SUBJECTIVE EVALUATION OF ACTIVELY CONTROLLED INTERIOR CAR NOISE

M. de Diego, A. González, G. Piñero, M. Ferrer[*]

Dept. of Comunicaciones
Universidad Politécnica de Valencia
Camino de Vera s/n, 46022, Valencia, Spain
email: mdediego@dcom.upv.es

J.J. García-Bonito

IDIADA
Inst. Automotive Application Research
L'Albornar-43710 Santa Oliva
Tarragona, SPAIN

ABSTRACT

This work is a preliminary study which focused on subjective improvements of vehicle interior noise by using active noise control techniques. A local active noise control system has been mounted inside a room in order to reduce synthesized and real engine noise in the area around the headrest of a typical car seat. Recordings before and after cancellation have been made using a *Head Acoustics* mannequin positioned in the seat with two calibrated microphones at the ear-canals. Two methods were used to evaluate the comfort improvements achieved by active noise control. First, a prediction model of comfort based on four psychoacoustic descriptors (loudness, roughness, sharpness and tonality) was applied. Secondly, the subjective evaluation of controlled signals was carried out by means of a jury test. The reduction of noise levels does not necessarily reduce the annoyance of car engine noise, that depends on spectral characteristics of noise.

1. INTRODUCTION

Usefulness of active noise control methods for low frequency noise reduction have been extensively shown in numerous works [1][2][3]. However, the final objective of active control inside a vehicle should be to achieve a more pleasant psychological sensation, in automotive industry words this means to improve the comfort sensation. Therefore, it seems necessary to analyze how active control influences comfort sensation.

Numerous factors affect human sound perception and play an important role in subjective sensations. In this work we analyze the subjective sensation caused by an active control system working inside an enclosure by means of two strategies: a jury test and a predictive comfort model [4] that uses some known psychoacoustic parameters. Our objective is to somewhat evaluate subjective improvements afforded by active noise control in car interiors and also to get some valuable information in order to predict its behavior in general cases. Four psychoacustic parameters have been considered: loudness, sharpness, roughness and tonality [5][6]. A prediction model of the noise pleasantness has been used in this preliminary study.

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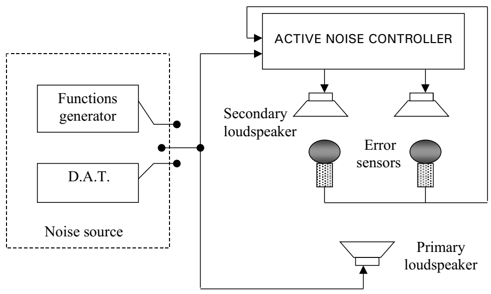


Fig. 1. Schematic diagram of the 2:2 ANC system (two secondary sources and two error sensors).

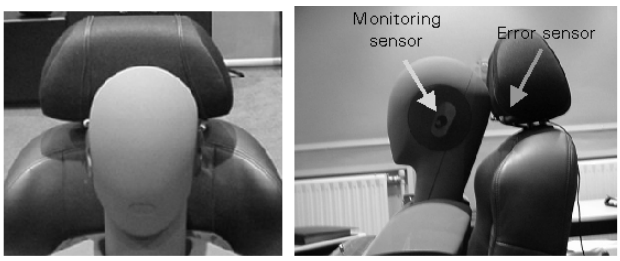


Fig. 2. Mannequin seated on the car seat illustrating the relative position of the error and monitoring sensors.

2. ANC PROTOTYPE DESCRIPTION

The local active noise control (ANC) system was tested in a listening room of dimensions 7.35 m x 4.16 m x 2.59 m. Two error sensors were mounted on the headrest of a typ-

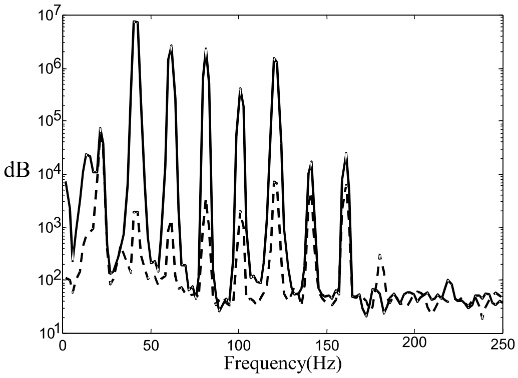


Fig. 3. Power spectral density of the signal measured at the left mannequin's microphone in the 2:2 system before the ANC operation (solid line) and after the ANC operation (dashed line) with real engine noise. Arbitrary units. Sampling rate 500Hz. Cut-off frequency 150Hz.

ical car seat. The primary loudspeaker and the two secondary sources were located facing the seat in the direction of the largest horizontal dimension of the room. Figure 1 shows an schematic diagram of the ANC system (2:2 system). Reference signals were generated using alternatively a DAT player or a HP function generator. The multichannel control algorithm was the Multiple Error LMS [1], implemented on a DSP card. Recordings were made using a *Head Acoustics* torso with two calibrated microphones, see figure 2. A similar experiment was developed by the authors in [2].

