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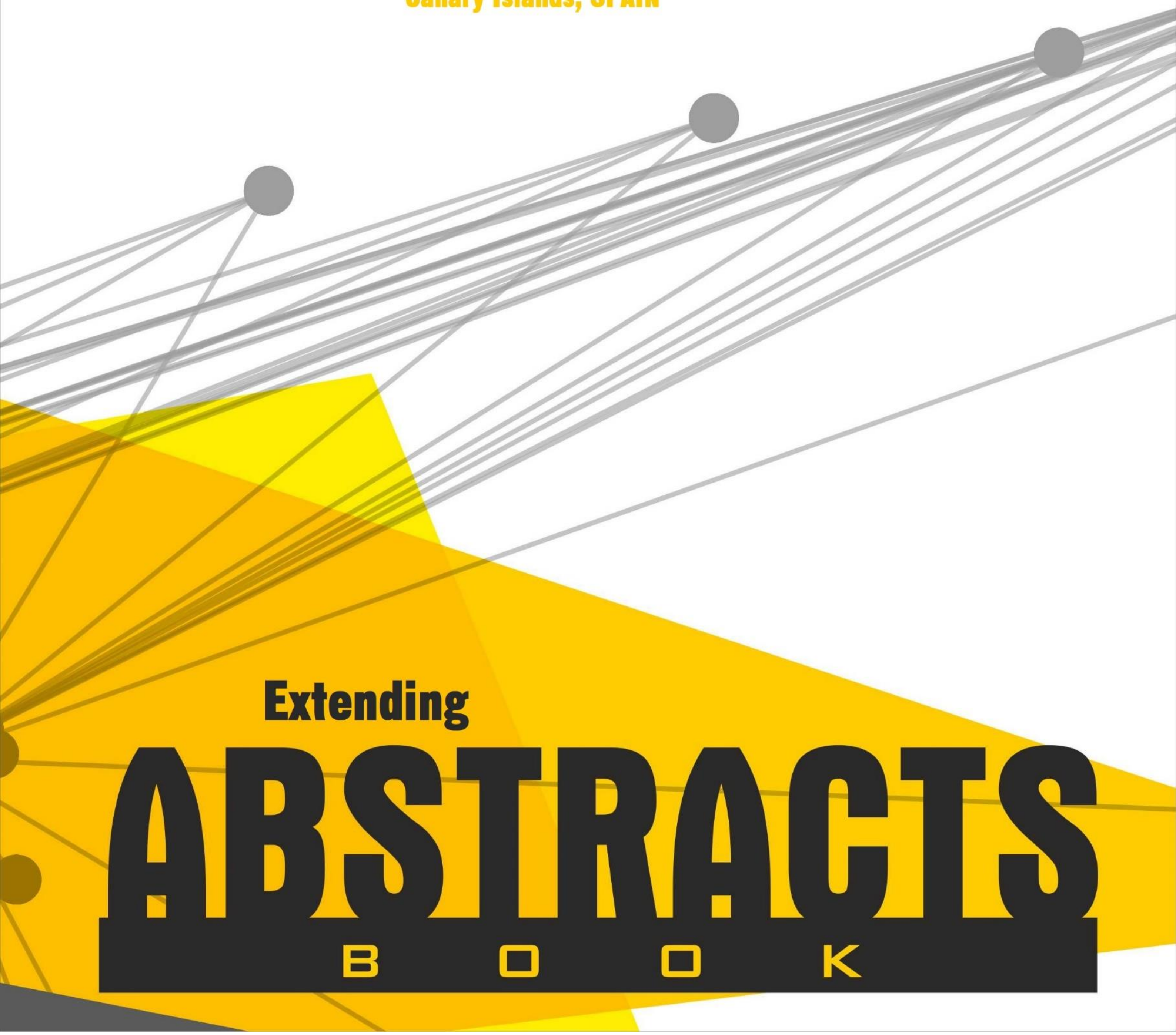

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BOOK

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Application of boundary elements in the optimization of noise barriers

