INSERTION LOSS PROVIDED BY A PERIODIC STRUCTURE – NUMERICAL AND EXPERIMENTAL EVALUATION

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ABSTRACT

Periodic structures as elements for the attenuation of noise propagation have been an active topic of research over the last decade. Although some studies have been published on the subject, there is still much research to be undertaken before these structures can be a viable and competitive alternative to conventional noise barriers. The present work aims to contribute to the study of sonic crystals through a joint experimental and numerical approach. Here, a comparison between numerical and experimental results is presented, for different scenarios, with the aim of validating a numerical model based on the method of fundamental solutions, devised for the analysis of these structures.

RESUMO

As estruturas periódicas enquanto elementos atenuadores da propagação do ruído têm vindo a ser investigadas ao longo da última década. Embora alguns trabalhos tenham sido publicados sobre o assunto, há ainda muita investigação a realizar antes de estas estruturas poderem constituir uma solução viável e competitiva. No presente trabalho procura-se contribuir para o aprofundamento do estudo dos cristais sónicos através de uma abordagem mista experimental e numérica. Apresenta-se, assim, o resultado de um conjunto de testes realizados no sentido de validar a utilização de um modelo numérico baseado no Método das Soluções Fundamentais para a análise destas estruturas.

1. INTRODUCTION

Sonic crystals get their name by analogy with ordered structures of semiconductor materials such as silicon crystals whose feature of allowing certain energy waves to pass through and block others is transposed, in sonic crystals, in the capacity to prevent or limit the propagation of certain sound frequencies. The shape of these structures corresponds to a "grid" or “lattice” consisting of a base element, which is repeated regularly in one, two or three dimensions.

It is generally considered that the first evidence that it was possible to achieve some effect of acoustic obstruction using structures in periodic arrays was derived fortuitously from a sculptural element, in the gardens of the Fundación Juan March in Madrid, consisting of a number of vertical metal tubes, arranged in a rectangular grid. A series of measurements, conducted in 1995, by placing a set of microphones along this sculpture revealed clear effects in attenuating certain frequency bands of sounds, which were a function of the direction of incident sound waves (Martinez-Sala et al. [1]).

Since then different aspects of the behavior of sonic crystals have been studied, some of which are essentially theoretical, while others focus some potential practical applications. In the first group aspects such as the influence of so called point defects (Wu et al. [2]) or the existence of waveguides in which the sound propagates with low attenuation (Vasseur et al. [3]) can be mentioned. In the field of the practical uses of sonic crystals, one which may be regarded perhaps as the most promising is precisely their use for the selective attenuation of sounds, for example as traffic noise barriers (Sánchez-Pérez et al. [4]). A very recent work on this topic (Castiñeira-Ibáñez et al. [5]) has addressed the classification of sonic crystal barriers in terms of the relevant European standards for the determination of the intrinsic characteristics of acoustic barriers.

Although a significant number of works has been published, the subject of sonic crystals is still under development, and there are several issues that need further studying. The present work extends previous work by the authors on the subject (see Martins et al [6]) concerning the numerical modeling of these structures, proposing a general numerical strategy based on the Method of Fundamental Solutions (MFS) to model a 2D sonic crystal noise barrier subjected to the incidence of acoustic waves generated by a line source. Here, a further extension of the proposed model is presented, and its experimental validation is addressed. First, the experimental setup used for the test problems is described; then, an overview of the numerical model is presented, including a new strategy to allow incorporating acoustic sources complemented by a horn structure; after this, a comparison between the numerical and experimental results is presented, a these results are discussed.

2. EXPERIMENTAL SETUP

In order to assess the level of adequacy of a numerical model, previously developed to estimate the insertion loss provided by sonic crystals when used as noise barriers, a set of experimental acoustic measurements was planned, which required the use of a smaller sized physical model of the sonic crystal.

2.1. DESCRIPTION OF THE PHYSICAL MODEL

As the numerical model, above mentioned, was developed to address the applicability of using a sonic crystal as a roadside noise barrier, the geometrical definition of the crystal was a consequence of wishing a not very dense structure as well as ensuring that the cylinder-shaped vertical elements are sufficiently robust. Since the possibility of using timber logs as the crystal’s cylindrical components was also an interesting prospect, from a sustainability-wise point of view, they ought to have a plausible dimension if obtained from trees.

Those broad requirements led to setting up, in the full size sonic crystal, the diameter of the cylinders at 0.20 m and the distance between the centers of cylinders, i.e. the lattice constant at a=0.40 m.