Different primary signals have been considered in the local ANC system. The synthesized signals were generated using the HP function generator: single tones, engine noise (repetitive noise with harmonics of 10, 20 and 25 Hz) and random noise. Real engine noise (idling, constant speed and acceleration signals) was recorded using the DAT recorder. As an example, figure 3 shows power spectral density measured at the left monitoring microphone (left ear) using the 2:2 ANC system with real engine noise as reference signal.

3. PSYCHOACOUSTIC PARAMETERS

Four psychoacoustic parameters [5][6] have been considered to evaluate the comfort produced by the noise with and without the application of ANC techniques:

- **Loudness**: It represents a dominant feature for any sound quality evaluation. It can be calculated by the ISO 532B norm and it is measured in *sone*.
- **Sharpness**: It represents an attribute for the evaluation of tone color. High values of sharpness indicate significant spectral components at high frequency. On the other hand, the addition of more low frequencies can reduce the sharpness value. Units are *acum*.
- **Roughness**: It represents the human perception of temporal variations of sounds. In this sense, it arises from amplitude modulation as well as frequency modulation of the sound, and depends on the modulation frequency (in the range of 20 to 300 Hz), modulation depth and sound pressure level. Roughness is measured in *asper*.
- **Tonality**: It is used to measure how many pure tones components has the noise spectrum.

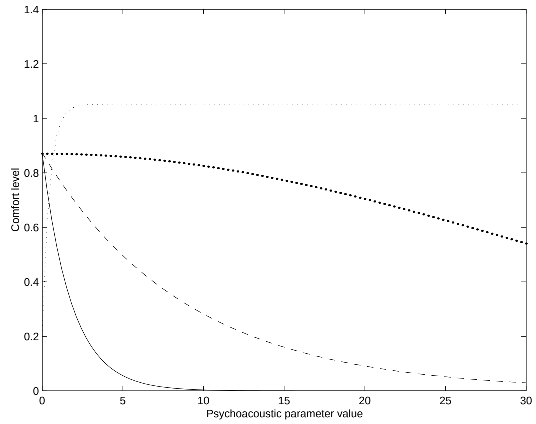


Fig. 4. Estimated comfort variation depending on psychoacoustic parameters changes: Roughness (solid line), Sharpness (discontinuous line), Loudness (thick dotted line) and Tonality (thin dotted line).

In this preliminary research an empirical model described in [4] has been used to estimate the comfort improvements using ANC systems. This model is a function of the parameters described above:

$$W = e^{-0.55R} e^{-0.113S} (1.24 - e^{-2.2T}) e^{(-0.023L)^2}, \quad (1)$$

where R is the roughness, S is the value of sharpness, T is the tonality parameter and L represents the loudness. W is the comfort descriptor which increases when estimated comfort improves. Figure 4 shows relationship between each independent psychoacoustic parameter and the W term (the other parameters are fixed). The greater sharpness, loudness or roughness the less the term W. On the contrary, W increases with tonality. Also it can be observed how sensitive is the model to sharpness and tonality changes.

4. EVALUATION OF COMFORT USING THE AURES MODEL

In order to evaluate how ANC affects comfort, the recorded noises before and after control using the *Head Acoustics*

