SOUND SYNTHESIS USING SOURCE ARRANGEMENTS WITH ACTIVE AND REACTIVE SOUND MODES

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An acoustic source array radiating active and reactive power modes has been used in the synthesis of sound fields. The objective is to generate a purpose designed sound field which can be specified according to a particular application. Of particular interest to the present study is the analysis of a field composed of plane waves impinging in a panel taking into account the acoustic transparency problem. The physical realization using transducers is also taken into account. Acoustic sources radiate both active and reactive components therefore requiring a more complete analysis to help to ensure that created sound fields can be used to fairly represent existing conditions in another sound field, the latter resulting from an operational condition which would otherwise be difficult to analyze. The matrices associated with the power arrays have been solved by means of a finite element analysis. The sound intensity associated with the modelled sources has been obtained via inverse problem solving assuming the pressure distribution over the panel under consideration. This procedure is intended to be used in the optimized design of source positioning and acoustic source strength. Parametric analysis, including variables such as frequency and distance from the array to the panel is briefly discussed therefore helping to indicate how optimal source configuration can be achieved for a typical real life practical application
Keywords: sound synthesis, source arrangement, transducers, acoustic transparency.

1. Introduction

In the last decades, ARMs (Acoustic Radiation Modes), mainly Far-Field Acoustic Radiation Modes (FFARMs), have been extensively studied because they demonstrate a great ability to control arrangements of sound sources independently. The most efficient modes have been used to improve the volume velocity distribution associated to a particular source arrangement so that the radiated sound power is sufficiently high without overloading the array[1]. However, Near Field Radiation Modes (NFARMs) still require further study because they are of interest in problems where the receiver is close to the source, such as in the synthesis of sound fields impinging on flat panels. This has proved to be particularly useful in the study of acoustic transparency and in spatial audio applications. FFARMS and NFARMS are related to the active and reactive portions of the sound power, respectively. For this reason, they can also be called active and reactive modes of radiation.

In addition to the SVD technique, ARMs and their radiation efficiencies can be obtained directly through the diagonalization of the square matrix that couples the sound power produced by the individual radiators of a source arrangement. Several researchers have successfully exploited both techniques in solving many problems associated with acoustic radiation, active noise control and sound field synthesis

This simulation can be conveniently achieved via a specific distribution of acoustic pressure (plane wave with a certain inclination and frequency) on a flat, finite and rigid surface (reproduction plane representing the panel to be tested) using a flat and finite arrangement of monopoles (Plane source) in free field and its respective image source arrangement. In this way, it will be possible to identify some parameters of the propagation model as bands of frequencies, slopes and distances between the arrangements that will produce the best results associated with the sound field synthesis problem.

2. Acoustic Field Decomposition

2.1 Plane Waves

Plane harmonic waves are characterized by constant amplitude and phase in any plane perpendicular to their direction of propagation [2]. The corresponding sound pressure field can be expressed as:

$$p(x,y,z) = Pe^{j(k_x x + k_y y + k_z z - \omega t)}. \qquad (1)$$

A useful visualization is provided in Fig. 1

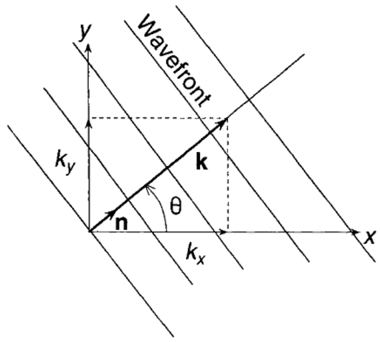


Figure 1: 2D Plane wave (23).

A spatial distribution of sound pressure, in steady state with constant, can be expressed by a sum of propagating and evanescent plane waves of different amplitudes and phases [1] of the form

$$p(x,y,z,\omega) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(k_x, k_y, z, \omega) e^{j(k_x x + k_y y)} dk_x dk_y \cdot \qquad (2)$$

where P is in Cartesian coordinates:

$$P(k_x, k_y, z, \omega) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y,z,\omega) e^{-j(k_x x + k_y y)} dx dy \cdot \qquad (3)$$

2.2 Monopole and Image Presentation

In free field conditions the complex pressure amplitude produce by a monopole can be expressed as:

$$p(r,k) = -j\omega\rho_0 Q \frac{e^{jkr}}{4\pi r}. \qquad (3)$$

Where $(-j\omega\rho_0 Q)$ is the source strength “acceleration”

The image method can be used to calculate the acoustic field of a source close to a rigid and flat border, representing, for example, the panel to be tested in acoustic transparency studies.

