta\left(\frac{1}{2} - \xi\right) \tag{5}$$

$$\begin{aligned} &\mathrm{x_1^m} = \mathrm{x_4^m} = -\frac{\mathrm{d_p}}{2} \; ; \; \mathrm{x_2^m} = \mathrm{x_3^m} = \frac{\mathrm{d_p}}{2} \; ; \; \mathrm{y_1^m} = \mathrm{y_2^m} = \frac{5}{6}\,\mathrm{h_{eff}} \\ &\mathrm{y_3^m} = \left(\frac{\mathrm{d_s}}{\mathrm{d_s} + (\mathrm{d_p}/2)}\right)(\mathrm{h_{eff}} - \mathrm{h_s}) + \mathrm{h_s} \; ; \; \mathrm{y_4^m} = \left(\frac{\mathrm{d_s} + \mathrm{d_p}}{\mathrm{d_s} + (\mathrm{d_p}/2)}\right)(\mathrm{h_{eff}} - \mathrm{h_s}) + \mathrm{h_s} \end{aligned} \tag{6}$$

In this paper $\mathrm{h_{eff}} = 3.0\,\mathrm{m}$ is proposed. This value and the maximum barrier projection to the ground $\mathrm{d_p}$ 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 Fig. 3). Its final dimensions are dependent, logically, on the placement of the noise source ($\mathrm{d_s}$).

4 Application of the proposed methodology to the assessment of the acoustic efficiency of different barrier designs

The proposed methodology previously described is applied on the study of two different barrier models by conducting a top edge design optimization. Fig. 4 shows a diagram summarizing the optimization process. Such models are based on a set of points defined by design variables in a transformed domain proposed by the EA, according to the geometric model definition. The point that lays on the ground (0) is located at the median of the feasible region and the top geometry is over a fixed, vertical 2.5 m height bar for both models. Model A) represents a barrier with seven vertical branches that are born from a horizontal tray. The distance among branches remains constant ($\mathrm{d_p}/6$) while their lengths vary throughout the optimization process. Model B) can be understood as an evolution of the broadly used 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 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.