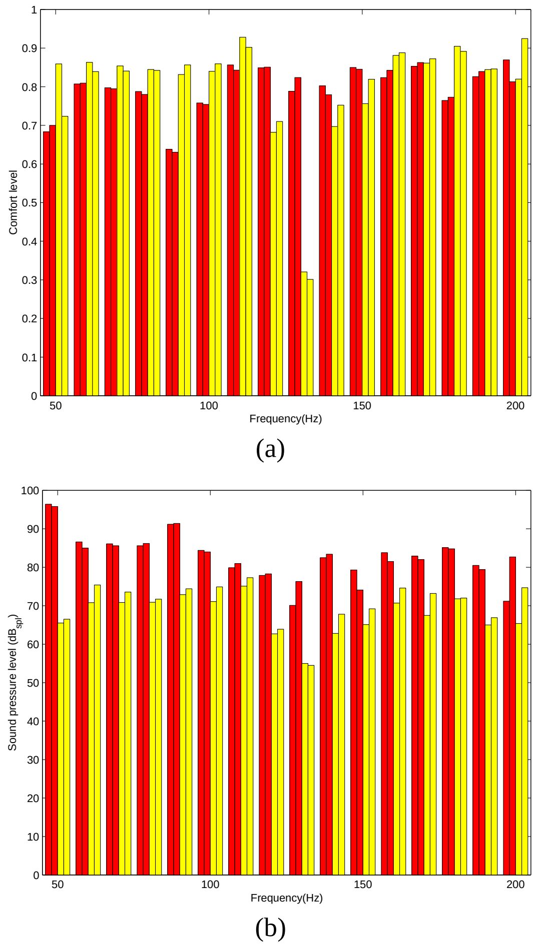


Fig. 5. (a) Comfort estimation obtained with Aures model and (b) noise pressure level, before (dark bars) and after (light bars) using ANC system. Measurements related to right canal (first bar) and left canal (second bar) of the mannequin.

mannequin were analyzed. After ANC operation, loudness changes improved comfort sensation. This is due to the fact that to minimize error signal power implies to reduce sound pressure level which consequently improves comfort, see figure 4. Changes of the other psychoacoustic parameters due to ANC did not provide estimated comfort improvements.

Figure 5 shows the estimated comfort (5.(a)) and the sound pressure level (5.(b)) for single tones from 50Hz to 200Hz with 10Hz steps before (dark bars) and after (light bars) using the ANC system. The first bar of each couple is related to the measurement obtained at different mannequin's ears (right ear-first bar and left ear-second bar). Clearly noise level always decreases but comfort does not. None the less, ANC should not be considered harmful for comfort improvement. A good explanation of this fact is that single tones are yet considered quite pleasant by the

Signal	Attenuat.(dB)	Comf.	Comf.(%)
Idling	-12.50	-0.27	-39
Accelerat.	-6.83	0.01	1.8
Const. speed	-7.20	0.02	9.5
Random	-13.20	0.08	38.1

Table 1. Attenuation achieves for different signals and estimated comfort improvements using ANC. Recordings at the left ear of the mannequin.

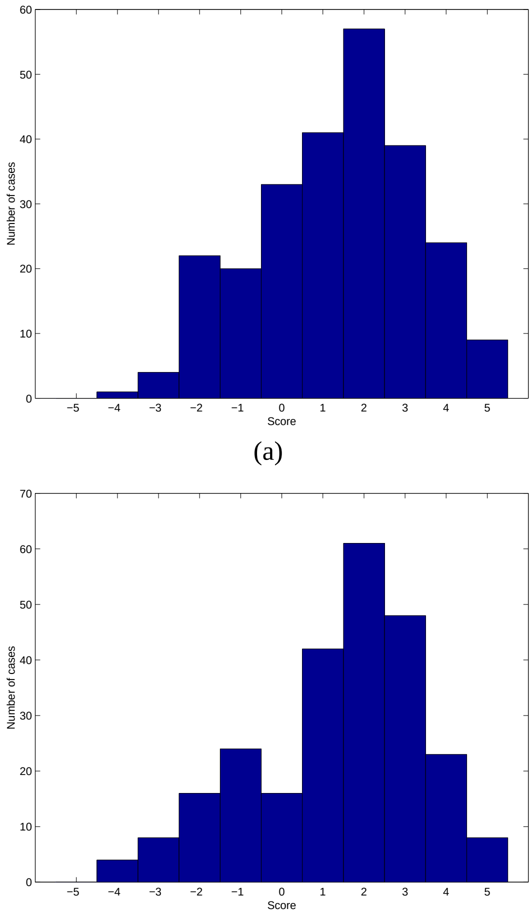
Aures model before applying ANC. However, ANC reduces noise power levels making residual noise poor in tonal components. That implies that loudness level decreases, related with noise power level. On the other hand, roughness, tonality and sharpness changes impair estimated comfort (roughness and sharpness increase, and tonality decreases), see figure 4.

