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Implementation of a double StereoDipole system on a DSP board - Experimental validation and subjective evaluation inside a car cockpit

Christian Varani[1], Enrico Armelloni[1], and Angelo Farina[1]

[1]Department of Industrial Engineering, University of Parma, Via delle Scienze 181/A, Parma 43100 Italy

ABSTRACT

Car cockpit is a critical environment for music; sound reproduction is in fact quite conditioned by reflections, echoes, engine noise and loudspeakers' set up. An important technique to improve sound comfort is a spatial equalization where both magnitude and phase of signal are controlled. This technique is performed by a stereodipole system where two closely loudspeakers are setting in front of listener and digital processing is performed real-time by a DSP board. Cross-talk cancellation is achieved using FIR filters, whose coefficients are obtained by inversion of the measured cockpit impulse response. In this paper an experimental validation of a double stereodipole system, one for driver and other for passenger, is performed by subjective evaluations inside a commercial car.

1. INTRODUCTION

Reproduce music inside a car cockpit is a difficult task, to improve sound comfort some technique are possible, here, one of that, spatial equalization is investigated.

This technique is performed by a stereo dipole system where two closely loudspeakers are setting in front of listener. The worse defect of a stereophonic system, ?, is the cross-talk effect at the listener ears due to loudspeakers. Cross-talk, that usually is not present in the music recording and is an artifact of a stereophonic reproduction, is a bad reproduction of sound at a location where it is not intended to be heard. For example the sound emitted from the left loudspeaker and heard at the right ear is a cross-talk. An opportune cross-talk cancellation is necessary to widen the stereo sound stage. Furthermore an equalization of the acoustic pressure response in the frequency domain allows achieving a good spatial equalization inside cockpit.

In this implementation two stereo dipole systems was set inside a commercial car, one for driver and other for passenger. Digital processing was performed real-time by a commercial ADSP 21161 EZKit Lite platform, an evaluation board supplied from Analog Devices. Crossover filter, cross-talk cancellation and acoustic equalization were obtained using filters based on a FIR structure, while inverse filter coefficients was calculated after Kirkeby theory.
Car audio system was modified setting two couple of closely loudspeakers in front of driver an passenger seats for reproducing frequencies above 500 Hz, while frequencies below were reproduced by typical car system. Some measurements were performed, by a B&K binaural dummy head, to obtain Head Related Transfer Function at driver position and passenger one. Evaluating them, opportune inverse filters were designed and implemented on the DSP platform.
Afterwards listening tests were performed inside the car cockpit to evaluate differences between a typical Hi-Fi system and new stereo dipole one. Subjective results show how a stereo dipole configuration achieves a better harmonization of the sound with respect to typical configuration. Listeners appreciated wider sound stage too.

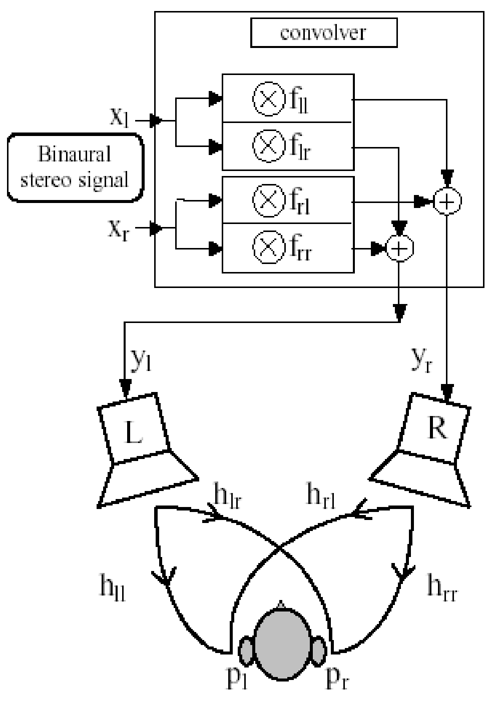

Figure 1: cross-talk canceling scheme.

