Numerical model of the sound field inside cars for the creation of virtual audible reconstructions

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Abstract

The research undertaken aims to the development of a new numerical predictive technique, capable of producing such a detailed simulation, so that it can be used for the creation of "virtual" sound samples, theoretically indistinguishable from binaural recordings inside a real car. This way, a proposed (not existing yet) sound system could be compared with the existing ones by direct listening tests.

This paper describes the implementation of the numerical model, based on Boundary Elements for low frequencies and Pyramid Tracing for higher frequencies. The results of the two models are merged together, producing a binaural impulse response which can be convolved with the music signal. The performances of the system were evaluated by listening tests, in comparison with experimental measurements taken in a 1:5 scale model of a car compartment.

1 Introduction

The experimental binaural technique is commonly used nowadays for the subjective evaluation both of the noise and of the sound system inside vehicles, making it possible to collect conveniently the subjective response of many listeners. Furthermore, this technique avoids not-acoustical biases in the test results.

The auralization technique [1] is a more advanced implementation, based on the separate measurement of the binaural impulse responses and the subsequent convolution with suitable test signal (usually selected music samples); this way it is possible to check the sound system with any kind of different signals without the need to make measurement inside the car again.

Often it is required to estimate the behavior of a new model of car before than the first prototypes are built. As for many other aspects, also for the simulation of the sound fields it is possible to make use of numerical models as soon as a geometrical description of the car is available. Finite Element models have been used for a while with the goal of predicting the noise produced by the engine and other mechanical parts inside the compartment [2], but they are not suitable for producing wide-band impulse responses, as required for the auralization process. Hybrid models were recently proposed for this task, coupling finite elements with image sources models [3].

In this work, a classic Boundary Elements formulation is adopted at low frequencies, while at higher frequencies, where the boundary elements approach becomes computationally too heavy and the phase relationships are less important, a new geometrical acoustics algorithm is employed (pyramid tracing) [4]. Although both these techniques have proven to yield reasonably accurate results in their optimal frequency domains [5,6], the suitability of the results for the auralization approach has to be evaluated by means of subjective listening tests, in comparison with effective recordings inside the modeled cars. In particular, the most delicate task is the proper merging of the results of the two simulations, which have to be converted in a single, wide-band binaural impulse response.

A test case on a highly simplified geometry was studied first: an 1:5 scale model of a car compartment was employed for the binaural measurements, excited by four small tweeters emulating a standard sound system; an 1:5 human head and torso, equipped with auricular microphones, was placed at the driver's position. The binaural impulse responses were measured through the MLS technique for each loudspeaker [7]. The same simplified geometry was then employed for the numerical simulations: two impulse responses were obtained (low and high frequencies), and they were joined together at the crossing frequency, making use of a standard digital waveform editor.

Thereafter, the impulse responses (both experimental and numerical) were used as numerical FIR filters, applied by convolution to the same original signals. The convolved signals were then comparatively evaluated thanks to a panel of selected subjects.
In the paper, details about the two numerical models are given, with mayor emphasis about the techniques for merging the results and transforming them in wide-band pressure impulse responses. Then the results of the experiment are reported and discussed, and a foreword of the future work is given.

2 Experimental measurements

MLS measurements were conducted in a scale model of a FIAT Cinquecento car, built with flat plexiglass panels and acoustically dampened by means of soft tissue tiles applied on a part of the internal surfaces. The geometry was very simplified in comparison with the true car, and also the distribution of the materials is quite simple, as only two boundary conditions have to be taken into account.

Two small loudspeakers, originally designed for notebook computers, were placed at the sides, and fed with continuous MLS signals coming from a MLSSA board. The response of the compartment was measured through two miniaturized (1/4”) microphones placed at the ears of a scaled human mannequin, made of wood. The sampling rate was 120 kHz, which correspond to a theoretical maximum frequency of 12 kHz. In practice, anyway, due to the limited frequency range of both the loudspeakers and microphones, and to the presence of the anti-aliasing filters on the MLSSA board, the scaled frequency response reaches only 8 kHz. These are enough, anyway, for reasonable auralization tests.
Figure 1 is a photograph of the scale model, taken during its construction, when it was almost finished. *Figure 2* shows the binaural impulse response measured at the driver’s seat, and *Figure 3* the corresponding frequency response spectra.

