Electro acoustic coupling in closed space

Pierre-Jean René

LEMA, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland, Email: pierre-jean.rene@epfl.ch

Introduction

The design of loudspeaker systems is usually undertaken under the assumption that load impedance is a radiation impedance into 2 or $4\pi sr$. This is not valid when the wave lengths at the frequencies used by the loudspeaker are of the same order of magnitude as the dimensions of confined space, for example for the low-frequency sounds in a room, control room, or in a technical volume in which active noise control is being carried out (engine nacelle), etc. The loudspeaker cannot be compared any more to a source of constant volume throughput: the flow depends not only on the system excitation but also on the source and load impedances. This requires better modelling of the electro acoustic coupling between the loudspeaker and room in which it radiates, particularly below the Schroeder frequency, where there are no or only few excited modes. Modal analysis of sound field in a room at low frequencies, based on the physics of the modal sound field with analytical and finite element methods, will be presented in this paper. Indeed the complete study of the sound field is necessary to determine the load impedance in front of the loudspeaker. The final objective is the calculation of the transfer function between the voltage at loudspeaker connectors and the acoustic pressure at any point of the closed space.

Steady state response in closed space

Every simulation or calculation can be validated only by measurements in exactly the same conditions. So first discussions about the three main variables of the problem are necessary. Firstly, the frequency range depends directly of the room size and moreover of the biggest dimension between two parallel walls. The frequency domain starts around 5 Hz, which is around the lowest frequency one loudspeaker can handle, to the 6th or 7th eigenfrequency. Secondly, the source chosen for calculation and measurement have to be dimensioned according to the output requirement in the low frequency domain. Last but not least comes the choice of the room, its three dimensions (for a rectangular room l_x, l_y and l_z) have to be different and their ratio should not be an integer to avoid eigenfrequencies regroupment [1]. Working with rigid-walled room simplify the problem since the wall impedance of standard rooms need time consuming studies to be precisely known. Indeed, in the chosen frequency domain, the wall behavior is closer to a plate vibrating than a rigid wall covered with a well known impedance material. Once all parameters are chosen, it is possible to represent the pressure at r, within the room, when excited by the loudspeaker of volume velocity q_ω at r_0. The relation can be written as follows:

$$p_s(r|r_0) = -\frac{i\omega\rho}{V} q_\omega \sum \frac{\psi_n(\omega, r)\psi_n(\omega, r_0)}{\Lambda_n({K_n}^2 - k^2)} \quad (1)$$

where $\psi_n(\omega, r)$ and ${K_n}^2$ are the eigenfunction and eigenvalue for the n^{th} $(n = nx, ny, nz)$ standing wave [2], Λ_n is a coefficient for each eigenmode determining its magnitude. As the effect of load impedance on the volume throughput was unknown, by default $q_w(r)$ was calculated for a monopole radiating in $2\pi sr$, the error made is shown further on. For calculations and measurements, we use an Audax HT210Fo loudspeaker mounted in a closed box which volume is $V_b = 34.8l$. To excite the maximum of eigenfrequencies, the source was placed in a corner of the room. To investigate on steady state response and confront measurements and calculations, it's clearer to work on axis rather than the whole room volume. The standard first eigenmodes shapes are well known with the minima on orthogonal symmetry axes and maxima near the walls. But for $\omega \neq \omega_n$, the sound pressure profile still presents minima as shown in the figure below.

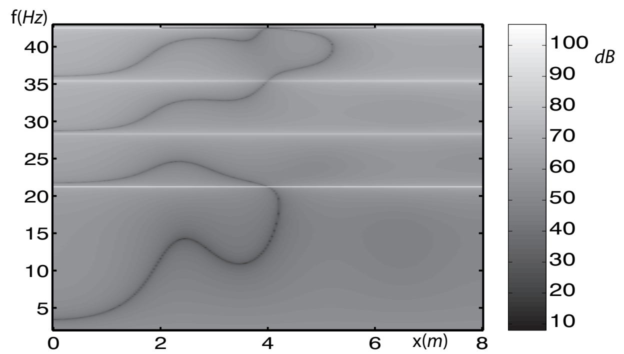

Figure 1: Sound level profile in a rectangular room along an axis.

It is interesting to note that the minima location depended on the location of the source, but near the source the minima were always at $f_n + \epsilon$ (see Figure 3).