In addition to single tones and synthesized repetitive noise, real car engine noise (idling, constant speed and acceleration) and random noise have been also used as reference signals. Table 1 shows attenuation and differences of estimated comfort after applying ANC. The percentage of comfort improvement is indicated in the last column. Estimated comfort improvements are only meaningful for random noise (around 40%) whereas comfort is severely impaired in idling noise case. For the other two signals comfort improves slightly. Attenuation noise levels are quite good with the four reference signals but sharpness increases and tonality decreases after applying ANC to idling noise which impair Aures model comfort.

5. JURY TEST

ANC performance has also been evaluated using a jury test. Different signals recorded before and after ANC system operation have been presented to a group of 27 volunteers in order to evaluate how the comfort and silence level have been modified.

Ten different sounds were tested (4 low-frequency single tones, synthesized repetitive noise (20 and 25 Hz harmonics), random noise and real engine noise (idling, constant speed and acceleration)). Jury people hear the noise pairs (firstly noise recorded before control and secondly the residual noise). After listening they expressed their impression by selecting a score. An improvement of comfort or silence is marked between 1 and 5, and if both subjective characteristics impair, evaluators asses from -1 to -5. Results of subjective evaluations using the jury test is shown in figure 6 (6.(a) silence evaluation and 6.(b) comfort evaluation). Most cases jury people decided noise was more pleasant after ANC, so they scored between 1 and 3. It is important to note that 94.12% of cases where noise gets qui-



(a)

(b)

Fig. 6. Histograms of the jury test results: (a) sense of silence and (b) sense of comfort.

eter, comfort also improves. This does not agree with Aures model, where comfort was not so affected by silence level. In table 2, subjective results of the jury test comparing noises before and after applying ANC are summarized. Control has been considered damaging in nearly 20% of cases.

It should be emphasized that almost all evaluators consider comfort improves for the 130 Hz single tone, in contrast to Aures model which estimated an impairment in comfort. The reason is that after applying ANC noise spectral peaks decrease making its spectral characteristics quite similar to random noise, which is considered by Aures model a poor pleasant noise. Besides, it should be noted that low frequency noise attenuation is not well scored in jury test because of human hearing masking effects.

6. CONCLUSIONS

This work evaluates the quality of sound after applying multichannel active noise control to real and synthesized car

(%)	Much worse	Worse	Same	Better	Much better
Sile.	0.4	18.4	13.2	54.8	13.2
Comf.	1.2	19.6	6	60.8	12.4

Table 2. Subjective evaluation of different signals with respect to their sense of comfort and silence using the jury test.

engine noise. Analysis has focused on estimated comfort of noise after active control using two methods.

Results show that Aures model fails to satisfactorily predict the pleasantness of engine sound because it depends on parameters which are not directly controlled by ANC, and in some cases their changes can negatively affect comfort estimation. Only random noise provides a good Aures comfort estimation. In current research new psychoacoustic parameters are being considered and a new predictive comfort descriptor is being developed, which better describe subjective engine noise character, following [7].

However, jury test validates ANC performance. On the other hand, the human perception of acoustic comfort does not necessarily match with silence increasing, since sometimes a louder noise is classified as pleasant. This is because subjective evaluation of noise is complex and shows considerably variation between different exposed populations.

Finally, ANC techniques can be considered as a useful method to minimize noise levels, which often causes a comfort improvement but depending on spectral characteristics of noise, and not always on the noise reduction levels finally achieved.

7. REFERENCES

[1] S. Kuo and D. Morgan, *Active Noise Control Systems*, John Wiley- Sons, 1996.

[2] M. de Diego, A. Gonzalez, C. Garcia, and M. Ferrer, “Some practical insights in multichannel active noise control equalization,” *Proc. ICASSP-2000*, june 2000.

[3] M. de Diego, A. Gonzalez, and C. Garcia., “On the performance of a local active noise control system,” *Proc. ICASSP-99*, march 1999.

[4] W. Aures, *Berechnungsverfahren für den Wohlklang beliebiger Schallsignale, ein Beitrag zur gehörbezogenen Schallanalyse.*, Ph.D. thesis, Munich University, 1994.

[5] H. Fastl, “The psychoacoustics of sound-quality evaluation,” *Acta Acustica*, vol. 83, pp. 754–764, 1997.

[6] E. Zwicker and H. Fastl, *Psychoacoustics - Facts and Models*, Springer-Verlag, 2nd. edition, 1999.

[7] R. Ingham, N. Otto, and T. McCollum, “Sound quality metric for diesel engines,” *SAE, Proceed. Noise and Vibration Conference*, vol. 01-1819, May Michigan, 1999.