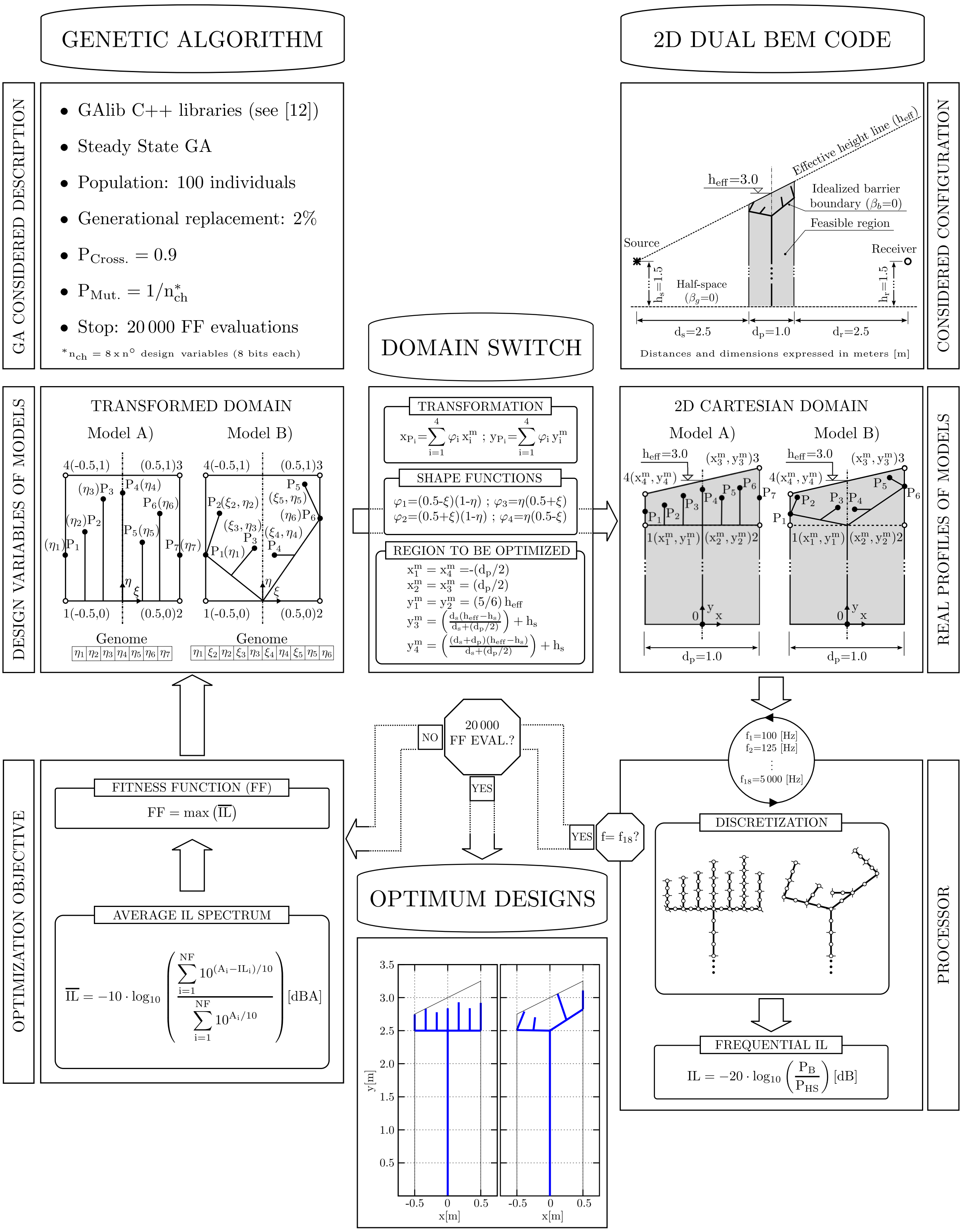

Figure 4: Genetic algorithm features, description of the problem configuration under study and diagram of the optimization process.

5 Results and discussion

Results are shown for the best individual found along the five runs concerning the optimization processes for each model. The left part of Fig. 5 illustrates the optimum designs. The fitness function value (FF) is on the upper side of its corresponding barrier profile. The rightmost graph shows the evolution of the IL for the considered frequential spectrum for both models and for a 3 m height simple barrier. With the purpose of facilitating the analysis of the most successfully acoustic strategies, Fig. 6 shows with colormaps the average IL spectrum for both the region under study and the top edge geometry of the models. Intuitively, warm colours represent regions with higher sound pressure levels. In contrast, cold colours represent regions where the sound abatement is higher as a consequence of the presence of the barrier.

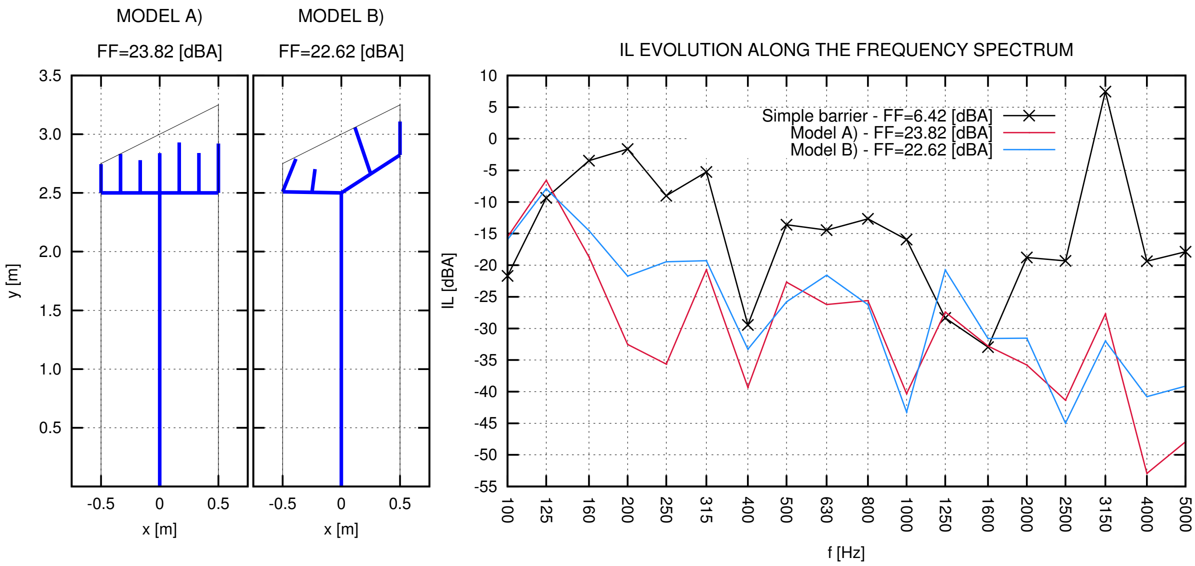

Figure 5: Optimum designs and IL evolution along the frequency spectrum.

