MSEL
Modelling in Science Education and Learning

Modelling in Science Education and Learning
Volume 10 (2), 2017 doi: 10.4995/msel.2017.7653.
Instituto Universitario de Matemática Pura y Aplicada
Universitat Politècnica de València

Numerical simulation of subwoofer array configurations using the Finite Element Method

Simulación numérica de un conjunto de altavoces subwofers utilizando Elementos Finitos

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Abstract

Teaching in the Master of Acoustic Engineering includes contents that require the modeling of acoustic systems of two types: simple systems through analytical theory and complex models using simulation techniques. In the present work, we describe an example of complex acoustic sources modeling using the finite element method: subwoofer sound radiation in different configurations. Numerical simulations in the frequency domain can calculate the radiation pattern of systems that do not have a simple analytical solution.

La enseñanza en el Máster de Ingeniería Acústica incluye contenido que requiere la modelización de sistemas acústicos de dos tipos: sistemas simples usando la teoría analítica y modelos complejos usando técnicas de simulación. En este trabajo, se describe un ejemplo de modelado de fuentes acústicas complejas mediante el método de los elementos finitos: la radiación sonora del altavoz de subgraves en diferentes configuraciones. Las simulaciones numéricas en el dominio de la frecuencia permiten calcular el patrón de radiación de sistemas que no tienen una solución analítica sencilla.

Keywords: Subwoofer arrays, sound source, Finite Element Method
Palabras clave: Sistema de altavoces subgraves, fuente sonora, Método de los Elementos Finitos

1. Introduction

The use of numerical simulations for modelization of acoustic systems has been proved to be very useful in two circumstances: 1) to solve problems presenting intrinsic complexity as analytical solution are complicated or do not exist and 2) as a tool to validate analytical models. In the context of teaching of subjects related to fundamental sciences and engineering, the possibility of contrasting results obtained analytically and with numerical methods provides to the student greater safety during the learning process. At the same time, the availability of design tools allows the simulation of systems without simple analytical solution and promotes the creativity of the student to solve new problems (Benito Muñoz et al., 2014).

In this work, an example of the numerical simulation of a complex acoustic system is proposed as it is used by students of the Master of Acoustic Engineering taught at the Escuela Politècnica Superior de Gandia (Universitat Politècnica de Valencia, Spain) in the subject 'Simulation Techniques in Acoustics'. As a first step, the student learns fundamental subjects related to physics, mathematics, and acoustics in which the analytical modeling of physical systems that are useful in the field of acoustics is proposed, such as sound sources, acoustic enclosures, resonators or waveguides. In subsequent subjects, the student learns more complex simulation tools that allow them to validate the previously acquired fundamental knowledge, as well as the modeling of more complex systems. In this work, as an example, the modeling of different configurations of subwoofer arrays is presented to show how the student .

A subwoofer is a speaker that handles the bass part of the audio spectrum. In concert venues, often, the specific conditions of the emplacement and distribution of the acoustic sources produces an irregular distribution of the acoustic field for certain frequencies. This causes that perception of sound strongly depends on the place where the public is located. The problem is particularly complicated for sonorization of subwoofer arrays since they are omnidirectional sources and their radiation pattern overlap in space (Olson, 1957). If two or more sources are used, the pressure generated depends significantly on the space because of the destructive and constructive interference produced in the waves propagation. Most sound companies use the same type of subwoofer array for all their mountings, not meeting the requirements of the space to be sonorized, either for simplicity in the mounting or by ignorance of the features offered by other arrays.

In the present study, we analyze the acoustic radiation field of different configuration arrays of a group of eight subwoofers. It is intended to show the benefits and disadvantages of each array and its suitability depending on the conditions of the area to be sound. As a first step, a numerical study is presented concerning the spatial distribution of a single subwoofer. Later, the acoustic characteristics of different types of arrays for a direct mounting are analyzed. The COMSOL software tool based on the Finite Element Method (FEM) is used in all the numerical simulations.

In order to reduce the computational cost and to have a subwoofers design tool, the numerical simulation has been performed in two different models:

- Single Subwoofer.
- Subwoofer arrays.

2. Single Subwoofer

The aim of this section is to evaluate the distribution of the sound pressure level radiated by a single subwoofer. The SF-1521A subwoofer (Figure 4), which is the standard model of the company D.A.S, is chosen for the design. The limit frequencies used to perform the numerical simulation using FEM correspond to the working frequency response of the subwoofer, that is between 28 Hz and 200 Hz.

Figure 1: Photography of the SF-1521A subwoofer (DAS Audio, 2016).