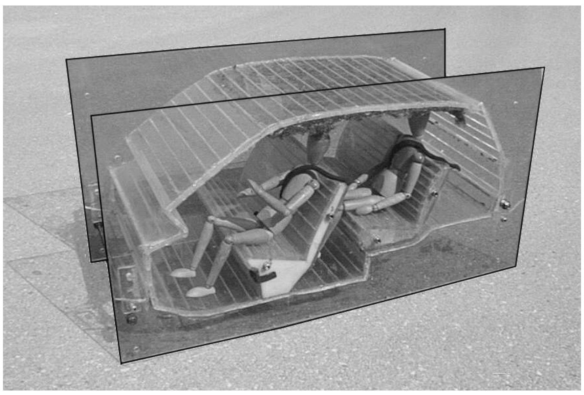

Figure 1 – 1:5 plexiglass scale model

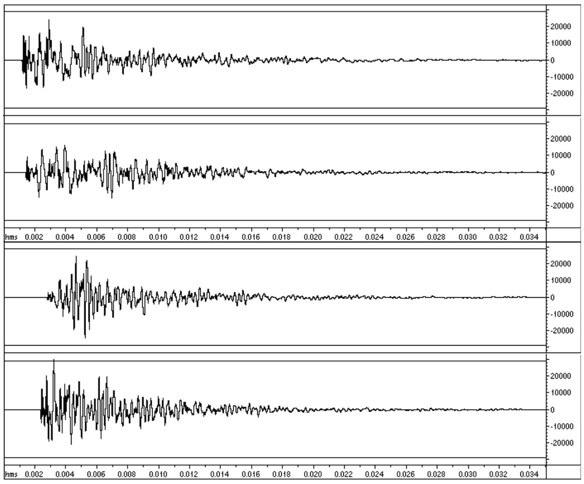

Figure 2. Experimental binaural impulse responses – Left speaker (above) and right speaker (below)

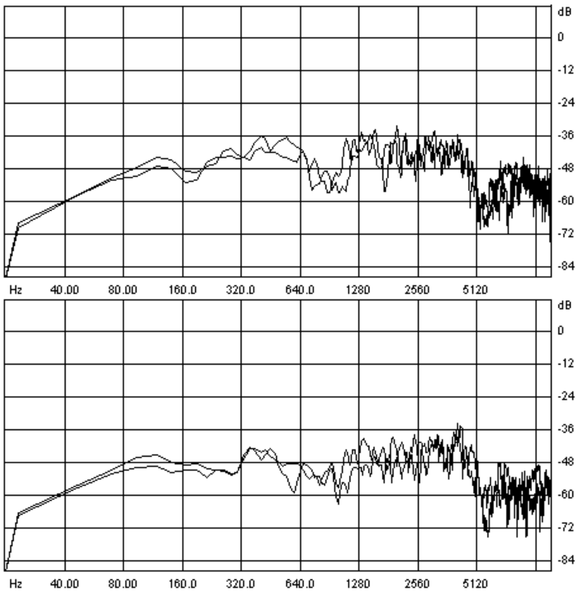

Figure 3 .Experimental binaural frequency responses –

Left speaker (above) and right speaker (below)

3 Numerical simulations

3.1 Low Frequency – Boundary Elements

A commercial Boundary Element software (BEASY) was employed for the low-frequency simulation, up to 500 Hz. The higher frequencies were studied by means of the Pyramid Tracing program Ramsete.
Both these models make use of the same geometrical description of the car compartment, made of 76 planar rectangles, as shown in *Figure 4.*

The Boundary Element simulation was conducted at 2 Hz increments, from 100 to 400 Hz. The complex acoustic impedance of the two boundary materials (plexiglass and soft tissue) were measured in a standing wave tube following the ASTM 1050-E standard. The loudspeakers were modeled as rigid pistons. The complex acoustic pressure was obtained at two selected points, located at the position of the driver's head. The human body of the driver was not modeled at all for the low frequency simulation. The pressure impulse responses were obtained by inverse Fourier transformation of the complex pressure spectra, after proper frequency-domain interpolation, for yielding the required time resolution corresponding to a sampling frequency of 24 kHz.

