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Sound quality of low-frequency and car engine noises after active noise control

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Abstract

The ability of active noise control (ANC) systems to achieve a more pleasant sound has been evaluated by means of sound quality analysis of a real multi-channel active noise controller. Recordings of real car engine noises had been carried out using a *Head acoustics*^{TM} binaural head simulator seated in a typical car seat, and these signals together with synthesized noise have been actively controlled in an enclosed room.

The sound quality study has focused on the estimation of noise quality changes through the evaluation of the sense of comfort. Two methods have been developed: firstly, a predictive method based on psychoacoustic parameters (loudness, roughness, tonality and sharpness); and secondly, a subjective method using a jury test. Both results have been related to the spectral characteristics of the sounds before and after active control.

It can be concluded from both analyses that ANC positively affects acoustic comfort. The engine noise mathematical comfort predictor is based on loudness and roughness (two psychoacoustic parameters directly influenced by ANC), and has satisfactorily predicted the improvements in the pleasantness of the sounds. As far as the subjective evaluation method is concerned, the jury test has showed that acoustic comfort is, in most cases, directly related to the sense of quietness. However, ANC has also been assessed negatively by the jury in the cases that it was unable to reduce the loudness, perhaps because of the low amplitudes of the original sounds.

Finally, from what has been shown, it can be said that the subjective improvements strongly depends on the attenuation level achieved by the ANC system operation, as well as the spectral characteristics of the sounds before and after control.

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1. Introduction

Active noise control (ANC) [1–4] is an advanced technique used mainly to minimize sound pressure levels at one, or several, points or zones inside a listening space. This technique consists of introducing a new acoustic field that, combined with the primary sound, leads to a reduction in sound levels at the controlled points and around them. Active control techniques are especially suitable for canceling low-frequency noise where traditional passive techniques based on absorbent materials and acoustic screens are inefficient.

Sound quality evaluation has emerged as a very active research area. It deals with the subjective response that sounds (mainly noise) cause on humans in an attempt to achieve better sound design and noise improvement techniques [5–7]. In particular, many car interior sound quality evaluations have been recently carried out [8–11]. In these studies, the methodology of the evaluation is stated and its complexity is easily observed. There are many kinds of interior car noise: road noise, wind noise, engine noise, and others. Each suffers from particular features. Therefore, it is very difficult to address all the features at the same time and sound quality studies often focus on only one feature as is the case in the present work. Applied psychoacoustics [5] is usually the starting point of any sound quality evaluation (also for the automotive industry, see Ref. [11]). Nevertheless, psychoacoustic studies are frequently complemented by jury tests and mathematical models to estimate the sound quality. Recent examples of sound quality studies for engine noise inside vehicles can be seen in Refs. [12–16].

Engine noise control, [2,17,18], is one of the most promising active control applications, since it is reasonable to suppose that ANC systems could be installed in future vehicles in order to adapt engine noise to customer preferences. In other words, to design sound fields for vehicle interiors. Many studies have shown the effectiveness of ANC systems in enclosed rooms [19], and other environments, for cancelling engine and low-frequency noise in general [20–22]. However, one could be forgiven for wondering if a reduction of noise levels improves acoustic comfort. So an open question arises, is there any connection between noise reduction levels and the acoustic comfort? In Ref. [23] a subjective sound quality evaluation of an aircraft interior was carried out and the effectiveness of an hypothetical ANC system was measured using jury tests. This evaluation used synthesized signals that emulated the active noise reduction of propeller tones and cut sound levels. In that work, the hypothetical noise control improved the interior noise quality, and the reduction of measured loudness levels could accurately predict the subjective improvement as assessed by a jury. We want to go further in the present work and carry out a similar study about engine noise and car interior sound quality using a real ANC system. In this way, the effects on sound quality due to the practical limitations of a real controller can also be observed.

Over the last decade, performance of ANC systems has improved mainly due to the evolution of digital signal processing. The merging of active techniques and digital signal processing has enabled noise to be cancelled actively and adaptively, that is, by means of algorithms which automatically adapt the control parameters and track temporal signal variations [24]. It should also be noted that ANC systems have performance limits imposed by either the statistical characteristics of the controlled noise (it should be a stationary signal or at least showing slow changes in its statistical parameters); or physical laws that rule the behavior of the system under control.