2. CROSS TALK CANCELLATION AND STEREODIPOLE

The approach employed here is derived from the formulation originally developed by Kirkeby and Nelson [1], with refinement from one of the authors [2]. Figure 1 shows the cross-talk phenomenon in the reproduction space.
The 4 cross-talk canceling filters *f*, which are convolved with the original binaural material, have to be designed so that the signals collected at the ears of the listener are identical to the original signals. Imposing that pl=xl and pr=xr, a 4x4 linear equation system is obtained. Its solution yields:

$$\begin{cases} f_{ll} = (h_{rr}) \otimes InvDen \\ f_{lr} = (-h_{lr}) \otimes InvDen \\ f_{rl} = (-h_{rl}) \otimes InvDen \\ f_{rr} = (h_{ll}) \otimes InvDen \\ InvDen = InvFilter(h_{ll} \otimes h_{rr} - h_{lr} \otimes h_{rl}) \end{cases}$$

The problem is the computation of the InvFilter (denominator), as its argument is generally a mixed phase function. In the past, the authors attempted [3] to perform such an inversion employing the approximate methods suggested by Neely & Allen [4] and Mourjopoulos [5], but now the Kirkeby-Nelson frequency-domain regularization method is preferentially employed, due to its speed and robustness. A further improvement over the original method consists in the adoption of a frequency dependent regularization parameter. In practice, the denominator is directly computed in the frequency domain, where the convolutions are simply multiplications, with the following formula:

$$C(\omega) = FFT(h_{ll}) \cdot FFT(h_{rr}) - FFT(h_{lr}) \cdot FFT(h_{rl})$$

Then, the complex inverse of it is taken, adding a small, frequency-dependent regularization parameter:

$$InvDen(\omega) = \frac{Conj[C(\omega)]}{Conj[C(\omega)] \cdot C(\omega) + \varepsilon(\omega)}$$

In practice, ε(ω) is chosen with a constant, small value in the useful frequency range of the loudspeakers employed for reproduction (100 – 20k Hz in this case), and a much larger value outside the useful range. A smooth, logarithmic transition between the two values is interpolated over a transition band of 1/3 octave.

In figure 2 is depicted a stereodipole system, and is shown the angle between the speakers.

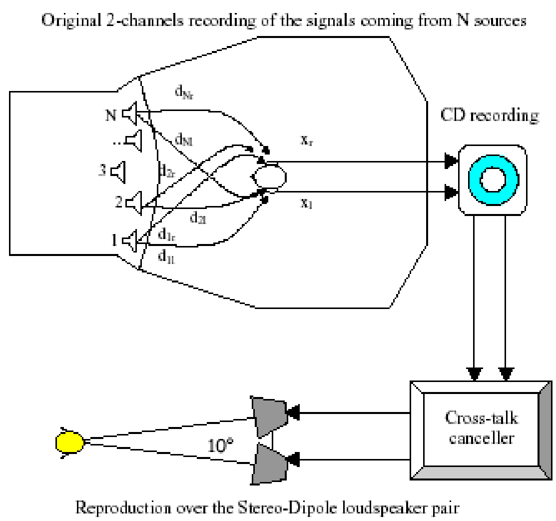

Figure 2: Stereodipole reproduction through cross-talk canceling digital filters.

3. DOUBLE STEREODIPOLE SYSTEM

Traditional car audio system was modified setting two couple pairs of closely loudspeakers in front of driver an passenger seats, it is shown in figure 3. This setup was used for reproducing frequencies above 500 Hz, while frequencies below were reproduced by typical car system.

Figure 3: Position of loudspeakers in stereodipole configuration.

To implement the system, no interaction between two stereodipoles was supposed.

Stereodipoles setup and reproduction layout are shown, respectively, in figure 3 and 4.

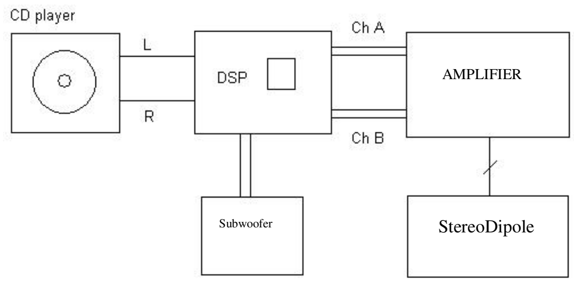

Figure 4: Reproduction layout.

In figure 5 shown connections about power amplifier used.

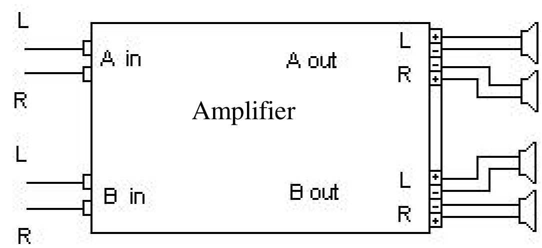

Figure 5: Connection layout for amplifier to stereodipole.

Inverse filters to obtain cross-cancellation were designed from binaural impulse response measured inside of car cockpit. They were implemented on 21161N DSP board. On this DSP board cross ? further filters for subwoofer and volume control for each channel was implemented too.