To reproduce such geometry in a practical and convenient to handle sized model, a scale of 1:5 was adopted, which led to in the model depicted in Figure 1. The cylinders are made of PVC_U 40 PN4 tubes, 1.00 m long with a nominal diameter of 40 mm.

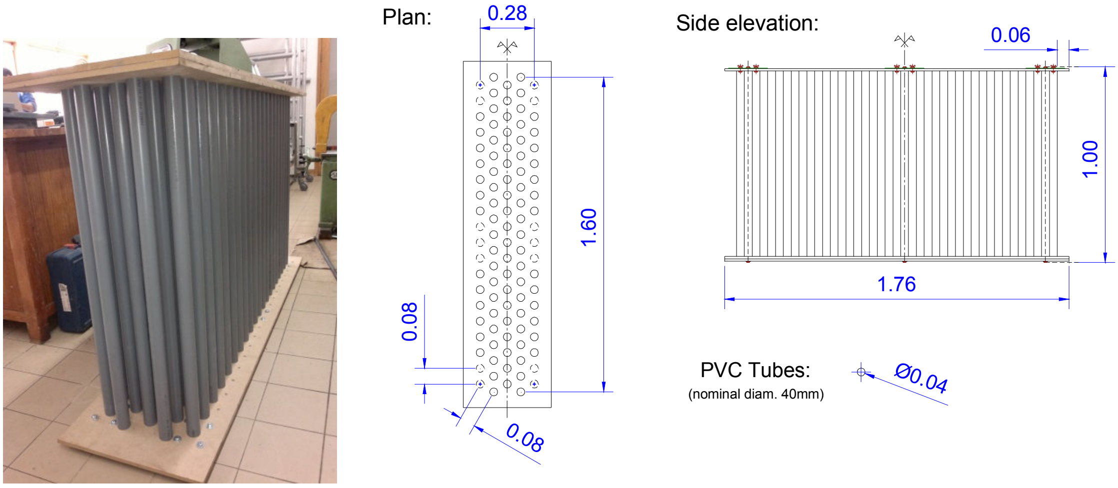

Figure 1 – View of the model and it's main geometrical characteristics.

A triangular lattice configuration was chosen, as preliminary results suggested that better results, in terms of sound attenuation, could be achieved with such arrangement. In order to confer greater flexibility in generating a larger number of different geometric arrangements, the model may have up to five rows of cylinders with up to 20 (or 21) cylinders each, enabling those rows to be totally filled or to have disruptions along them.

Another significant aspect of the setup had to do with the sound source used. Because the numerical model being evaluated considers a two dimensional analysis domain, a conventional omnidirectional sound source was deemed to be less adequate than using a driver source in combination with an acoustical horn that would provide more controlled sound directivity characteristics. For that purpose a Beyma TD460N Horn, as seen in Figure 2, was used.

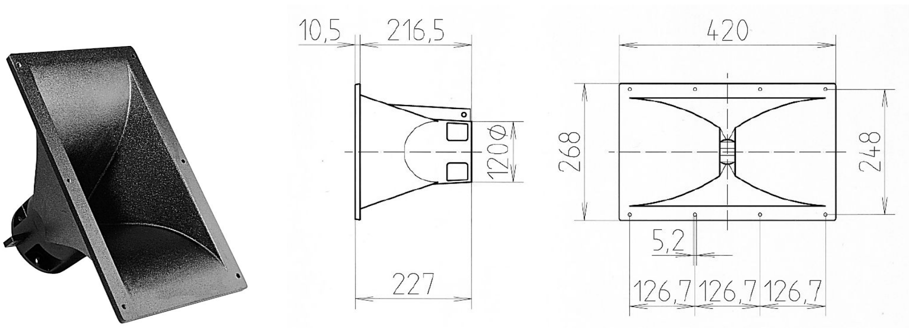

Figure 2 – Acoustical horn and it's main geometrical characteristics.

The setup still includes 01dB's Symphonie unit & dBBati32 software, used for data acquisition and as white noise generator, and a GRAS 40 AF ½" microphone and preamplifier.

2.2. THE EXPERIMENTAL MEASUREMENTS

The experimental tests carried out consisted of measuring sound pressure levels in an array of 25 receiver points, 0.50 by 0.50m, where the microphone was successively placed, both with and without the sonic crystal, while noise was emitted from the source's location, as observed in Figure 3. The site where the setup was placed was selected because of the absence of reflecting elements in front and in either side of the source, with exception of the ground which was carefully covered with highly absorptive mantles.