- In line with other authors ([13], [14], [15], [16], [17]), acting on the top of the barrier is found to be an appropriate strategy to minimize the acoustic impact. This is illustrated by the fact that the highest levels of acoustic energy get trapped among the top boundaries of the models studied in this work (see right maps of Fig. 6).
- The proposed barrier designs appear to be a valuable, successful alternative to the simple sound screen by clearly outperforming its acoustic efficiency (over 15 dBA) for the maximum effective height to be permitted ($h_{eff} = 3.0\,m$) and the considered source-receiver configuration.

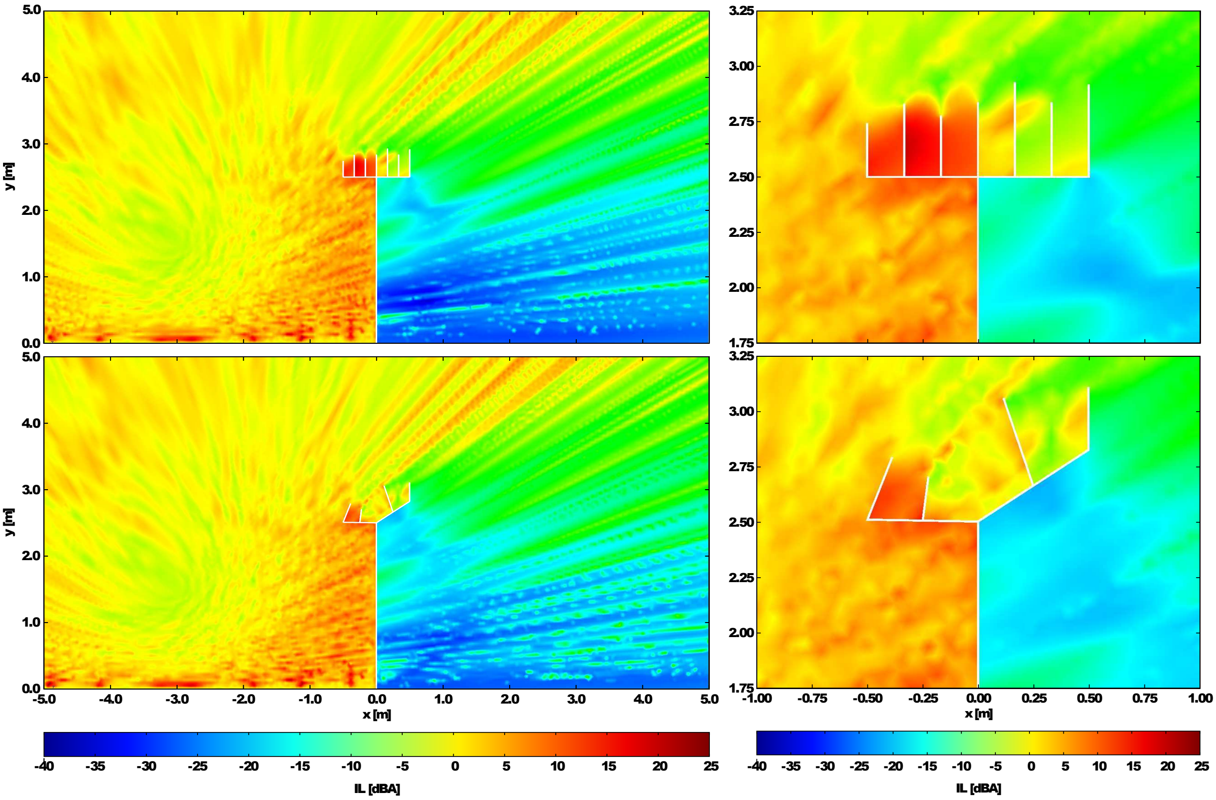

Figure 6: IL colormaps of the models under study. Noise source at (-3.0, 1.5).

6 Conclusions

A methodology to successfully optimize thin noise barriers by idealizing their profiles as null cross-section boundaries has been presented. This procedure has been applied to two specific noise barrier models although its applicability covers a wide designs spectra, ranging from complex straight boundary configurations to curve-shaped profiles [18].

The versatility of the algorithm responsible for the geometry generation of the barrier makes the building of the profile to be easily accomplished. This is a significant advantage over the case when dealing with geometries of real barrier profiles, as the evaluation process for the feasibility of the design proposed by the EA is often complex and difficult to establish.

The presented procedure is a useful method to assess the acoustic behaviour of thin complex noise barriers configurations and yields conclusions that might have been hardly drawn without its implementation.

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