Considering a perfectly rigid plane at x = 0 the resulting pressure field in a region will be given by the superposition of the respective fields, that is, by the sum [2]

$$p(r^-,k)+p(r^+,k)=-j\omega\rho_0 Q\left(\frac{e^{jkr^-}}{4\pi r^-}+\frac{e^{jkr^+}}{4\pi r^+}\right). \tag{4}$$

Also it can be demonstrated that the normal component of the velocity is null over the plane Oyz, as required by a rigid panel condition [2], [3].

3. Acoustic Field Synthesis Overview

For the construction of the sound propagation model, we will consider an arrangement of monopoles, uniformly distributed, oscillating in the same wave number and with velocities of volume where. In addition, we will consider the respective arrangement of image monopoles, also containing monopoles. Thus, using the superposition principle, the sound pressure generated by the arrangement at position (x_j, y_j, z_j) is given by

$$\mathbf{Aq}=\mathbf{p}. \tag{5}$$

Where $\mathbf{A}$ is the complex $m\times n$ transfer matrix of the propagation model having elements defined by:

$$a_{ij}=-j\omega\rho_0\left[\frac{e^{jkr_{ij}^-}}{4\pi r_{ij}^-}+\frac{e^{jkr_{ij}^+}}{4\pi r_{ij}^+}\right]. \tag{6}$$

$\mathbf{q}$ is the monopole complex volume velocity and $\mathbf{p}$ is the pressure amplitude vector. Matrix $\mathbf{A}$ contains all the properties of of the propagation model.

The inverse problem can be solved using a minimum square method taking:

$$\min\|\mathbf{Aq}-\mathbf{p}\|_2. \tag{7}$$

and

$$\mathbf{q}_{MQ}=\left(\mathbf{A}^H\mathbf{A}\right)^{-1}\mathbf{A}^H\mathbf{p}. \tag{8}$$

Matrix $\left(\mathbf{A}^H\mathbf{A}\right)^{-1}\mathbf{A}^H$ is the pseud inverse of $\mathbf{A}$, representing the standard matrix inversion. The matrix defining the particle velocity having b_{ij} elements of x_j of a rigid panel is

$$\mathbf{Bq}=\mathbf{u}. \tag{9}$$

4. Results

A physical realization for a typical array is shown in Fig. 2, where nine monopoles are positioned over a flat panel.

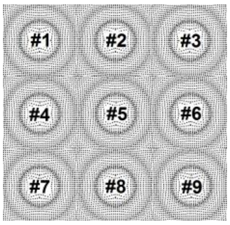


Figure2: Arrangement of an Array having 9 monopole sources.

The resulting eigenvalue behavior can be observed in Fig 3, where active power (a) and reactive power depend on the distance between the rigid panel and the discretizing plane surface, for a fixed frequency of 1 kHz, considering that both the source array and its image are positioned at one meter from the rigid panel.