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1. Introduction - The Boundary Element Method (BEM) arises as the most suitable technique in the study of outdoor sound propagation prediction [1-3]. However, the exclusive implementation of the Method in its classical formulation makes the study of certain barrier configurations unaffordable in many cases. On one hand, fictitious frequencies (representing the natural frequencies of the barrier) may be revealed when dealing with non-thin configurations. On the other hand, the complexity normally associated with some barrier designs raises the need to consider some geometric simplification to ease their assessment. A proper solution to tackle these challenges demands a specific BE formulation. In this respect, the so-called Dual BEM approach (a BE formulation that combines the standard singular integral equality of the Method with a hyper-singular variant -obtained by derivation of the former-) arises as the most appropriate strategy involving BE to address the proposed problems numerically by allowing us 1) to assume a simplification of reality by idealizing very thin elements as null-thickness type, greatly facilitating the geometric definition of complex configurations with no substantial influence on the acoustic performance for the considered thickness of very thin sections [4] (widely present in diverse barrier designs) and 2) to mitigate the fictitious eigenfrequencies associated with the inner domain of the barrier that may adversely affect to the assessment of the screening efficiency. In dealing with these issues with BE often results, according to the individual case, in serious numerical drawbacks if not to a singular system of equations when dealing with the idealization of very thin elements.

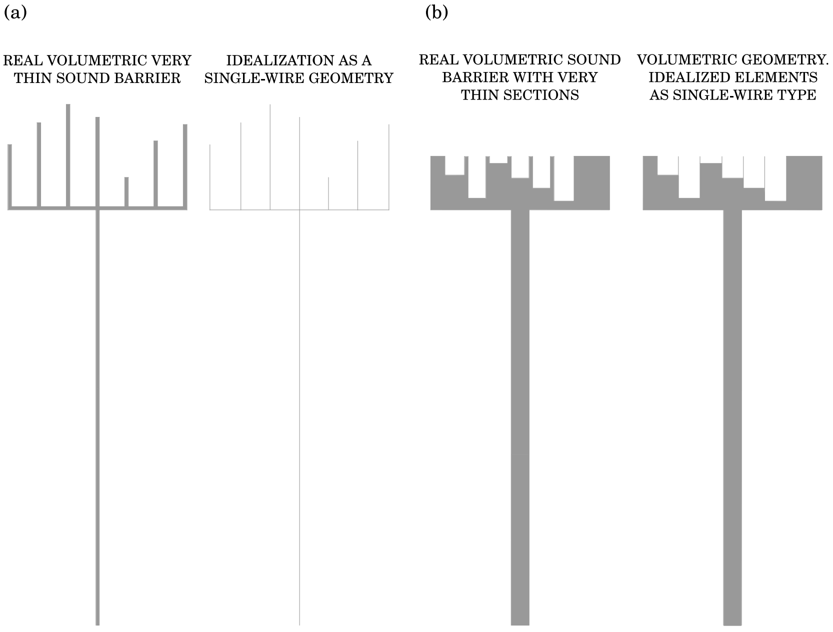

Image 4. Examples of complex designs eligible for geometric idealizations. (a) Fork-shaped barrier. The very thin cross-section along the overall configuration suggests its modeling as a single-wire geometry. (b) Quadratic Residue Diffuser (QRD)- based barrier with very thin elements idealized as null thickness bodies.

Depending on the geometric nature of the barrier, the Dual approach is applied differently to enable us to deal with: i) volumetric barrier designs. It is the case of real barriers featuring thick elements, such as M-shaped barriers; ii) very thin barriers. The assessment of these types of barriers is performed by idealizing the whole design as a single-wire body –see Image 1(a)–; iii) volumetric barriers featuring very thin elements. It is a mixed case. The general configuration remains its real geometry while the very thin elements are idealized and studied as null-thickness type –see Image 1(b)–.

This contribution intends to be an overview of the achievements made so far by the authors of this work in this research line, framed into a methodology involving the coupled use of Boundary Elements (BE) and Evolutionary Algorithms for the systematic geometric modifications of road barriers in pursuing ever-increasing performance.

