Noise control by BEM in large scale engineering problems

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SUMMARY. In the present contribution the interior noise of the aircraft is investigated. The Boundary Element Method (BEM) is adopted to analyze the noise performance of the aircraft cabin under different noise sources and with various seat textiles.

1 INTRODUCTION

The interior noise of aircraft is an important concern because it affects the passenger comfort. In order to reduce the noise, the designer must pay close attention to the response of the cabin to various acoustic sources. The odd shape of the cabin does not allow an analytic solution. The mathematical resolution becomes more difficult when the designer begins to apply acoustically absorptive materials in a nonuniform manner to the cabin surface. There are many techniques available for modeling interior sound fields, including modal expansions, method of images, finite element (FE) and boundary element (BE) methods. The modal expansion method [1]-[2] is based on the analysis of the acoustic motion in terms of the normal modes of the enclosure. A good approximation in the interior can be obtained by using the acoustic modes for the rigid wall enclosure. Such a solution is not correct in the region near the boundaries. FEM and BEM [3]-[4] are both based on the discretisation of the Helmholtz wave equation for simple-harmonic waves. With regard to internal problems, the main difference stands in the dimension adopted: FEM requires the discretisation of the entire volume under analysis whereas BEM meshes the boundary only. The present paper presents some results obtained inside the project "Smart technologies for stress free air travel (SEAT)" under the 6^{th} Framework Programme. All the numerical results are obtained by direct BEM. The results are given in terms of pressure/velocity on the boundary. The value at any internal point can be determined in the post-processing step on the basis of the knowledge of the solution on the boundary. The adopted elements are of quadrilateral/triangular linear type and the mesh is set in order to have 6-8 elements per wavelength. The numerical experiments are aimed at investigating the level of noise reduction inside the aircraft cabin obtained by adopting different textiles and different headrest geometries. The current results refer to a specific signal spectrum related to one of the common flight operations of an aircraft. The geometry under investigation coincide with an actual aircraft cabin. The absorbing properties of the panels of the cabin were determined on the basis both of the scientific literature [5] and of some experimental results obtained by one of the partners of the project. The numerical experiments which will be presented have two goals: 1) to recover the results obtained in the experimental tests, 2) to investigate the level of noise control obtained by adopting different textiles and different headrest geometries. It must be pointed out that in the high frequency range it is common to consider more convenient to use geometrical acoustics, following the "rays" of sound as they reflect back and forth from various portions of the wall surface. On the other hand, in recent years, the development of fast iterative procedures, such as the Fast Multipole

Method and the Hierarchical Matrix approach, has opened new scenario in the BE context: such fast techniques have offered the possibility to also cope with the high frequency acoustic problems by considering the oscillating nature of the acoustic phenomenon rather than simplifying it as repetitive reflection/absorption of rays.

2 THE GOVERNING BOUNDARY INTEGRAL EQUATION

The propagation of time-harmonic acoustic waves in a homogeneous isotropic acoustic medium (either finite or infinite) is described by the Helmholtz equation:

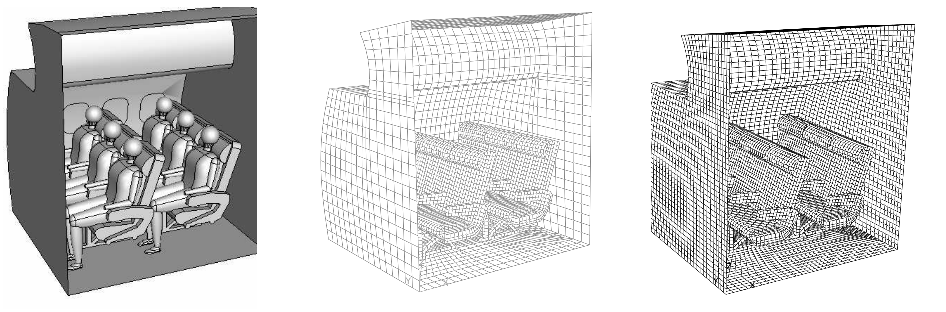
$$\nabla^2 p(\mathbf{x}) + k^2 p(\mathbf{x}) = 0 \tag{1}$$

under the boundary conditions:

$$p(\mathbf{x}) = \overline{p}(\mathbf{x}) \qquad \mathbf{x} \in \Gamma_1 \tag{2a}$$

$$q(\mathbf{x}) = p(\mathbf{x})_{,n} = \overline{q}(\mathbf{x}) \qquad \mathbf{x} \in \Gamma_2 \tag{2b}$$

where p is the acoustic pressure, $k = \omega/c$ with ω = angular frequency and c = sound velocity, comma indicates partial derivative, $\Gamma_1 \cup \Gamma_2 = \Gamma$, Γ is the boundary of the domain Ω under analysis, $n = n(\mathbf{x})$ is the outward normal to the boundary in $\mathbf{x}$, q is the flux and the barred quantities indicate given values.