The stability and convergence conditions require that elements of the calculation mesh have to be less than one eighth of the wavelength to provide sufficient spatial resolution (Courant, Friedrichs and Lewy, 1967). A mesh size of $\Delta \mathrm{x} = 0.215$ m has been used which is sufficient to obtain an accurate calculation up to the upper limit frequency, 200 Hz, as shown in the following calculation:

$$\Delta \mathrm{x} < \frac{\lambda}{8} = \frac{\mathrm{c}}{8\mathrm{f}_{\mathrm{max}}} = 0.215\mathrm{m} \tag{1}$$

where c is the velocity of sound in air, f_{max} is the upper limit frequency, and $\Delta \mathrm{x}$ is the mesh size. The mesh used for the subwoofer model is shown in the Figure 2. As can be seen, the mesh is denser around the domain area of the source because it requires higher resolution (Courant et al., 1967).

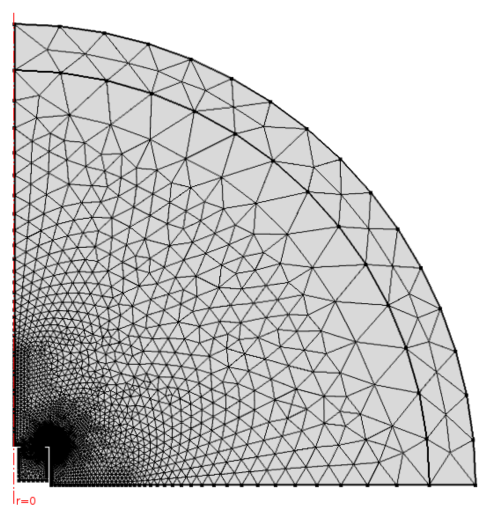

Figure 2: Mesh of the subwoofer's simulation model.

The computing time used to perform the simulation of model a) on a machine with i7-4712MQ processor and 8 GB of RAM is approximately 4 minutes and a half. The result of the simulation of the loudspeaker radiation at frequency of f=200 Hz is shown in Figure 3. The physical magnitude represented is the Sound Pressure Level (SPL) in the source's working frequency range. Figure 5 shows the radiation pattern of the subwoofer by representing the SPL in a polar plot at f=200 Hz.

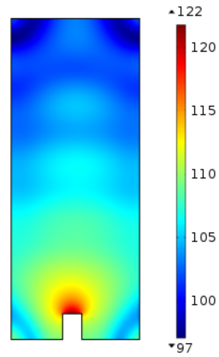

Figure 3: Sound Pressure Level of a single subwoofer at f=200 Hz.

The physical magnitude to be analyzed in the present study is the Sound Pressure Level (SPL) that is the difference between the pressure produced by a sound wave and the ambient atmospheric pressure at the same point in space.

$$20\log_{10}\left(\frac{\mathrm{p}}{\mathrm{p_{ref}}}\right) \quad \mathrm{dB} \tag{2}$$

where p is the root mean square sound pressure and p_{ref} is the reference sound pressure: in air 20μPa is used.

In Figure 4, the result of the simulation in 3D of the loudspeaker radiation field at frequency of 200 Hz is shown. It should be noted that, although the model has been solved in 2D, the software reconstructs the 3D representation taking into account the axial symmetry of the problem (Oladejo et al., 2012). Figure 5 shows the radiation pattern of the subwoofer by representing the SPL in a polar plot at f=200 Hz.

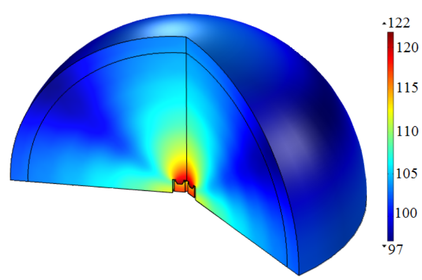

Figure 4: 3D Representation of Sound Pressure Field of a single subwoofer at frequency f=200 Hz.

3. Subwoofer arrays

It is intended to study of the acoustic behavior of several configurations of subwoofers emitting in a typical audience. For this purpose, SIMES (Company of Sound, Lighting and Concert Production) was consulted in order to obtain the following data to perform the modeling: the measurements of the stage, the pit, and the number of subwoofers usually used in this type of

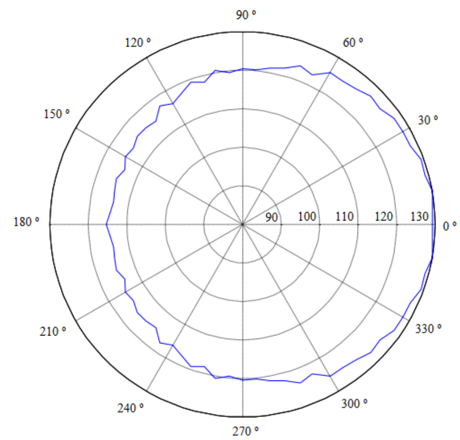

Figure 5: Radiation polar plot of a single subwoofer at f=200Hz.

mountings. The size of the stage correspond to the most standardized among companies in the acoustic sector: $12 \times 10 \times 1.8$ m^3. Since the analysis is to be carried out in the horizontal plane of the audience, the problem has been simulated in 2D in order to reduce the computational cost. In this way, it is not necessary to take into account the height of the stage in the analysis. The audience zone has been designed with dimensions 60×40 m^2. To enable the circulation of cameras and workers during the event, two meters of pit between audience zone and the stage have been reserved.