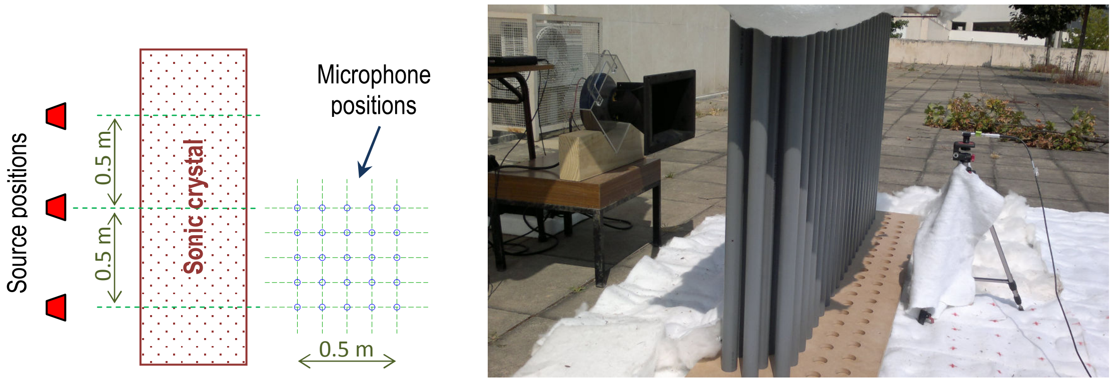

Figure 3 – General scheme and view of the experimental measurements.

In relation to the frequency analysis domain, as the sonic crystal noise barrier is originally intended to tackle road traffic noise, the most significant frequency range can be seen as spanning from 500 to 1500 Hz, as that noise peaks at around 1000 Hz in most cases. As the model used is 1/5 of the original size the preponderant frequency analysis domain to be used in the tests should span at least from 2500 to 7500 Hz, although during measurements the surveyed range was 125 Hz-12.5 kHz.

3. NUMERICAL MODEL

3.1. FORMULATION OF THE MFS

It is usual to consider that the propagation of sound in a two-dimensional space, in the frequency domain, can be represented mathematically by the Helmholtz equation. This equation has the usual form

$$\nabla^2 p + k^2 p = 0 \qquad (1)$$

where $\nabla^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$, p is the acoustic pressure, $k = \omega / c$, $\omega = 2\pi f$, f is the frequency, and c is the propagation velocity within the acoustic medium.

Given the differential equation (1), it becomes possible to define analytical solutions that satisfy the equation under certain conditions. One such situation corresponds to free-field conditions, in which the medium is considered infinite, and for which a two-dimensional pressure field is generated by a sound source located at point $\boldsymbol{x}_0$ of coordinates (x_0, y_0). This solution, known as the fundamental solution, allows the definition of the acoustic field in terms of pressure generated by the source at any receiver located at point $\boldsymbol{x}$ of coordinates (x, y) as

$$G^{2D}(\boldsymbol{x}, \boldsymbol{x}_0, k) = -\frac{\mathrm{i}}{4} \mathrm{H}_0^{(2)}(kr) \qquad (2)$$

where $r = \sqrt{(x - x_0)^2 + (y - y_0)^2}$.

To allow obtaining a solution for equation (1), considering additional boundary conditions of the physical problem, the MFS is here used, considering a set of NVS virtual sources located outside the field of analysis, and assuming that the pressure field at any domain point $\boldsymbol{x}$ can be represented by a linear combination of the effects of the NS sources positioned at points $\boldsymbol{x}_j$ so that

$$p(\boldsymbol{x}, k) = \sum_{j=1}^{NVS} Q_j G(\boldsymbol{x}, \boldsymbol{x}_j, k) + \sum_{m=1}^{NS} A_m G(\boldsymbol{x}, \boldsymbol{x}_0^{(m)}, k) \qquad (3)$$

where the second summation represents the effect of real sources that illuminate the analyzed system. This second summation is, indeed, the incident field of the problem, and is here used to simulate non-trivial source geometries.

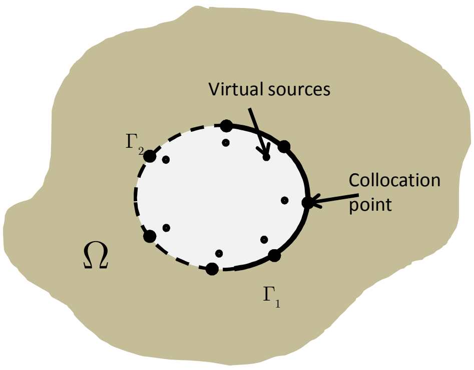

Figure 4 – Schematic representation of the problem.