Several classifications of digital ANC systems currently exist [1,4]: multi-channel and single-channel systems, global and local control, equalizers or cancellers, narrow band or broad band, feedforward or feedback, etc. However, most ANC systems are based on digital adaptive filtering. Existing ANC systems try to minimize a measure of the signal power but usually without taking into account other sound parameters, which mean that its effect over the final sound quality is difficult to predict. One, or several, error sensors (usually microphones or another devices which provide information about the acoustic primary field) are located at a point in the space in order to achieve a zone of quiet, or a zone in the vicinity of the controlled points where the noise levels are reduced. Different secondary sources (usually loudspeakers) can be used to generate the canceling noises. A typical ANC system was used in the present work, and this local multi-channel ANC system is described below. The set of experiments carried out gives some useful ideas about the human perception of the sound quality resulting from ANC system operation.

It should be emphasized that the study of the relationship between ANC techniques and sound quality is a task as ambitious as the sound quality study itself and, in short, it is a question of evaluating the characteristics of the sound and the comfort sensation it produces when heard. This paper deals with the subjective impact of ANC, given that ANC provides quiet zones (whose size increases as frequency decreases), where the reduction of noise level can reach 25 dB [25]. We will analyze how these noise level reductions influence comfort sensation by means of two methods: firstly, an objective metric based on psychoacoustic parameters [5,26], which allows one to develop empirical models of comfort [13,14,27,28]; and secondly, the opinion of a jury.

2. Description of the ANC experiment

The ANC experiment was developed in two phases: firstly, measurements concerning real-time experiments were carried out using the ANC system; and secondly, the data obtained were analyzed by means of different methods.

A feedforward ANC system was developed using a digital signal processing board equipped with a TMS320C40 floating point DSP processor. The multiple error LMS algorithm (multi-channel version of the filtered-X LMS) was used as a control algorithm [2,24]. Noise level reductions of between 12 and 35 dB were achieved in an area of approximately 900 cm^2 around each ear at listener ear height, which is reported in Ref. [25]. Fig. 1 shows the block diagram of the system. The prototype was mounted in a room measuring $7.35\ \mathrm{m} \times 4.16\ \mathrm{m} \times 2.59\ \mathrm{m}$ with a reverberation time of approximately 0.044 s. A *Head acoustics*^{TM} head and torso simulator was seated in a typical car seat and an array of two microphones were used as error sensors and located at the headrest, see Fig. 2. Two loudspeakers worked as secondary sources.

Depending on the experiment, a signal generator or a DAT recorder, generated the primary signal which was fed to a loudspeaker. The working frequency range was 40–250 Hz and the disturbance signals were two types of synthesized noise (repetitive noise comprised of a fundamental tone from 15 to 30 Hz and a number of harmonics, and random noise), and three real engine noise recordings (idling, constant speed and acceleration). Two calibrated microphones at the ear canals of the head simulator recorded binaural sounds.

Binaural noise signals were acquired with the ANC system turned on and off. Measurements that could be reproduced with the same binaural sensation were recorded using calibrated

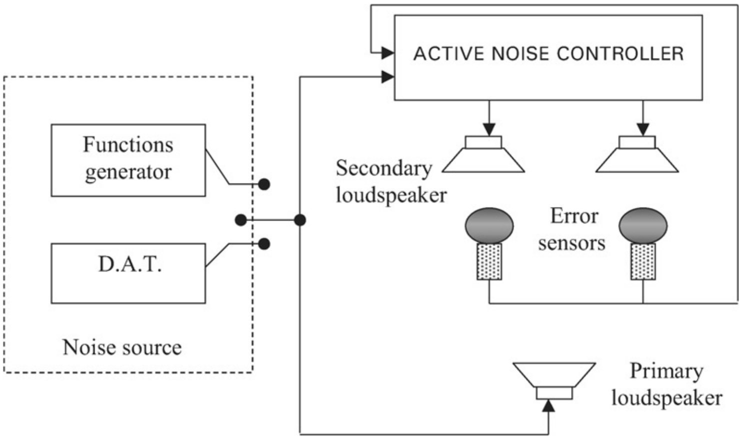


Fig. 1. Schematic diagram of the 2 × 2 ANC system: two secondary sources and two error sensors.