(a) (b) (c)

Figure 1: Geometric model (a), Coarse mesh (b), Fine mesh (c).

The boundary value problem described by the above equations can be transformed into the following integral representation [3]-[4]:

$$c(\boldsymbol{\xi})p(\boldsymbol{\xi}) + \int_\Gamma q^*(\boldsymbol{\xi}, \mathbf{x})p(\mathbf{x})d\Gamma(\mathbf{x}) - \int_\Gamma p^*(\boldsymbol{\xi}, \mathbf{x})q(\mathbf{x})d\Gamma(\mathbf{x}) = 0 \tag{3}$$

where $c(\boldsymbol{\xi})$ occurs in the limiting process from the internal point to the boundary point, being equal to 0.5 for boundary points where the boundary is smooth. The fundamental solutions p^* and q^* are given by:

$$p^*(\boldsymbol{\xi}, \mathbf{x}) = \frac{1}{4\pi r} e^{-ikr} \tag{4a}$$

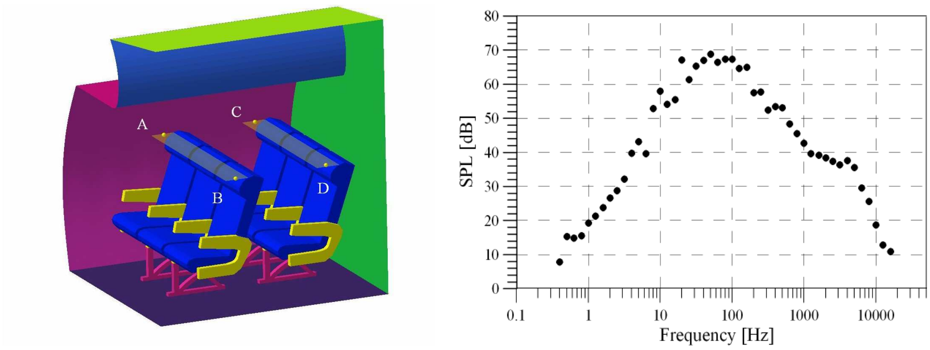
$$q^*(\boldsymbol{\xi}, \mathbf{x}) = -\frac{1}{4\pi} \left(\frac{1}{r^2} + \frac{ik}{r}\right) e^{-ikr} r_{,n} \tag{4b}$$

where $r = \parallel \mathbf{x} - \boldsymbol{\xi} \parallel$ is the distance between the collocation point $\boldsymbol{\xi}$ and the field point $\mathbf{x}$.

The conventional BEM numerical procedure is based on two steps: first, the discretisation of the boundary Γ, second, the collocation of the Eq. (3) in each node in order to build a final (square) system of equations in the unknowns either p or q on the boundary.

3 THE MODEL

The model under analysis consists of two lines of three seats surrounded by the aircraft fusolage. The surfaces were meshed with linear either quadrilateral (quad) or triangular (tri) elements. The initial geometric model (see Fig. 1a) was simplified in order to reduce the computational effort without influencing the acoustic behavior, i.e. by reducing the high curvature surfaces. The investigation was limited to the frequency range 31.5-1000 Hz. The adopted coarse mesh (see Fig. 1b) and fine mesh (see Fig. 1c) were formed by 9876 nodes and 13806 nodes, respectively. The former was used up to 100Hz whereas the latter in the range 125-1000Hz. Both meshes were sufficient to guarantee 6 elements per wave length. Two triangular meshes (with about 20200 and 32280 nodes, respectively) were also used to check the correctness of the results with regard to the highest frequency of 1000 Hz. The acoustic source was located in the middle of the corridor, therefore it was possible to take into account the symmetry with respect to the vertical plane (as it is clear from the meshes represented in Figs. 1b-c).



(a) (b)

Figure 2: Position of the microphones (a), Spectrum signal (b).