3.2. INCORPORATION OF THE ACOUSTIC SOURCE

In order to simulate the effect of complex source shapes, such as the one described in the experimental setup (including an acoustic horn), a simple strategy has been devised. The aim of such strategy was to allow the analysis of the source shape as an independent problem, which may even be solved with alternative numerical methods, and then compute adequate coefficients A_m for a set of sources placed within the domain, thus replicating in a sufficiently accurate manner the effect of the real source shape. In the present work, the analysis of the real source was performed using a Boundary Element code, and thus the process can be summarized as:

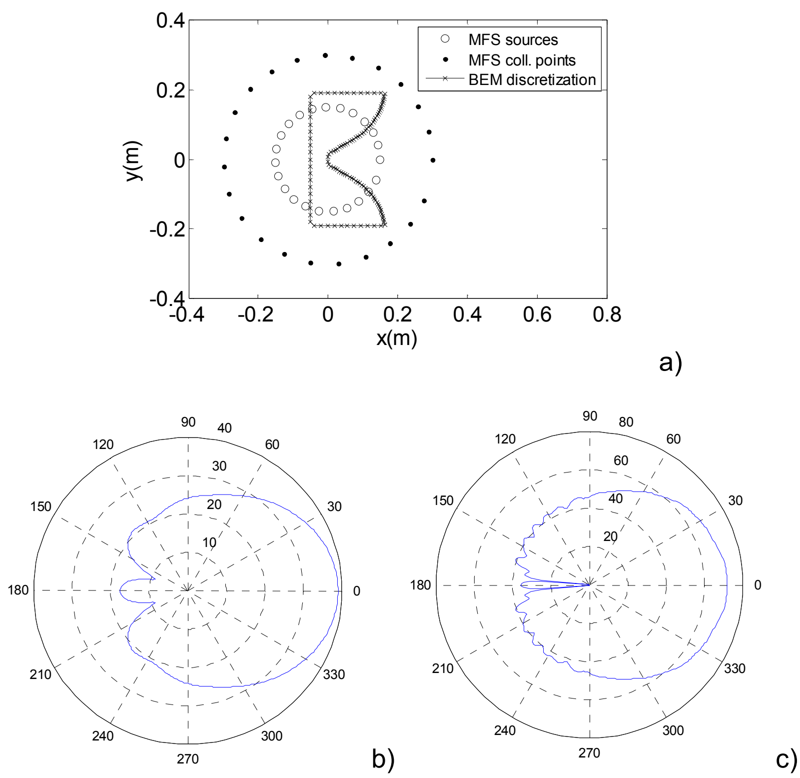

Figure 5 – a) Model of the horn including the MFS and BEM problems; b) Calculated directivity of the horn for 1000 Hz; b) Calculated directivity of the horn for 5000 Hz.

i. Define the geometry of the source to be analyzed, and discretize its boundary using boundary elements (a maximum element size of 0.015m was considered, always ensuring at least 8 elements per wavelength). This discretization can be observed in Figure 5a.

ii. Solve the problem using the BEM code, computing the acoustic pressure (complex number) at a set of points located along a circumference with a radius of 0.3 m surrounding the horn (see also Figure 5a).

iii. The calculation points of the previous step (ii) will be used as collocation points for a new MFS problem, in which a set of sources is placed along an inner circumference and the pressure values from (ii) are enforced as boundary conditions.

iv. Solution of this MFS problem gives the values of the amplitude coefficients A_m .

As stated before, the TD460N horn has been used coupled to a driver source, since it can produce a sound-field that is closer to a 2D configuration in the horizontal plane. For this case, the geometry of the horn in the horizontal plane is the one depicted in Figure 5a, and the corresponding MFS collocation points and sources are also displayed. To show the importance of correctly defining the source geometry, directivity plots for 1000 Hz and 5000 Hz calculated 1m from the source center are included in Figures 5b and 5c. One should note that if a point source was simulated, the directivity curve would be a circle with equal sound levels for all directions, which would clearly be a very rough approximation of the real problem.