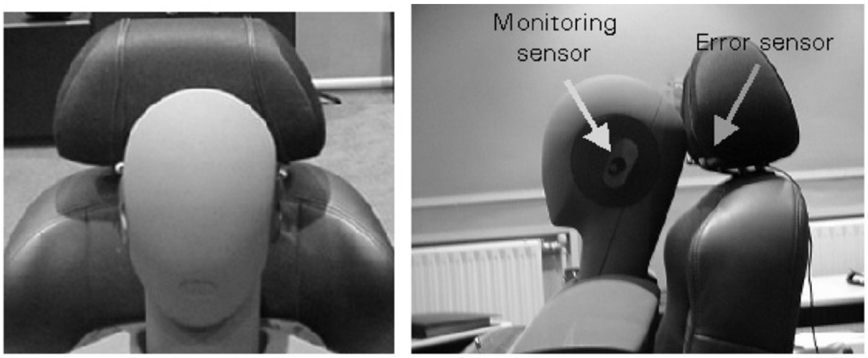


Fig. 2. Head and torso simulator seated on the car seat illustrating the relative position of the error sensors and monitoring sensors.

headphones. In all cases, except for acceleration noise, a 10 s sample was acquired before ANC system operation and then a new sample was recorded when the ANC system was working after its convergence time. Two forty-five second samples of continuous sequences were recorded for acceleration noise. The sampling rate was 44.1 kHz.

2.1. ANC experiment results

The pressure level reductions obtained for different noise signals are shown below? Even though the amplitudes of the different generated signals were identical, the noise levels measured at the different sensors varied with frequency due to the frequency response of the enclosure, which is shown in Fig. 3.

Firstly, four different synthesized repetitive noises comprising of a fundamental frequency (15, 20, 25 and 30 Hz) plus nine harmonics were considered. As is said above, the spectrum of

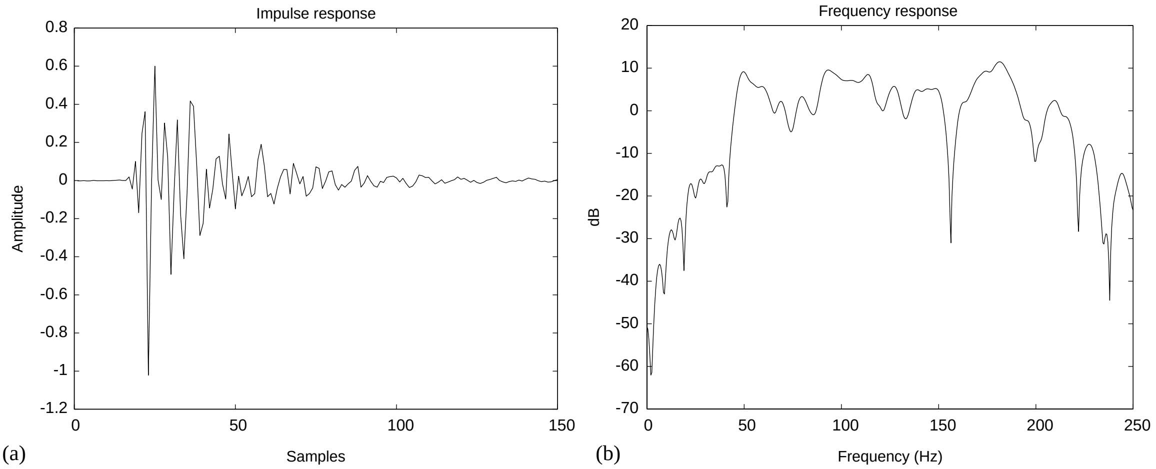


Fig. 3. Impulse response (a) and frequency response (b) of the enclosure.