2. Methodology – The need of the implementation of the Dual BEM formulation in this work is clarified in Image 2. As stated above, the strategy of the application of both formulations (the standard approach and its variant hyper-singular) varies depending of the nature of the element under consideration. This way, with the purpose of mitigating the effects of the fictitious eigenfrequencies when dealing with non-thin bodies, a Dual approach based on the combined use of the standard boundary integral equation (SBIE) and the hyper-singular boundary integral equation (HBIE) coupled by means of a frequency-related complex value is proposed [5]. The nature of the issue is different when dealing with very thin bodies. In this case, numerical integration problems may appear affecting to the barrier performance. As shown in Image 2(b), the boundaries at both sides of elements with null sections (featuring different values of sound pressure and flux) are represented by the discretization itself. The application of the SBIE on both sides of nodes yields a singular system of equations that does not allow the solution to be obtained. However, the joint implementation of the SBIE and its derivative on the collocation node (HBIE) provides a compatible system of equation that allows us to know the solution at both sides of the barrier. With this aim, the SBIE and the HBIE are then applied separately. As a result, this formulation enables the idealization of very thin elements as single-wire bodies. Such a simplification of reality is a real asset, especially when compared with the case of the faithful, detailed definition of real complex volumetric barriers.

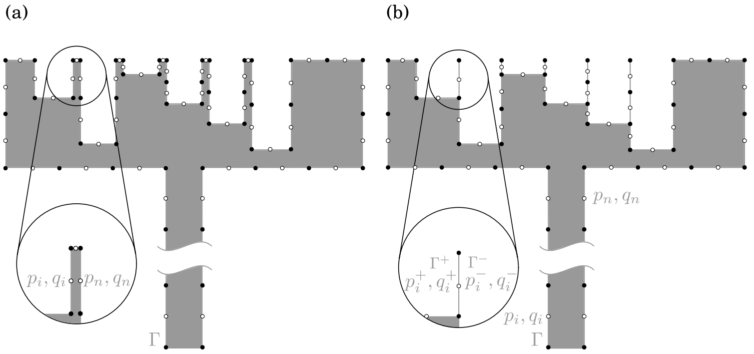

Image 5. Example of the discretization with parabolic elements (3 nodes) for f=500 Hz of a QRD-based design. (a) Discretization of the real geometry. (b) Discretization after idealization of very thin bodies as null-width elements.

The next lines are focused on the description of the implemented Dual BEM formulation to make possible the numerical treatment of barriers featuring thick and/or very thin bodies that can be idealized as boundaries with null thickness. Further details concerning both the SBIE and the HBIE formulation are provided in [6].

Dual BEM for avoiding fictitious eigenfrequencies.

Some undesirable problems may arise at certain frequencies when dealing with volumetric elements in exterior problems. These mathematically related effects reveal the eigenfrequencies of the interior acoustic problem (the eigenvalues of the classical BEM matrices) and may seriously distort the screening performance of the barrier. An appropriate solution to this problem is that derived from the formulation proposed by Burton and Miller [5] for the exterior problem featuring a fictitious resonances-free solution. This formulation is based on the combined use of both the SBIE and the HBIE coupled by a frequency-related complex value (α). In this case, the expression for the boundary point i to be solved by BEM can be written then:

$$0.5(p_i + \alpha q_i) + \sum_{j=1}^{N} \left(h_j + \alpha\, m_j\right) = \sum_{j=1}^{N} \left(g_j + \alpha\, l_j\right) + \left(G_o + \alpha\, \frac{\partial G_o}{\partial n_i}\right) \qquad (1)$$

being p the acoustic pressure field over the barrier surface, q the flux (the derivative of the pressure with respect to the normal at each boundary node) and G_o and $\alpha\, \frac{\partial G_o}{\partial n_i}$ the half-space fundamental solution and its derivative concerning the external noise source, respectively. Finally, h and g are the integration cores of the BEM formulation and l and m the integration cores of the hyper-singular one, involving just the variables of the problem along the barrier boundary with N nodes after the discretization process. The most commonly used value for the coupling parameter is found to be $\alpha = i/k$ [7, 8], being i the imaginary unit and k the wave number. The hyper-singular formulation of the method demands the collocation point j to be inside the element. This way, the free term is assumed as 0.5 in all cases.