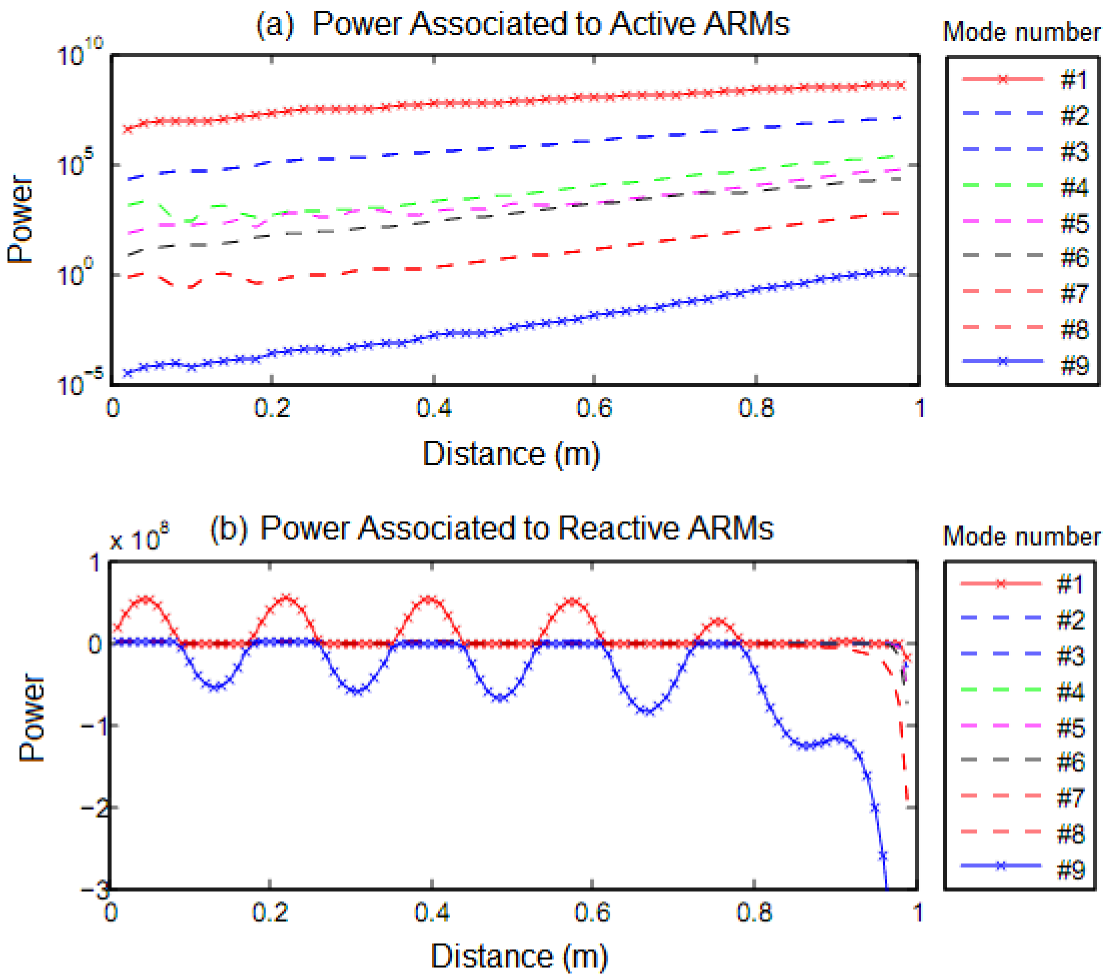


Figure 3: Active/Reactive Power w.r.t. the distance from a rigid panel to the discretizing surface at 1kHz

For distances very close to the rigid panel, the reactive power is positive, which indicates a greater contribution of rigidity to the mechanical impedance of the system. On the other hand, for distances close to the sources the effect of the mass of radiation has greater contribution in the mechanical impedance of the system which produces a reactive power with negative signal.

The reactive power presents a great contribution to distances very close to the sources, decreasing with the increase of this distance, especially for the less effective ARMs, according to Fig. 3(b).

Another aspect on ARMs concerns the distribution of source $Q_i / \|\mathbf{q}\|$,where Q_i is the source strength of the ith source and $\mathbf{q}$ is the associated velocity vector of the array. As an example, Fig.4 shows the activation patterns of the 9 sources of the array. Mode # 1, associated with the highest eigenvalue (power), is the most efficient in terms of acoustic radiation, independent of frequency or distance and being active or reactive, presents constant gains for sources. Similarly, Modes # 6 and # 9, with only a pattern of distribution of source gains, and Mode # 9 is associated with the lowest radiation efficiency of the array, i.e. the lowest eigenvalue (power).