Furthermore, two panels, one in the front (which was not depicted in the figures for the sake of clearness) and the other one in the rear of the cabin, were added to the model in order to obtain an ”internal closed surface” to be correctly modeled by a BE approach. The external panels and the seats were all modeled as absorbing surfaces with different impedance values, i.e. the model was subdivided into the following panels: left, front and rear panels, floor, ceiling, seats with their armrests and supports. The impedance boundary conditions were set on each part of the model on the basis of an experimental/parametric analysis (detailed in the next section).

3.1 *The experimental results*

The numerical model was first tested by some experimental results obtained by one of the partner of the project. An aircraft cabin mockup was built and subjected to an acoustic source located in the middle of the corridor. Four microphones (A, B, C and D in Fig. 2a) were positioned in order to measure the sound pressure level (SPL). The signal is represented by its frequency spectrum in Fig. 2b. It is clear that the experimental acoustic source was not periodic. The numerical response of the mockup under the acoustic source was obtained by a multifrequency BEM analysis. The BEM furnishes the numerical response in terms of pressure/velocity at the central frequency of each octave band. The amplitude of the numerical monopole at each frequency was set on the basis of the experimental SPL (depicted in Fig. 2b). The experimental results were useful to set the correct boundary conditions on the various panels of the cabin.

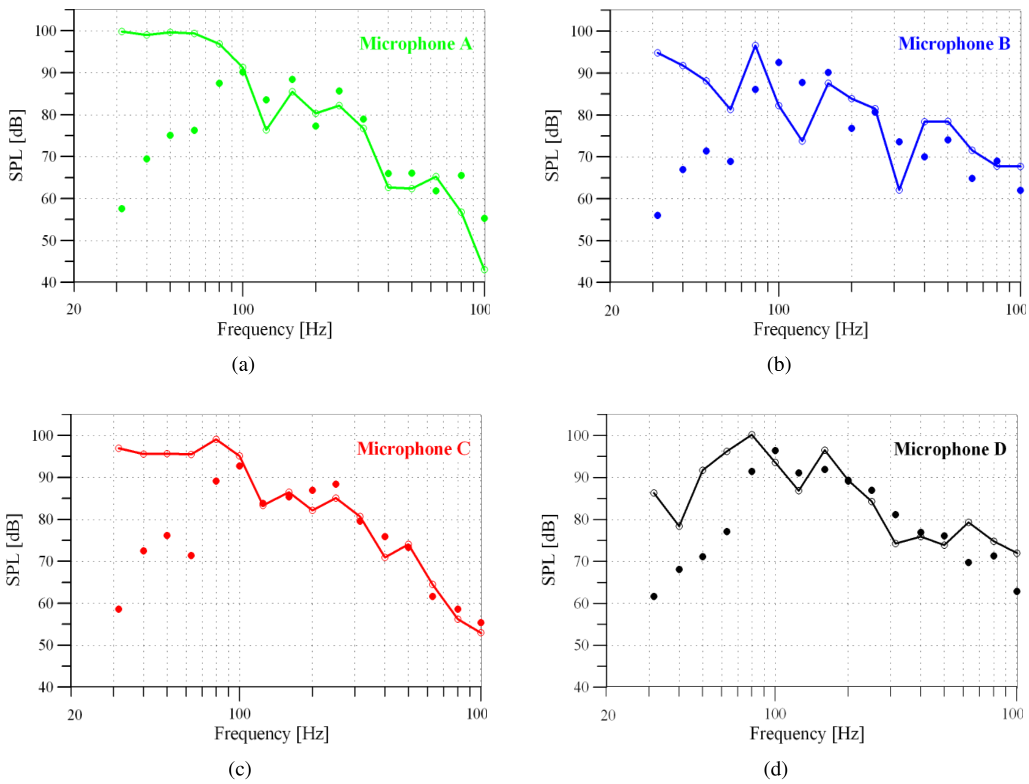


Figure 3: Comparison between experimental (dashed circle) and numerical (line with circle) results at the microphones.