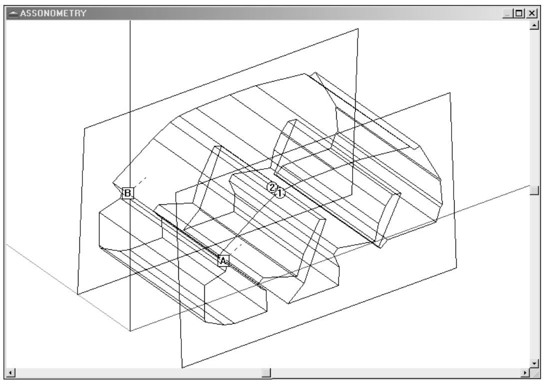

Figure 4. 3D surface model for numerical computations

3.2 High Frequency – Pyramid Tracing

As the frequency increases, the boundary elements should become smaller and smaller, in such a way that their longest side is always less than ¼ of the wavelength. This complicates the geometrical modeling, and it takes a lot of time to make the computations with very detailed surface grids.

Thus, above 400 Hz, a very different numerical approach was employed: in the hypothesis that the surfaces are large compared to the wavelength, the geometrical acoustics assumptions are accepted. Three kinds of numerical models exist under these assumptions: Image Sources, Ray Tracing and Beam Tracing.

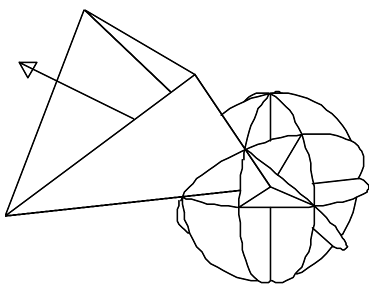

Figure 5. Generation of pyramidal beams

Pyramid Tracing is a particular case of the Beam Tracing computing scheme, in which the acoustic energy travels within "waveguides" having form of triangular beams. The whole energy radiated inside each pyramid always follow the path of the central axis of the pyramid, without interaction with the adjacent pyramids. *Figure 5* illustrates the scheme for the generation of pyramids from an ideal point source, as implemented in the employed Ramsete program [4,6].

As only the energy of the sound wave is taken into account, the boundary surfaces are characterized simply by their acoustic absorption coefficients in octave bands. Furthermore, the contributions which arrive at a receiver point within the same time slot are summed energetically, with no regard of their relative phase. It is obvious that these simplifications are reasonable only for wide-band, random noise, in absence of resonance or interference effects. Only at high frequencies these hypotheses are suitable for musical signals reproduced by loudspeakers.

3.3 Conversion to wide-band pressure impulse responses

Ramsete (as many other Ray Tracing or Beam Tracing programs) produces energy impulse responses of unlimited length, sampled at intervals typically of 1 ms or less; a separate response is computed for each octave band (31.5 to 16000 Hz). To obtain reasonably good binaural simulations, two receivers must be located at the sides of a sound diffracting sphere, approximating two ears. In this way, the response in one receiving point is a couple of arrays, each of them with 10 columns (the frequency bands) and some hundreds or thousands of rows (the time intervals).

It is necessary to convert each of these two arrays in a single pressure response, with a bandwidth of 20 Hz to 20 kHz, sampled at 44.1 or (better) 48 kHz. Usually these impulse responses are stored in standard WAV format, or in proprietary Impulse Response formats as the TIM format of the MLSSA system. Powerful software tools already exist, enabling any kind of mathematical manipulation of these pressure response files, as the Cool Edit program here employed.

The conversion process begins with the generation of a sample of white noise with proper length and sampling rate, covering the impulse response duration. Ten copies of this white noise signal are made, and each of them is "modulated" with an amplitude envelope obtained by the square root of the energy impulse response in the corresponding frequency band. After this, each modulated white signal is passed through a 6-pole IIR digital octave filter, centered on the corresponding frequency. The ten filtered signals are then summed together, obtaining a wide-band pressure response. Eventually, the result is normalized and converted to 16-bit integer.