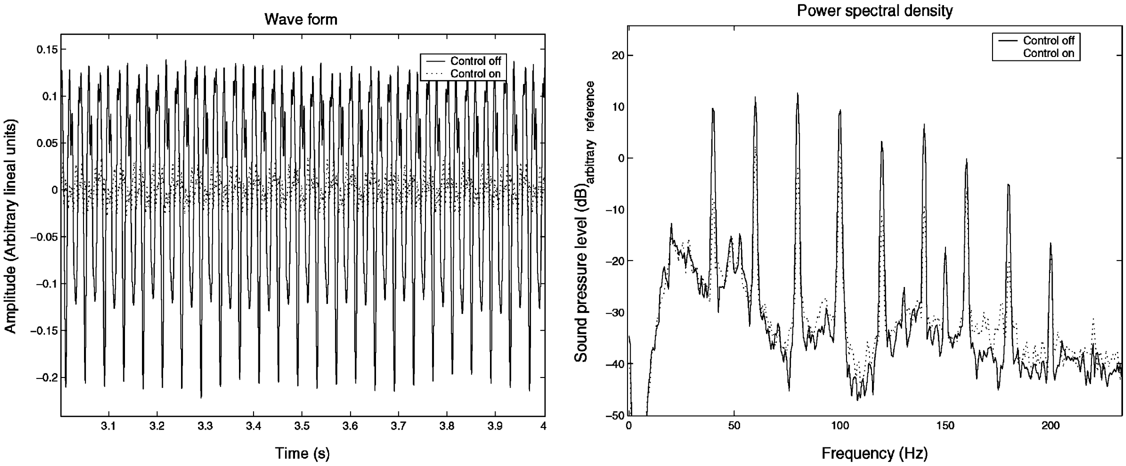


Fig. 4. Attenuation achieved for repetitive noise with 20 Hz fundamental frequency: (a) amplitude, (b) power spectrum.

these signals at the monitoring microphones was modified by the physical characteristics of the room, in such a way that these synthesized noises present certain similarities with real engine noise. Fig. 4 shows a cancellation example of one of these signals. It can be seen that different reduction levels are obtained for different harmonics, however reduction levels can reach 30 dB.

Random noise was also cancelled. This kind of noise is difficult to control by means of active techniques due to its broadband spectrum. In order to have random noise available, 230 Hz filtered white noise was generated.

Finally, real car engine noise was used: idling, acceleration and constant speed noise, which were recorded from the position of the front seat passenger inside the car using a binaural recording system. The unsteady character of acceleration noise makes it more difficult to control with an ANC system. However, the experiment shows that it changes slowly enough to be tracked by the controller. Cancellation of idling and constant speed noise exhibits a behavior similar to the synthesized repetitive noise. Fig. 5 illustrates the time–frequency spectrum of the acceleration signal before, and after, control. Fig. 6 shows the temporal evolution of its waveform and power. The results of ANC can be easily appreciated.

3. Effects of ANC over psychoacoustic parameters

Psychoacoustic parameters can be defined as measurable objective characteristics of the sound that help predict its human perception. They provide a way to measure several aspects of the subjective sensation that sounds can produce on human listeners [5].

With the aim of analyzing how ANC operation affects sound quality, one begins by studying the effects of active control over four common psychoacoustic parameters: loudness, sharpness, roughness and tonality [26,29].