The absorptive capacity of the barrier boundary is usually determined by means of the Robin boundary condition, so the pressure value and its derivative at each node are related:

$$q_j = -ik\beta_\Gamma p_j \qquad (2)$$

This way, Eq. (1) can be written in matrix form as:

$$[0.5(1+\beta)\mathbf{I} + \mathbf{H} + (i/k)\mathbf{M} + (ik\mathbf{G} - \mathbf{L})\beta] \cdot \mathbf{P} = \mathbf{G_o} + (i/k)\,\frac{\partial \mathbf{G_o}}{\partial n_i} \qquad (3)$$

with **I** being the identity matrix.

Dual BEM for very thin bodies.

When dealing with very thin bodies numerical integration problems, involving quasi-singular points, may appear affecting 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 SBIE and the HBIE are applied separately [4, 9]. Image 3 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.

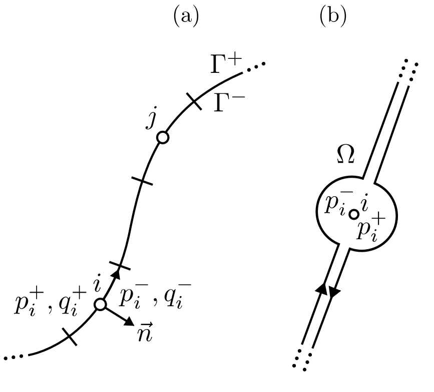

Image 3. (a) Geometric idealization as single-wire configuration of a barrier featuring a very thin section. (b) Strategy used to avoid the singularity around the collocation point in the dual approach for the treatment of elements idealized as null-thickness type.

Image 3(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 3(b) [10, 11]. Thus, the BE expression for these boundaries can be written as follows:

$$0.5(p_i^+ + p_i^-) + \sum_{j=1}^{N}\left(H_j^+ p_j^+ + H_j^- p_j^-\right) = \sum_{j=1}^{N}\left(G_j^+ q_j^+ + G_j^- q_j^-\right) + G_0(k,r) \qquad (4)$$

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

$$0.5\left(\frac{\partial p_i^+}{\partial n_i^+} + \frac{\partial p_i^-}{\partial n_i^+}\right) + \sum_{j=1}^{N}\left(M_j^+ p_j^+ + M_j^- p_j^-\right) = \sum_{j=1}^{N}\left(L_j^+ q_j^+ + L_j^- q_j^-\right) + \frac{\partial G_0(k,r)}{\partial n_i} \qquad (5)$$

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. (4) and Eq. (5), the following matrix system is obtained for the proper assessment of noise barrier configurations idealized as bodies with null section:

$$\begin{bmatrix} 0.5\mathbf{I}^* + \mathbf{H} + ik\beta\mathbf{G} \\ ik\beta(0.5\mathbf{I}^* + \mathbf{L}) + \mathbf{M} \end{bmatrix} \cdot \{\mathbf{P}\} = \begin{Bmatrix} \mathbf{G_0} \\ \dfrac{\partial \mathbf{G_0}}{\partial n_i} \end{Bmatrix} \qquad (6)$$

Dual BEM for volumetric configurations featuring very thin bodies idealized as null sections.

This general Dual BEM approach incorporates both versions of the Dual formulation, permitting us to assess the shielding efficiency of road barriers based on volumetric structures featuring very thin elements. According to some of the expressions obtained above and denoting:

$$\mathbf{A_1} = 0.5\,(1+\beta)\mathbf{I} + \mathbf{H} + (i/k)\mathbf{M} + (ik\mathbf{G} - \mathbf{L})\beta \qquad (7)$$

$$\mathbf{A_2} = 0.5\mathbf{I}^* + \mathbf{H} + ik\beta\mathbf{G} \quad ; \quad \mathbf{A_3} = ik\beta(0.5\mathbf{I}^* + \mathbf{L}) + \mathbf{M} \qquad (8)$$

$$\mathbf{B_1} = \mathbf{G_0} + (i/k)\frac{\partial \mathbf{G_0}}{\partial n_i} \quad ; \quad \mathbf{B_2} = \mathbf{G_0} \quad ; \quad \mathbf{B_3} = \frac{\partial \mathbf{G_0}}{\partial n_i} \qquad (9)$$