Although this process can be criticized in many ways, it is very fast and produces impulse responses that exhibit the same energy/time curves, the same reverberation times, and almost exactly the same objective acoustical parameters as the original energy responses. Obviously this is not enough to be accepted as realistic for audible simulations: a subjective evaluation need to be made for this.

4 Numerical results

After the computation were made with both numerical models, the wide-band impulse responses obtained were merged together through the editing capabilities of the shareware program Cool Edit. In more detail, the low-frequency impulse responses obtained from the boundary element program were low-passed with a 10^{th} order Butterworth filter having a cut-off frequency of 400 Hz. Similarly, the Pyramid Tracing results were high-pass filtered. Then the impulse responses were mixed together, after temporal alignment of the first non-zero samples corresponding to the arrival of the direct wave.

In this way, two binaural impulse responses were obtained (one for each sound source), as shown in *Figure 6*. *Figure 7* shows the computed spectra, obtained by FFT transformation of the impulse responses.

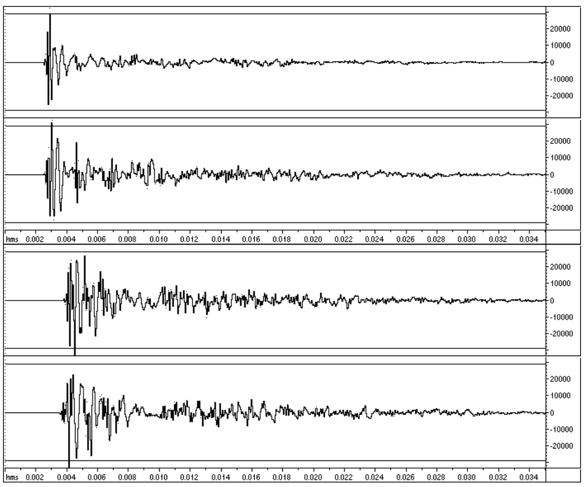

Figure 6 – Simulated binaural impulse responses Left speaker (above) and right speaker (below)

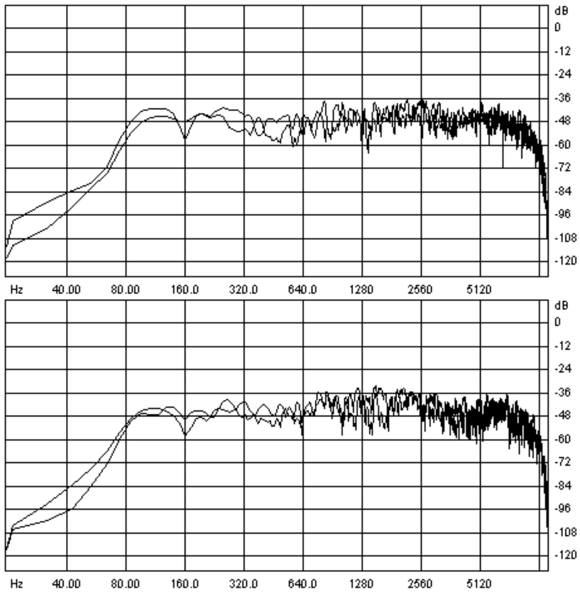

Figure 3 – Simulated binaural frequency responses – Left speaker (above) and right speaker (below)

5 Subjective listening tests

Although a direct comparison with the experimental results (*Figure 2* and *Figure 3*) is possible, the effectiveness of the numerical simulations has to be ascertained by subjective listening tests.

A preliminary, informal test was made, asking simply to 5 subjects if they were able to recognize as different two sound samples listened by headphones: one of them was obtained from the auralization of the experimental measurements, the other from the numerical simulations.

All 5 subjective recognized immediately the sound samples as different, so it was clear that the simulation results were not so good to “fool” anyone. Nevertheless, it was important to establish what are the reasons for the differences, and thus a more detailed comparative test was employed, as already described in [1] for the comparison of the auralization of different cars.

In practice, each subject seats in front of a personal computer, where a specially-made software presents him a series of sound samples. The user can listen at each sound sample at will, filling up a software questionnaire made of 9 counterposed-attributes scales.

The results of this second phase are not available yet at time of writing, but they will be presented at the DAFX-98 conference.

References

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