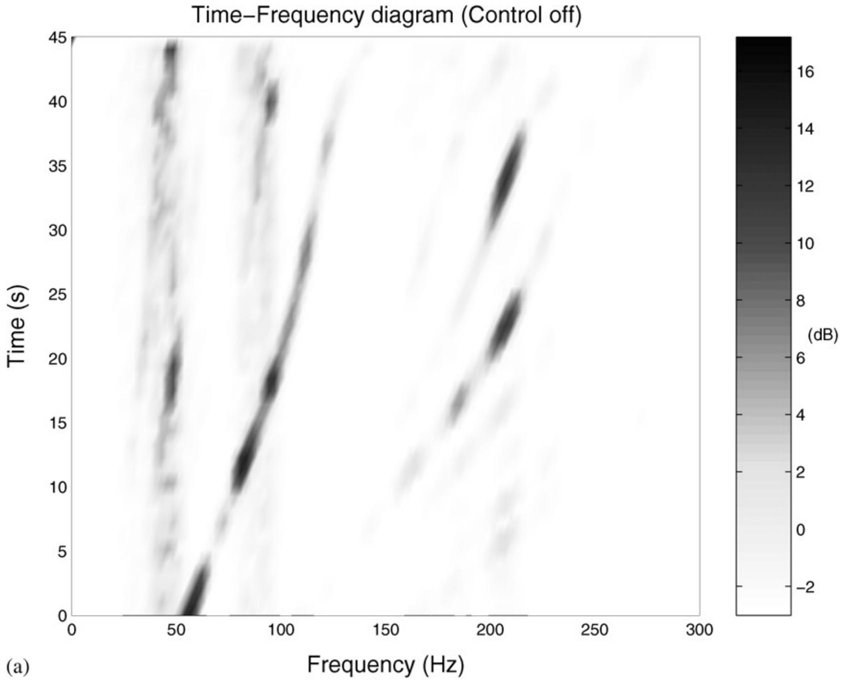
- *Loudness*: This is a dominant feature for any sound quality evaluation. In some way, it is a measure of the sound *strength*. It can be calculated by the ISO 532B norm and is measured in sone.
- *Sharpness*: Is an attribute for the evaluation of spectral colour. High values of sharpness indicate significant spectral components at high frequencies. The addition of low-frequency components can reduce the sharpness value. It is measured in acum.
- *Roughness*: Describes the human perception of temporal variations of sounds. In this sense, it arises from amplitude modulation, as well as frequency modulation of sound, and depends on: modulation frequency (in the range of 20–300 Hz), modulation depth, and sound pressure level. Roughness is measured in asper.
- *Tonality*: Measures how many pure tones can be found in the noise spectrum. This parameter gives information about the harmonic nature of sound. For example, random noise has its power spectral density distributed all over the band so it suffers from a low tonality.

From now on, the measurement of any psychoacoustic parameter is its mean value during the sound duration.

3.1. Repetitive noise

Fig. 7 shows the effects of ANC over the four psychoacoustic parameters for different repetitive noises (dark bars before ANC and light bars after ANC). Frequency axis indicates the fundamental frequency of each repetitive noise.

Clearly, loudness changes are related to active control. This is due to the fact that minimizing the error signal power implies reducing the sound pressure level, and therefore the loudness measure decreases. Furthermore, the experiment shows that sharpness levels can increase after ANC operation, mainly for very low-frequency signals. Reduction of the low-frequency content of noise signals causes this effect, since high-frequency components become dominant in the final spectrum.



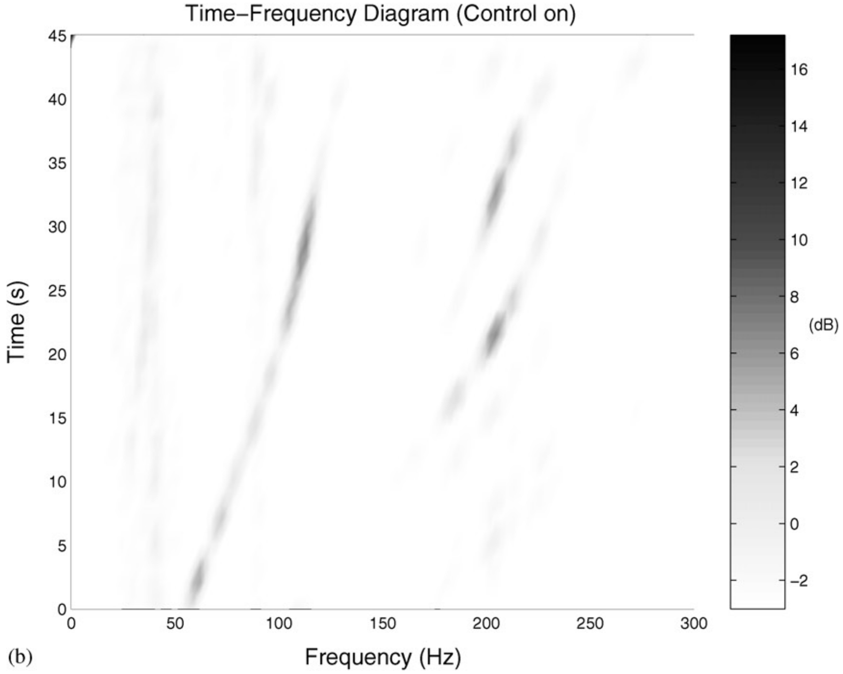


Fig. 5. Time-frequency spectrum of the acceleration signal: (a) before ANC and (b) after ANC.