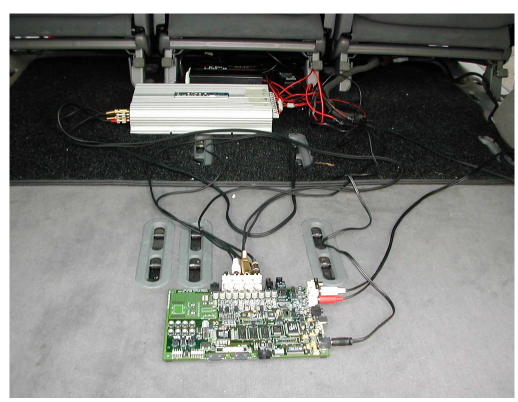

Figure 6: DSP board and amplifier.

In order to perform IR measures a Bruël & Kaer 4100 dummy head was used, equipped with Falcon 4190 50mv/Pa microphone and suitable pre-amplifier.

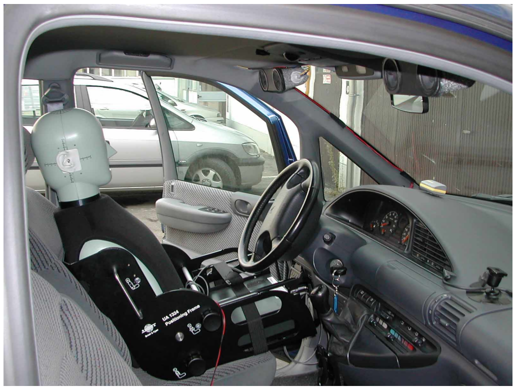

Figure 7: Recording system with binaural dummy.

Figure 9: Spectrum of one direct path and cross path.

4. MEASUREMENTS

The measurements performed with the dummy head have allowed computing the HRTF too; therefore a more accurate stereodipole system could be synthesized.

Measures were employed two times, before to get IR and after to verify the exact cross-talk cancellation on the driver and the passenger's seats, using digital filters.

Figure 8 shows the measured impulse responses of the system, corresponding to the 4 impulse responses referred to as *h* in figure 1.

These measures were used to design inverse filters, obtained employing a CoolEdit plug-in.

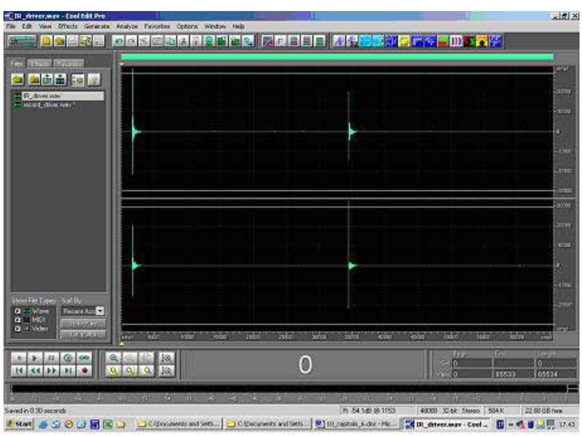

Figure 8: Impulse response of car cockpit.

Frequency responses of direct path (right-to-right) and cross path (right-to-left) are shown in figure 9.

The following figures (figure 10 and figure 11) show how the inverse digital filters work. Impulse responses were measured inserted in reproduction chain DSP board, so digital filters are depicted in figure 10. It is easy noting how cross-impulse responses (left-to-right and right-to-left) are noticeably lower than direct ones.

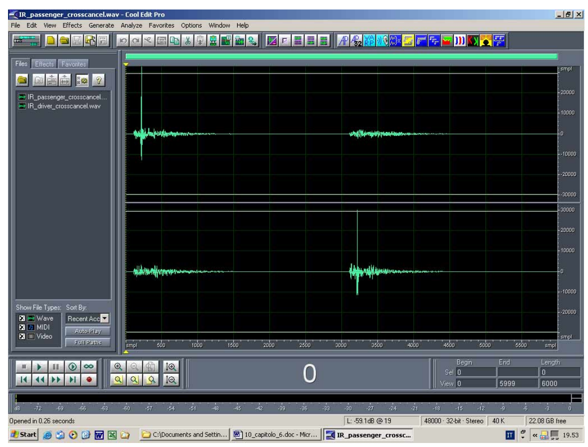

Figure 10: Impulse response measured with digitals filters.

This appreciable cross-talk cancellation is also obvious in figure 11, which shows the frequency responses of direct path and cross path.

Is possible checking how the spectrum of cross path is 10 dB lower than direct spectrum across the whole spectrum.