The problem analized is symmetric with respect to an axis that passes through the center of the stage in such a way that audience can be divided into two parts (right and left). If we consider the symmetry in the simulation, the computing time is significantly reduced. However, in many cases, this symmetry is altered by tents, bars and other common elements in this type of mountings. In order to allow reusing and adapting the model to new particular requirements of different situations, this symmetry has not been considered. Different types of subwoofer arrays are analyzed in the present study (Figure 6):

a) LR Parallel Array: Four subwoofers are placed on each side of the stage with a separation of $\lambda/2$ between the loudspeakers on each side.

b) Centered Parallel Array: Eight subwoofers are placed on the center of the stage with a separation of $\lambda/2$ between the loudspeakers.

c) LR Cardioid Array: Four subwoofers are placed on each side of the stage in a front-rear cardioid configuration. Between the front and rear loudspeakers the separation is $\lambda/4$ and the lateral separation is $\lambda/2$.

d) Centered Cardioid Array: Eight subwoofers are placed on the center of the stage in a front-rear cardioid configuration with the same separations as the previous case.

It is intended to evaluate and analyze the different types of subwoofer arrays for direct mounting. For the domain discretization, a mesh with a mean element size $\Delta x = 0.43$ m was used. This mesh is sufficient to obtain a precise calculation up to 200 Hz. The computing

 ISSN 1988-3145

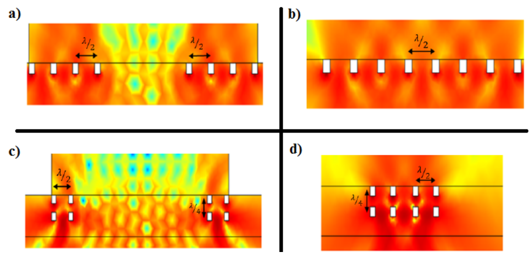

Figure 6: Scheme of the four configurations of subwoofer arrays. Detail of the Sound Pressure Level at f=200 Hz.

time used for the model is approximately 10 minutes. For the different types of arrays, the arrangement of the acoustic elements changes, but the computing time is similar. Since the real domain is an open field, numerical absorptive boundary conditions are used to avoid the effect of reflections. The excitation is imposed as a normal acceleration in the cone of the subwoofer. Due to the large dimensions of this model, the source has been simplified by a rectangle, measuring $0,3 \times 0,4$ m^2. Like with the single source model, it has been ensured that the subwoofer at 4 m provides the desired sound pressure level of 107 dB as indicated by the specifications.

Cardioid Array is achieved by separating the subwoofers a distance of $\lambda/4$ of the upper cut-off frequency of the system, along with a time lag of 1.2 ms and 180º in acceleration between the front and rear box over the whole subwoofer frequency band. At the front, at the frequency chosen for reference, the phase value for each subwoofer is the same (La Roda, 2009).

As an example in Figure 7 a scheme of the model is shown in which the placement of the loudspeakers presents the LR cardioid array configuration. The distance between the boxes of the front line and the rear line, for a frequency of 200 Hz ($\lambda = 1.715$ m) is 43 cm.

To achieve an optimum rear cancellation, the phase difference have to be 180º, which is achieved by reversing the polarity of the rear subwoofer. In addition, the delay between paths of the back loudspeaker and the previous one have to be added (12 ms to cover the 43 cm) and the pressure levels have to be equal.

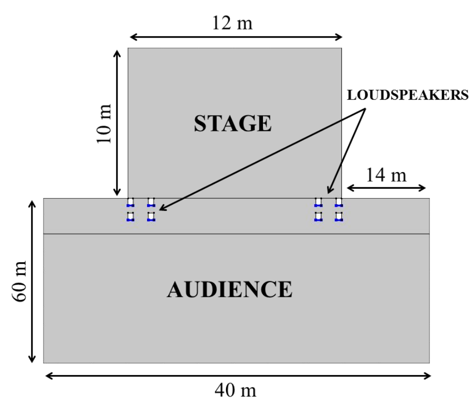

Figure 7: Location of the loudspeakers in the LR Cardioid Array simulation model.