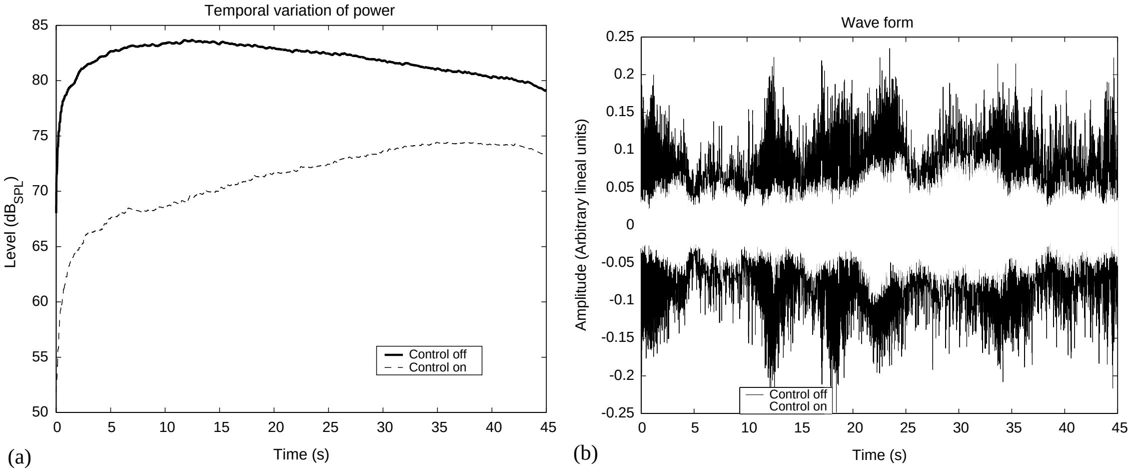


Fig. 6. Temporal evolution of the acceleration signal: (a) instantaneous level and (b) amplitude.

On the other hand, significant reduction of roughness can be observed since differences of amplitude of tones before, and after, control affects roughness measures. The tonality values obtained in this case are relatively low because the signals exhibit smoother spectra before and after active control operation.

3.2. Real engine noise and random noise

In addition to synthesized repetitive noise, real car engine noise (idling, constant speed and acceleration) and random noise were also used as reference signals when analyzing the psychoacoustic parameters. See Fig. 8.

One can also observe that the loudness level decreases and the sharpness level increases when ANC operates, although these variations are not always as significant as we could expect. The tendency is for the roughness of signals to decrease. Changes of the tonality parameter after ANC operation become significant only for noises with high tonality values. It must be noted that loudness does not change for idle and random sounds, in spite of the observed decrease of their power levels. The same behavior in the sharpness can also be appreciated. Both signals present low harmonic content, as can be seen by their very low tonality values before, and after, control. On the other hand, their roughness values noticeably decrease after ANC.

3.3. Conclusions about ANC effects

As a result of the experiments, it can be concluded that ANC directly influences the loudness level. It should be pointed out that this dependence agrees with expectations according to the ANC objectives and the meaning of this psychoacoustic parameter.