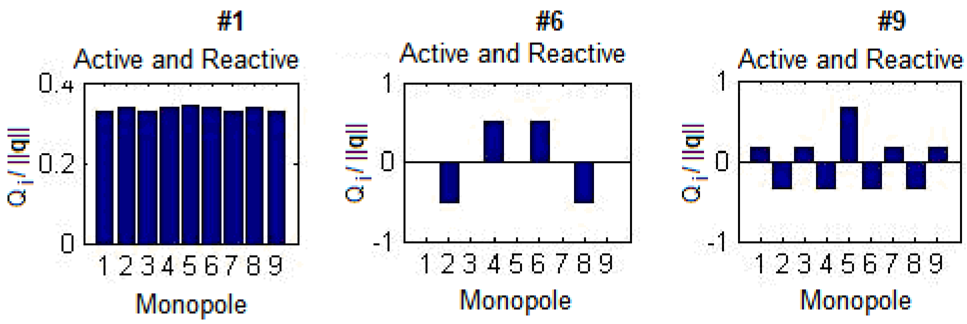
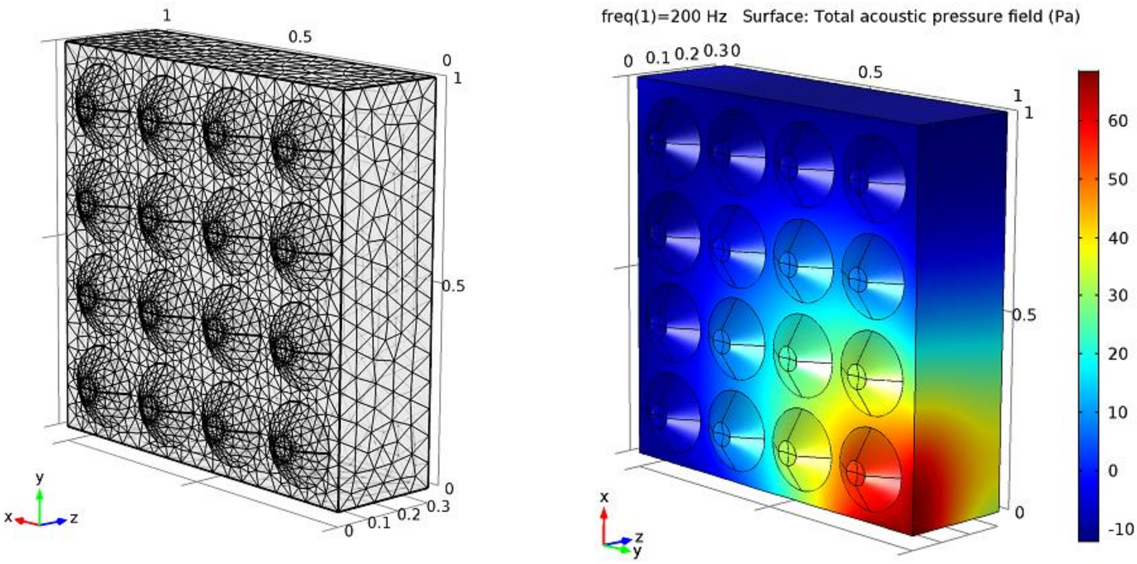


Figure 4: Typical monopole gain distribution with respect to frequency and distance.

For the finite element simulation an arrangement which enabled comparison with previous work produced by other authors [4]. [5] was chosen.

The model consists of two flat, rigid and square arrays, with 1m of side distant from each other of 0.3m, the source arrangement containing 4 x 4 speakers with a diameter of 0.21m each and the second representing the panel of Test.

As the power matrix $\mathbf{W} = \mathbf{B}^H \mathbf{A}$ is obtained from the relation between pressure matrix and particle velocity, we will have to simulate for each speaker with unit velocity the field of pressure and particle velocity in the plane of synthesis for the construction of these matrices. As an example, Fig. 5 shows the pressure distributions for a particular loudspeaker set up.



Mesh with 34847 elements in the domain.

Acoustic Pressure :

Figure 5: Acoustic Pressure and Discretizing Mesh, Loudspeaker with 1m/s velocity

As a final remark it should be mentioned that the previously shown arrangement is a useful tool for simulating acoustic fields which would otherwise be difficult to reproduce or study. Applications such as the study of the acoustic field around an aircraft fuselage at cruise conditions can be dealt with without having to carry out expensive and sometimes no viable flight testing [5] [6].

During cruising flight an important contribution to the overall noise inside the cabin is due to the turbulent flow around the aircraft body [5] [6]. Research on this area has become increasingly important as different materials and construction techniques have been introduced by the manufacturers, a fact which has changed the acoustic transmission properties of the airframe.

5. Conclusions

The results obtained in this work using the monopole array propagation model suggest that it is possible to synthesize, in the near field, the pressure distribution generated by a plane wave on a finite and rigid panel for several inclinations and frequencies in a reasonable way, even if the model may not be fully compatible with this type of sound pressure distribution.

By analyzing the approximation error and the norm of the volume velocity vector of monopoles for cases with and without regularization, it is possible to identify the best frequency bands, slopes, number of monopoles and distances between the source arrangement and the plane that will produce more satisfactory solutions.

Through numerical simulations, it was shown that both the error of synthesis and the norm of the vector of amplitudes of the sources increase with the inclination desired for the plane wave. It could be observed that increasing the distance between the array of sources and the synthesis plane results in a growth of the array condition number κ_A of the propagation model. Similar result is obtained by increasing the amount of monopoles used in the model. As expected, the greater the number of sources, the better the result obtained in the sound synthesis.

Therefore, it was concluded that the linear system conditioning is not associated with the quality of the solution estimated by the model, but with the solution stability of the algebraic equation system. Thus, the model with better conditioning will not always present better results in the sound synthesis. In general, a high condition number is associated with an instability of the propagation model solution at perturbations in the target pressure field.

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