The final Dual BEM matrix expression for barriers with thin and non-thin bodies may be written as follows:

$$\begin{bmatrix} \mathbf{A_1} \\ \mathbf{A_2} \\ \mathbf{A_3} \end{bmatrix} \cdot \{\mathbf{P}\} = \begin{Bmatrix} \mathbf{B_1} \\ \mathbf{B_2} \\ \mathbf{B_3} \end{Bmatrix} \qquad (10)$$

In Eq. (10), $\mathbf{A_1}$ is a $N_{Thick}xN_{Unk}$ matrix and $\mathbf{A_2}$, $\mathbf{A_3}$ are $N_{Thick}xN_{Unk}$ ones. In this case, N_{Thick} and N_{Thin} represent the number of nodes involving the discretization of elements with real sections and those idealized as null-thickness type, respectively, while N_{Unk} is the unknowns of the problem ($N_{Thick} + 2xN_{Unk}$). In accordance with this nomenclature, $\mathbf{P}$ is a N_{Unk}–dimension array that stores the pressure values according to the barrier discretization, $\mathbf{B_1}$ is a N_{Thick}–dimension array and $\mathbf{B_2}$**,** $\mathbf{B_3}$ are N_{Thin}–dimension ones.

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:

$$p^i = G_0(k,r) - \sum_{j=1}^{N_{Unk}} (h_j + ik\beta g_j)\, p_j \qquad (11)$$

3. Results and discussions – This section collects the validation cases conducted of the Dual BEM approaches introduced above. Analyses are presented in terms of the acoustic behaviour of road barriers when assessed both with the reference standard BE formulation and with the corresponding Dual approach.

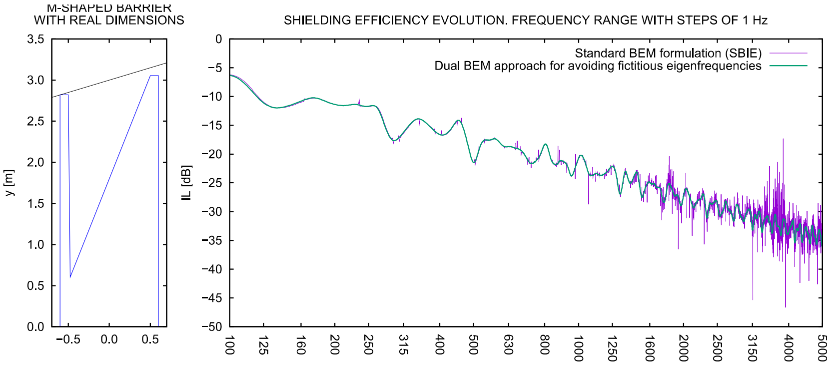

Image 4. Validation of the Dual BEM approach in a volumetric M-shaped barrier. Noise source and receiver are located at (-10.0, 0.0) and at (50.0, 0.0), respectively

The need of implementing the Dual formulation when dealing with volumetric structures is clarified in Image 4. As easily observable, the Dual approach provides an efficient, adequate solution to avoid the resonance frequencies associated with the inner structure of the barrier. In spite of the problems studied here are outdoor-type, these fictitious frequencies are revealed when applying the standard formulation of the Method, greatly distorting the shielding efficiency (high peak values of IL in the graphic) of the barrier at such frequencies. The importance of the issue is undisputed, especially within an optimization process where the best individuals may be selected according to this unrealistic screening performance.