3.2 *Boundary conditions*

The boundary conditions were set by imposing that each panel constituting the model, except the seats supports considered perfectly rigid, were absorbing, i.e. by setting Robin boundary condition of the type:

$$v = \frac{p}{Z} \tag{5}$$

where p and v are pressure and velocity, respectively, and Z is the impedance value. Such an impedance is in general a complex number and it can be written in terms of the absorption coefficient α by the following relations:

$$r = 1 - \alpha \tag{6a}$$

$$r = \|r_p\|^2 \tag{6b}$$

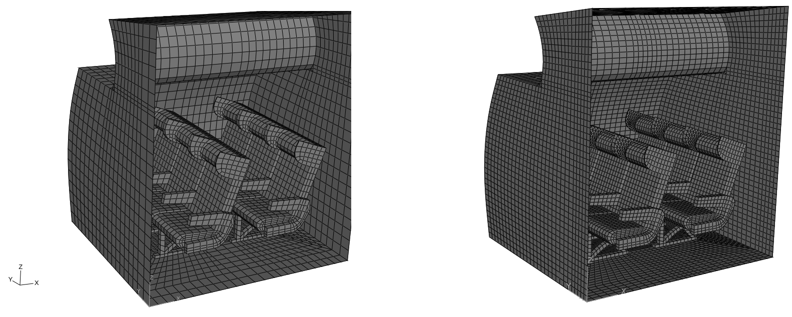
$$Z = Z_0 \frac{1 + r_p}{1 - r_p} \tag{6c}$$

where α includes both absorption and transmission and Z_0 is the impedance of the air ($Z_0 = \rho c$ with $\rho =$ density and $c =$ sound velocity).

Some of the absorption coefficients of the mockup were determined experimentally (in particular the value referred to the seat textile). The remaining α coefficients were initially gathered from the scientific literature (see for instance [5] pagg. 944-945) and then correctly assessed by a parametric comparison (whose results are shown in the next section) between numerical and experimental results.

4 NUMERICAL RESULTS

Two groups of numerical results are presented. The first group was aimed at assessing the "optima" boundary conditions by comparing the numerical results with the experimental ones at the microphones depicted in Fig. 2a. The second group of results measure the influence of both the absorption property of the seat textile and the shape of the seat headrest on the noise reduction in the cabin.



(a) (b)

Figure 4: Model with lateral caps located at the headrests: coarse mesh (a), fine mesh (b).

4.1 *Comparison with the experimental results*

An experimental test was carried out at the laboratory of one of the partners of the project. An aircraft cabin was built and subjected to different acoustic sources. The results here presented refer to the loudspeaker located on the symmetry plane of the cabin at 1.42m from the floor. The SPL was measured at each octave band at the four microphones depicted in Fig. 2a. A numerical parametric study was performed in order to set the correct impedance of the various panels of the cabin. Some numerical experiments were conducted by changing the impedance of the panels in the cabin in order to measure the sensitivity of the numerical results with respect to the boundary conditions. For the sake of simplicity such a parametric analysis is here omitted and the main results only are summarised.

The ”optima” values of the absorbing coefficients are reported in Tables 1-2.

		f [Hz]										
		8	10	12.5	16	20	25	31.5	40	50	63	80
α	FLOOR	0.002	0.003	0.005	0.01	0.015	0.02	0.025	0.03	0.05	0.09	0.12
	REAR	0.002	0.004	0.007	0.01	0.014	0.018	0.02	0.03	0.04	0.05	0.1
	FRONT	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.15	0.2	0.3
	CEILING	0.001	0.003	0.005	0.005	0.01	0.01	0.01	0.02	0.03	0.05	0.07
	ARMRESTS	0.001	0.001	0.002	0.002	0.003	0.004	0.005	0.005	0.005	0.006	0.008
	SEATS	0.05	0.05	0.05	0.05	0.05	0.065	0.075	0.075	0.1	0.14	0.175

Table 1: Values of the absorption coefficient in the range 8-80 Hz.

		f [Hz]										
		100	125	160	200	250	315	400	500	630	800	1000
α	FLOOR	0.15	0.25	0.275	0.3	0.325	0.35	0.375	0.4	0.45	0.5	0.6
	REAR	0.15	0.2	0.23	0.26	0.3	0.34	0.37	0.4	0.45	0.5	0.6
	FRONT	0.6	0.9	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	CEILING	0.1	0.15	0.175	0.2	0.225	0.25	0.275	0.3	0.325	0.35	0.375
	ARMRESTS	0.01	0.02	0.021	0.023	0.025	0.029	0.036	0.05	0.06	0.08	0.1
	SEATS	0.210	0.49	0.509	0.533	0.565	0.614	0.689	0.8	0.817	0.84	0.88

Table 2: Values of the absorption coefficient in the range 100-1000 Hz.