Figure 11: Spectrum of one direct path and cross path with digital filters.

5. EXPERIMENTAL LISTENING AND SUBJECTIVE TESTS

After impulse responses measurements, also an experimental listening and a subjective test were performed. Task of these tests were to evaluate the perception of the position of sound source comparing two different reproduction systems inside the car: a traditional and a steredipole system.

5.1. Experimental listening test

Procedure used to perform this test was first, recording a source sound positioned in specific points around the binaural dummy head, and then reproducing the recording on the stereodipole system. The subject listening to the recoding reported where he or she actually perceived the origin of the source sound.

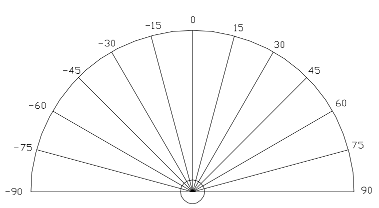

Figure 12: Position of sound sources.

Evaluation of results is reported in the next graphs, where the abscissa axis represents the real position of source sound and the ordinate axis represents the perceived position. The ray of the circles is proportional to the percentage of people who perceive the sound source in that position. The interpretation of graphs is simple: if the system works well then the circles with greater percentage will be located on the diagonal.

To evaluate the actual interference between the two stereodipoles the tests are done like this:
Sitting on the driver's seat with only driver's stereodipole "on" (figure 13); sitting on the passenger's seat with passenger's stereodipole "on" (figure 14); and then sitting on both seats with both stereodipoles "on" at the same time (figure 15, 16).

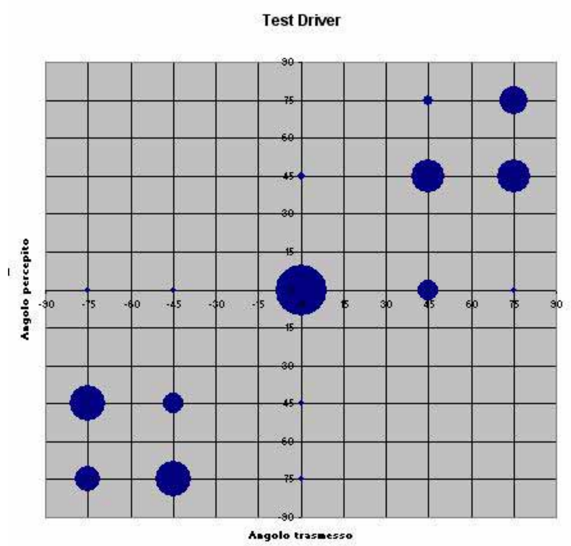

Figure 13: Graph of sound perceiving for driver position with only stereodipole driver "on"

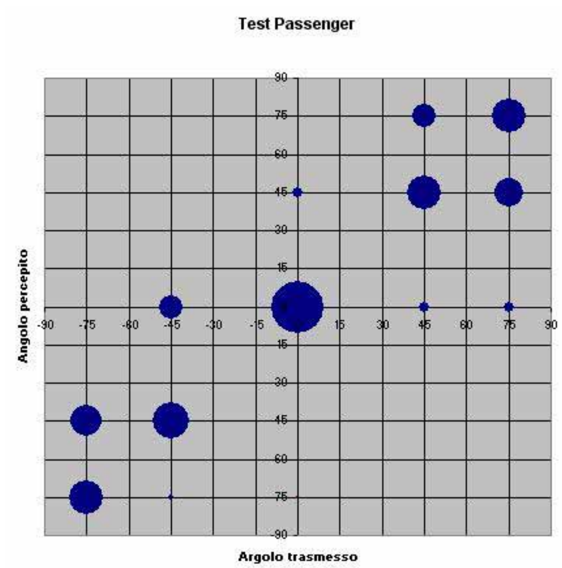

Figure 14: Graph of sound perceiving for passenger position with only stereodipole passenger "on".

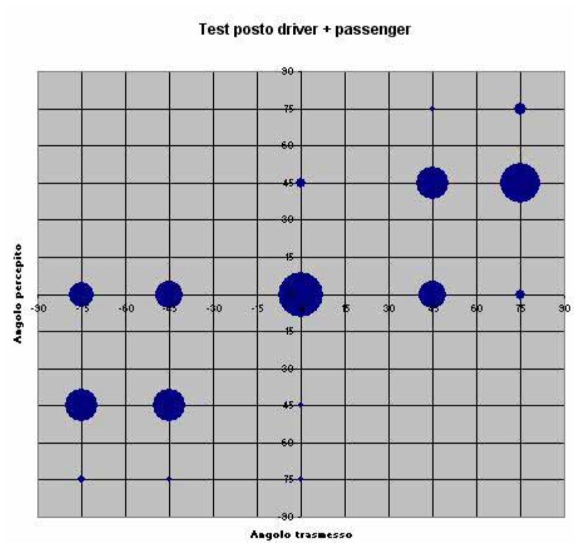

Figure 14: Graph of sound perceiving for driver position with both stereodipole "on".