4. RESULTS AND DISCUSSION

To assess the reliability of the predictions provided by the above defined numerical model, a number of field tests was performed for different configurations of a sonic crystal noise barrier, using the setup described in section 2. The tested configurations are graphically identified in the left column of Figure 7, and, for each of them, the insertion loss (IL) was computed. In these calculations, the response is evaluated at a set of 25 receivers (crosses in the schemes of Figure 7), and an average IL is then computed for each frequency band. Narrow band (100 Hz) calculations are performed for this purpose.
The results in Figure 7 clearly reveal that the predictions provided by the numerical model are very close to those evaluated experimentally, revealing that, besides being efficient, the proposed hybrid BEM-MFS model is also accurate.
A second set of tests was performed deviating the acoustic source from the central position, and placing it closer to the extreme positions of the barrier. The corresponding configurations are depicted in the left column of Figure 7. The results presented in the right column reveal, once again, an excellent agreement between both sets of results, and clearly indicates that the developed model can be a powerful tool in the analysis of sonic crystals.

5. CONCLUSIONS

The present work presents the extension of previous work by the authors (see Martins et al. [6]) in what concerns the numerical modeling of sonic crystal structures. Here the authors proposed and successfully implemented a methodology based in a hybrid BEM-MFS implementation which allows incorporating the effect of non-trivial source shapes illuminating the sonic-crystal. In addition, the authors performed an experimental campaign in order to assess the reliability of the numerical predictions, comparing them with experimental measurements. From the presented results, it can be concluded that the proposed model allowed incorporating a horn-shaped source by adding a relatively low computational cost to the model; in addition, the experimental test campaign, which analyzed five different configurations of the sonic crystal, allowed obtained insertion-loss results for each of those configurations; the numerical and experimental results matched very well, with very similar IL curves being computed throughout the frequency domain.
Finally, is should be mentioned that the present work indicates that the devised model can be quite useful in the analysis of sonic-crystal barriers, and that it can be a valuable tool in the prediction of their behavior.