Next, the results of the four simulations performed are presented.

- **LR Parallel Array:**

Subwoofers are grouped in two blocks, one on each side of the stage. Each loudspeaker is separated a distance of $\lambda/2$ from its nearest. Each block behaves as an independent source

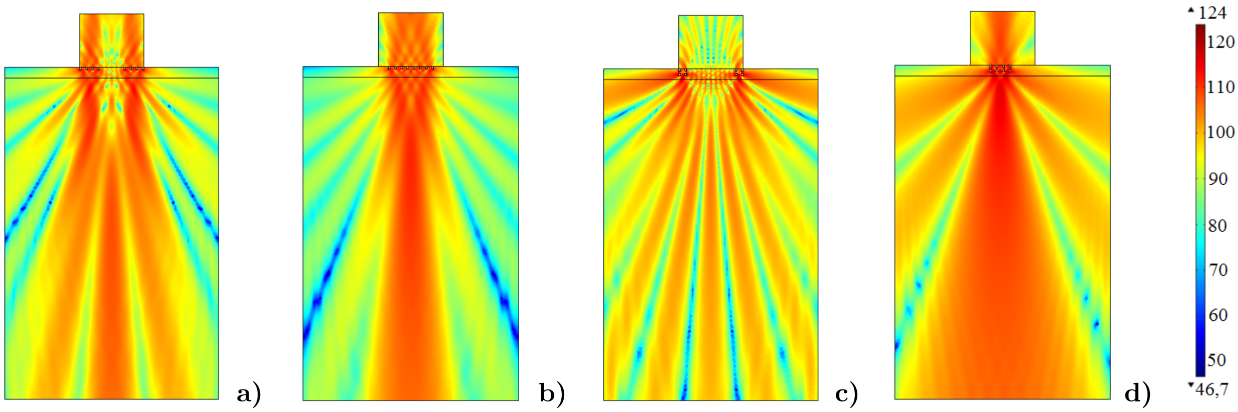

Figure 8: Simulation of four types of arrays. **a)** LR Parallel Array; **b)** Centered Parallel Array; **c)** LR Cardioid Array; **d)** Centered Cardioid Array.

(Figure 8.a). This causes both in the central area of the audience closer to the stage and on the sides of it, important cancellations and corridors (lines of minima and maxima of SPL) are observed. However, the coverage angle is quite wide, covering most of the side areas with a pressure level greater than 100 dB. The loudness on the stage is high and concentrated on the sides.

- **Centered Parallel Array:**

In this configuration, loudspeakers are centered (Figure 8.b), with a $\lambda/2$ spacing between them. The central area of the audience receives much more uniform radiation than in the case mentioned above at the expense of a significant loss of pressure level on the sides. The appearance of corridors, although existing, is less important than in the case of the LR Parallel Array. The sound pressure level is significantly high in the stage.

- **LR Cardioid Array:**

The cardioid configuration located on the sides of the stage has a great advantage over the previous configurations (Figure 8.c), as it reduces the sound pressure level on the stage. This level reduction reaches -10 dB. The coverage angle (angular extent of the acoustic field) is wider than in any of the parallel arrays. However, the presence of corridors is remarkable. In fact, reducing loudness on stage and expanding the coverage angle is achieved at the expense of losing uniformity in the sound pressure level of the audience.

- **Centered Cardioid Array:**

Finally, placing the eight loudspeakers in Centered Cardioid configuration (Figure 8.d) results in a very wide coverage angle and a great uniformity for the entire audience. It is the configuration with the least number of corridors. On the stage, the SPL is not reduced as much as in the LR Cardioid configuration. However, there is a reduction of the SPL with respect to the Centered Parallel configuration, especially on the sides.

4. Conclusions

This study has focused on mountings for sound events of half capacity (1.000-3.000 people). Several practical recommendations for the use of subwoofer arrays are proposed in this study as a result of the analysis of numerical simulations. For the cases where a long shot and narrow angle coverage are needed and do not require the reduction loudness on, it is recommended to use a Centered Parallel Array configuration. However, when the coverage angle to be achieved is wide there are several options. If acoustic pressure uniformity is required in the audience, the recommended configuration is the Centered Cardioid Array. If, instead, the reduction of loudness on the stage is prioritized, it is recommended to use the LR Cardioid Array configuration. The LR Parallel Array, for the dimensions of the stage and audience established, it is not recommended, since the Centered Cardioid Array is superior in all aspects with respect to this configuration. As a future perspective, we intend to carry out a study with bigger mountings, with a greater number of acoustic boxes and, consequently, an increase in the possible combinations of their arrangement.

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