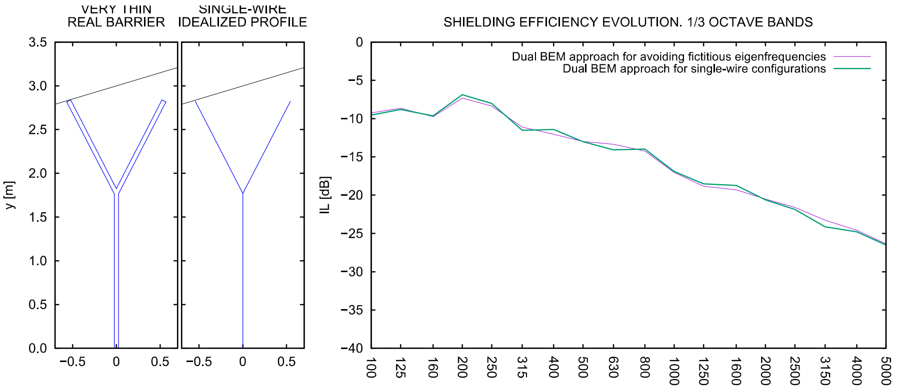

Image 5. Validation of the formulation in a benchmark very thin Y-shaped barrier. Noise source and receiver are located at (-10.0, 0.0) and at (50.0, 0.0).

The convenience of representing very thin road barriers as single-wire bodies is highlighted in Image 5. In this case, the Dual BEM approach greatly eases the geometry generation of the barrier profile when compared with the real representation. This effect is more noticeable as the topological complexity of the barrier increases. Besides, and no less important, the idealization of very thin sections as null-thickness type helps mitigate numerical integration problems that may appear when dealing with quasi-singular points. As observed in the graphic, this latter issue, however, is not of concern for this particular case.

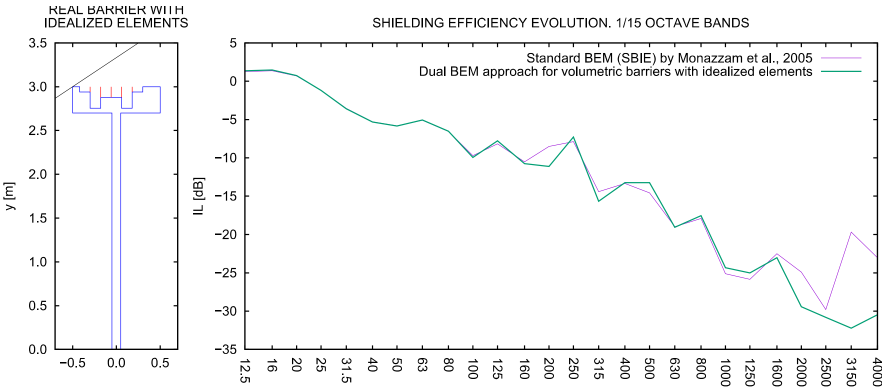

Image 6. Validation of the presented Dual BEM formulation for volumentric barriers with very thin elements. Comparative results with those by Monazzam et al. [12]. Noise source and receiver are located at (-5.0, 0.0) and (50.0, 0.0), respectively.

Finally, Image 6 represents the acoustic performance evolution derived from the analysis of a road barrier previously studied in the literature by Monazzam et al. [12] (the QRD (Quadratic Residue Diffuser) top). In accordance with the results presented in such work, the validation is performed on the basis of 1/15 octave band center frequencies. The Dual BEM approach proposed is truly convenient when dealing with complex configurations eligible for some sort of geometric simplification, as in the presented case. For the ease of viewing, the general volumetric structure of the QRD-based barrier is represented in blue, while very thin sections are idealized as single-wire bodies and depicted in red. As observed in the graph, despite the differences observed at some frequencies, results derived from the Dual approach agree well with numerical outcomes from the aforementioned work with the standard BEM formulation.

4. Conclusions – The main issue of this work is the Dual BEM formulation for the analysis of any type of 2D acoustic problem. Firstly, the bases of the Dual formulation in its different variants were introduced. In this sense, a detailed description of the approach for 1) avoiding the fictitious eigenfrequencies that may appear when dealing with barriers featuring real dimensions, 2) the idealization of very thin elements as single-wire bodies and 3) dealing with volumetric barriers featuring elements with small sections that can be idealized as null-thickness type was provided. Validation examples for the aforementioned approaches were presented, showing the advantages of the Dual approach versus the exclusive implementation of the standard formulation of the Method for the analysis of noise barriers of diverse nature.

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