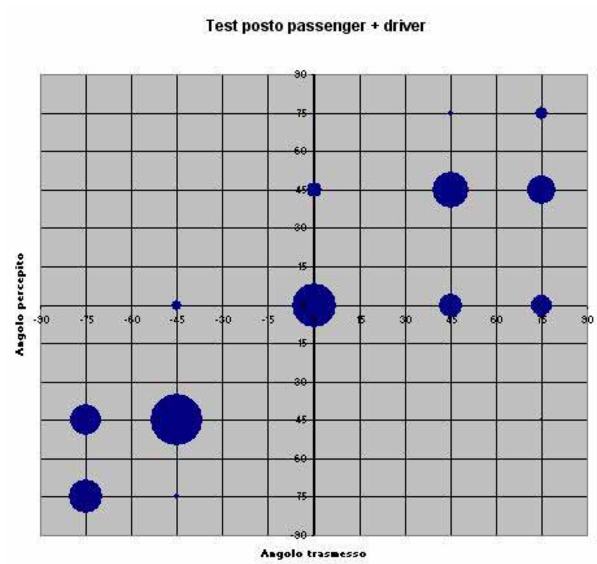

Figure 15: Graph of sound perceiving for passenger position with both stereodipole "on".

When only a single systems (driver or passenger) was working, sound front and the positions of source sounds was correctly perceived. While when both systems were switched "on" an interaction between two stereodipoles, is present. Figure 15 and 16 show, in fact, a little "smearing" of the results. And the sound perceiving stops at 45°.

5.2. Subjective test

Subjective tests were performed to collect data of some listeners, in order to compare two different reproduction systems inside the car: a traditional and a steredipole system.
People, selected with a test that marks them like "good listeners", answered to question concerning sound quality, localization and harmonization. The test was composed by the evaluation of the following quality benchmarks:

1) Initial sensation of the sound;
2) Musical scene localization (voice and instrument position);
3) Width of sound front;
4) Naturalness of sound reproduction;
5) Low frequency response;
6) Medium frequency response;
7) High frequency response.

The value reported is the mean score. It is easy to observe that an increase of the score is occurred, using the stereodipole system (black histogram).
This confirms the effectiveness of the proposed approach.

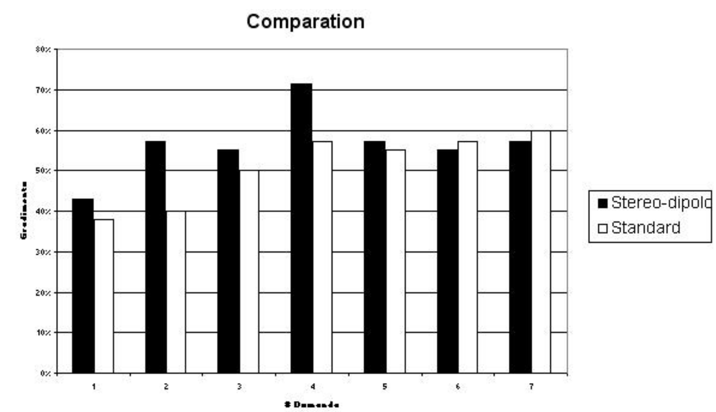

Figure 16: Comparison between stereodipole system and classic system reproduction.

6. CONCLUSIONS

The stereodipole was implemented on a commercial ADSP 21161 EZKit Lite platform supplied from Analog Devices. Kirkeby's theory was used for design filter to perform cross-talk cancellation.
This system was inserted in a car audio system, and it was also modified using two pairs of closely loudspeakers in front of fore seats for reproducing frequencies above 500 Hz.
Listening test was performed to evaluate the perception of the position of sound source inside the

car and compare two different Hi-fi reproduction systems: a traditional and a steredipole system.
Analysis of results of these tests, points out how the stereodipole system turns out to be able to emphasize sensations such as localization of sound source and naturalness of sound reproduction.
Future developments of this work could be about position of stereodipoles inside the car and about inverse digital filters.
With some improvements, the stereodipole system could even replace a classic reproduction system in a car cockpit

7. REFERENCES

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