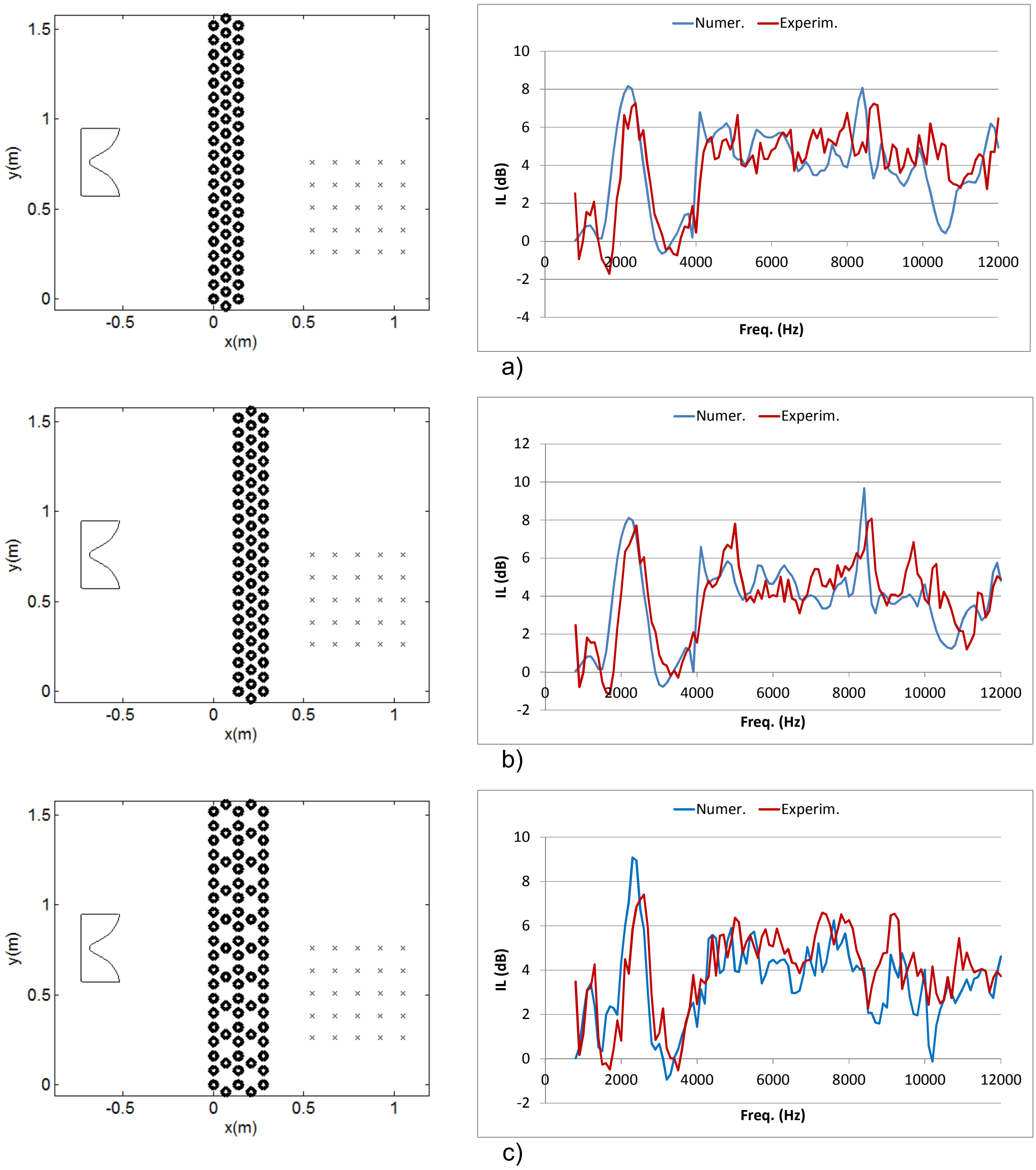

Figure 6 – Comparison of numerical and experimental results for three different configurations (left column, a, b and c) of the sonic crystal. The right column illustrates the insertion loss obtained for each configuration.

ACKNOWLDEGMENTS

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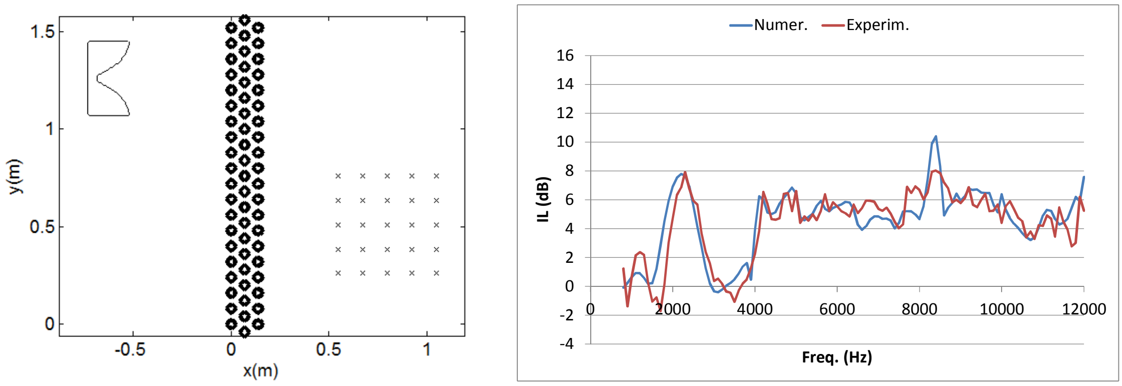
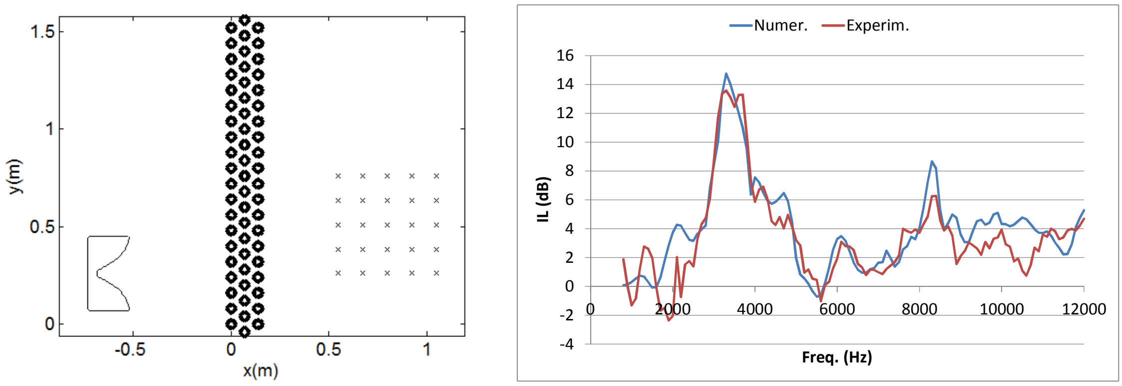


a)



b)

Figure 7 – Comparison of numerical and experimental results when the source is not centered with the barrier. The right column illustrates the insertion loss obtained for each source position.

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