Femlab simulation

As said before, a rigid-walled room was needed to have enough peaks level. Moreover their impedance had to be precisely known. That's the reason why, a reverberant room was chosen. But one new difficulty was that its shape was not a rectangle, no adjacent wall were orthogonal. A finite element method software like Femlab can manage various partial differential equations problem with this kind of shape. For the steady state sound field in the reverberant room D, the equations used in Femlab are the following (equation 2):

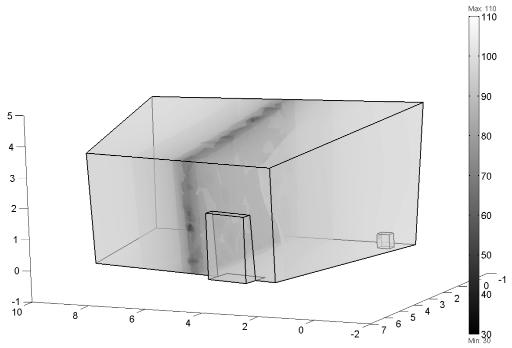

Figure 2: Reverberant room first eigenmode.

$$\begin{cases} \Delta p_\omega(r) + k^2 p_\omega(r) = 0 & \forall r \,\epsilon\, D \\ \nabla p_\omega(r) = 0 & \forall r \,\epsilon\, \delta D \\ \nabla p_\omega(r_0) = -\frac{i\omega\rho_0}{S_d} q_\omega(r_0) & \text{on loudspeaker membrane} \end{cases} \quad (2)$$

The loudspeaker was considered as a boundary condition more than a real source in the room. After modelling the room, eigenfrequencies were calculated and compared with measurements performed along a straight line right through the room. The first axial mode was at $20.37Hz$ with Femlab against $20.31Hz \pm 0.1Hz$ with meausurements. For the next eigenfrequencies, the confrontation between Femlab results and measurements showed increasing slight differences. To converge to a similar result, it could be useful to integrate in the boundary conditions the wall impedance and to evaluate the influence of the door impedance. The error due to finite element method has to be quantified.

Volume velocity modification

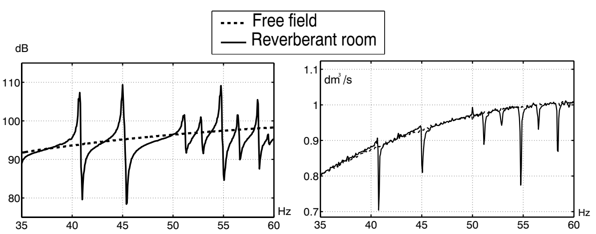

Figure 3: Sound level in the near field and volume velocity of the Audax loudspeaker.

Once the pressure profile is determined in the room, it is possible to calculate the reaction force on the loudspeaker. The measurements showed variations of the volume velocity when the speaker was located in a zone of peaks, like in the corners of the room. Two methods were retained to calculate the volume velocity modification. One of them consists in calculating, from the pressure in the near field of the loudspeaker, the space reaction force on the membrane ($F_r = pS_d$ where S_d is the membrane surface of the loudspeaker). With some iterations, the model quickly converge and we find the δq_w giving the corresponding δp_w (Equation 1). One other way to find the steady state volume velocity and pressure, is to determine the charge impedance, and then recalculate the complete system starting with Thiele and Small (TS) parameters of the loudspeaker, the source voltage and the room specifications (size and loudspeaker location) as shown in figure 4.

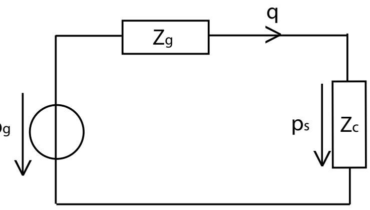

Figure 4: Equivalent schematic of the system.

Z_g depends on loudspeaker TS parameters and closed box dimensions; Z_c is the load impedance which depends on source and reception location, room dimensions and wall impedance [3]. p_g is directly linked to the voltage at loudspeaker connectors. Both Z_g and U_g can be considered as constants. Then the variables $p_{s\omega}(r)$ and $q_\omega(r_0)$ depends on Z_c.

Conclusion

In the preceding sections we have attempted to give the influence of load impedance on the loudspeaker. The main difficulty encountered with the steady state response study is linked with wall impedance which is the main disruptive factor. If the room geometry do not allow the analytical study, the finite element method can enable us to get similar results but the calculation time and the incertitude due to discretisation has to be taken into account seriously. The modification of the volume throughput of a loudspeaker is quite important when exposed on peaks zone of modal response, but the feedback on the sound pressure radiated seems to be much smaller. It will be very interesting to compare both different methods for determining the transfer function, the iterative method and the load impedance calculation. The further studies will be performed with different sizes of loudspeaker. Indeed as the feedback force of the pressure in the near field on the membrane depends on its surface, we can suppose that two loudspeakers of similar flow but different size will not be influenced in the same way. The behavior of the system in the time domain will be analyzed.

References

[1] Room Acoustics, Heinrich kutruff

[2] Theoretical acoustics, Morse and Ingard,McGraw-Hill,1968

[3] Traité d'électricité XXI Electroacoustique, Mario Rossi, Presses polytechniques Romandes,1986