All the above values, but the front panel, were kept fixed in the remaining numerical simulations. The comparison between experimental and numerical results with the above boundary conditions are depicted in Fig. 3. In the range 125-1000Hz the error is acceptable (from 0 to 15%) but it increases in the low frequency range 31.5-100Hz (no experimental results are available in the range 8-25 Hz). The higher error in the low frequency range is related to the fact that the low frequency response is mainly driven by the geometry of the model and not by the boundary conditions. In fact, only a slight difference in the numerical results was observed when changing the impedance at the low frequency range.

4.2 *Passive noise control*

A sensitivity analysis of the noise reduction in the cabin due to the seat's cover and shape was performed. First, the noise reduction related to a change in the seat textile's acoustic properties was investigated. Then, the results were compared with the new shape of the seat headrests obtained locating two lateral caps. Two new meshes (one up to 100Hz, the other one in the range 125-1000Hz) were considered (see Fig. 4) in order to include the lateral caps.

All the simulations were performed with reference to the above described experimental loudspeaker. Two new seat textiles, 10% and 20%, respectively, more absorptive along the entire frequency range, were investigated. The comparison was enriched by a change in the headrest shape. The comparison was carried out at the microphones. The noise reduction is depicted in Fig. 5. It is clear how the seat textile can influence the noise level in the cabin. The presence of the caps located laterally to the headrests is able to guarantee the best noise control. As it could be expected, the passive noise control is more effective in the high frequency range where it is possible to obtain up to 8 dB of reduction.

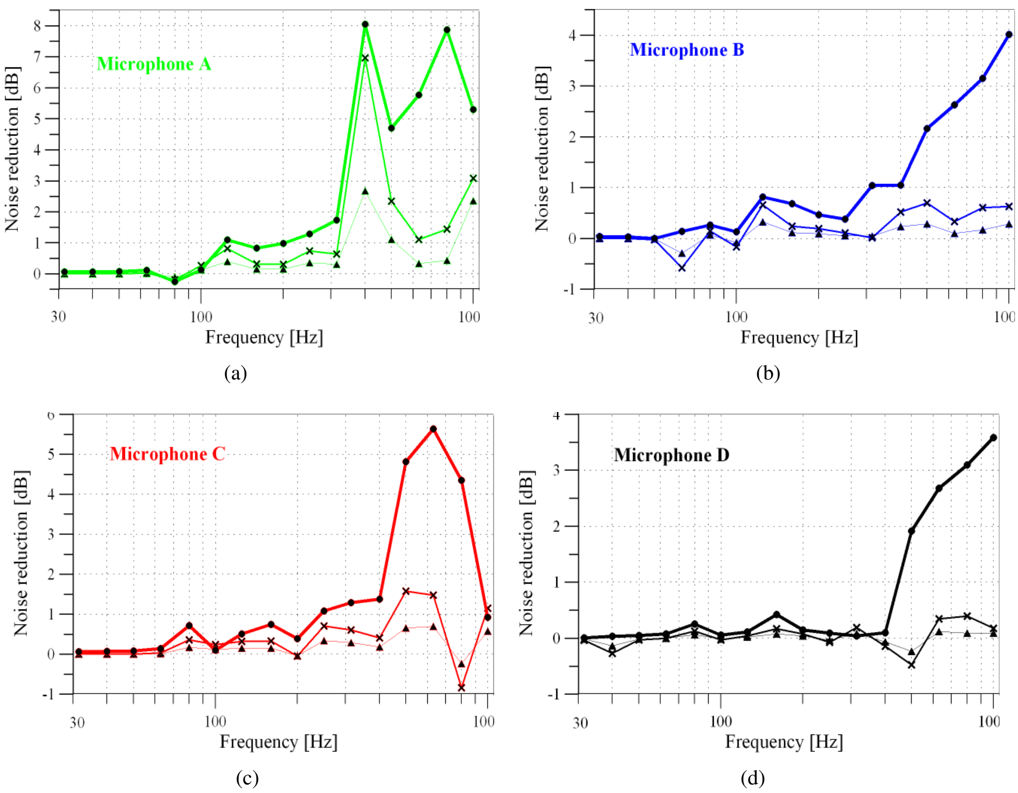


Figure 5: Noise reduction at the microphones. ▲ 10% more absorptive textile. × 20% more absorptive textile. ● Headrests with lateral caps.

5 CONCLUSIONS

The analysis of the noise reduction in the aircraft cabin obtained by adopting different seat textiles and headrest shape was carried out. The boundary conditions, i.e. the impedance of each panel of the model, were set on the basis of some experimental results. The numerical analyses were performed by using the 3D-BEM.

6 ACKNOWLEDGEMENT

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