The other psychoacoustic parameters are not so clearly controlled by ANC. Sharpness values tend to increase after ANC operation. This is mainly due to the original spectrum of the signals,

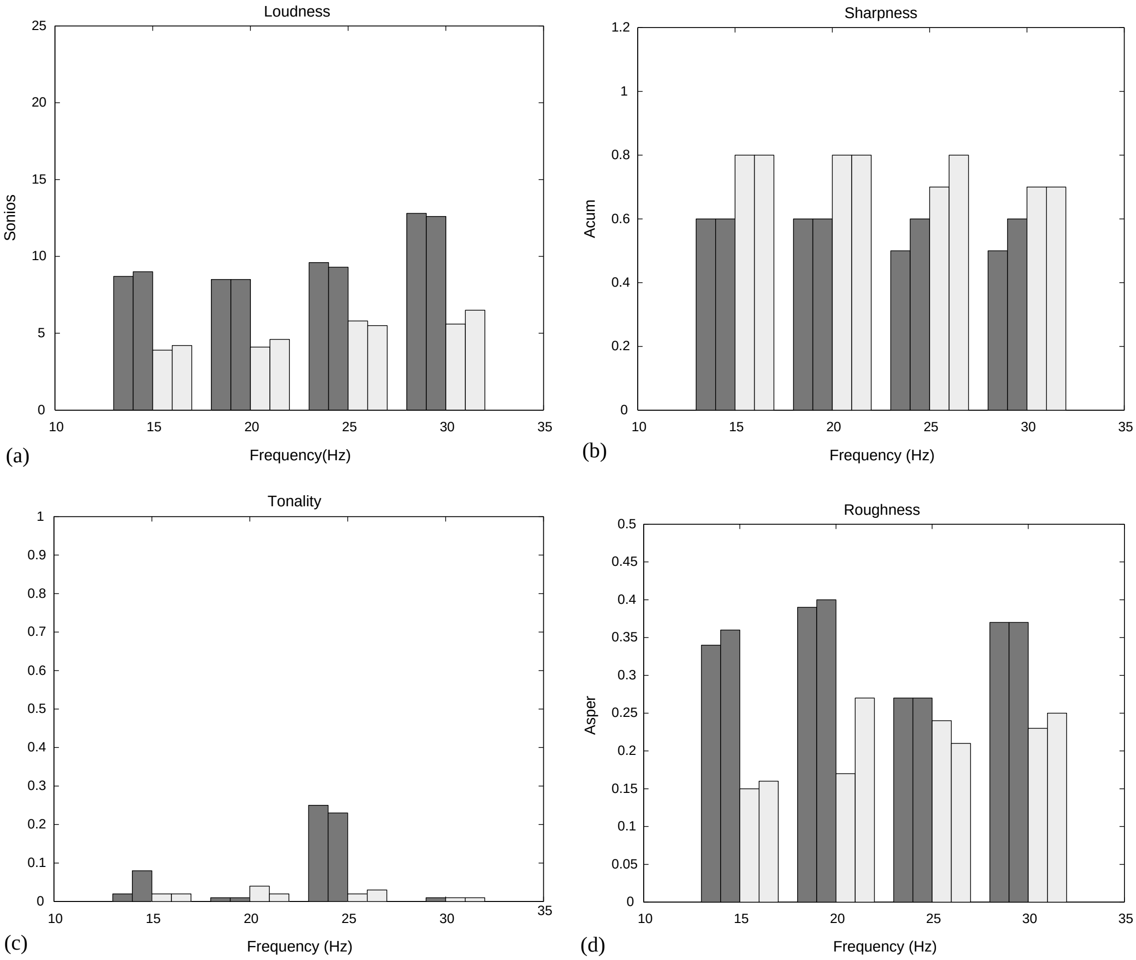


Fig. 7. Psychoacoustic parameters for the repetitive noise tones before (dark bars) and after (light bars) ANC. Bars refer to right canal (initial dark and light bars at each frequency) and left canal (second bar at each frequency): (a) loudness, (b) sharpness, (c) tonality, and (d) roughness.

which are low-frequency signals (below 250 Hz). ANC reduces these low-frequency components and therefore sharpness increases.

On the other hand, roughness tends to decrease after ANC application as a consequence of the reduction of the low-frequency spectrum content. A similar tendency of the tonality parameter can be appreciated. For the sounds tested, tonality does not significantly vary when original values are very low, whereas it tends to decrease with ANC when its original values are high. This behavior is easily explained as ANC reduces the spectral peaks of the sound and so the tonality of the final spectrum is lower.

Although these results have been obtained for a particular set of very low-frequency noises, it is not difficult to extrapolate the ANC outcomes for the psychoacoustic parameters of other sounds,

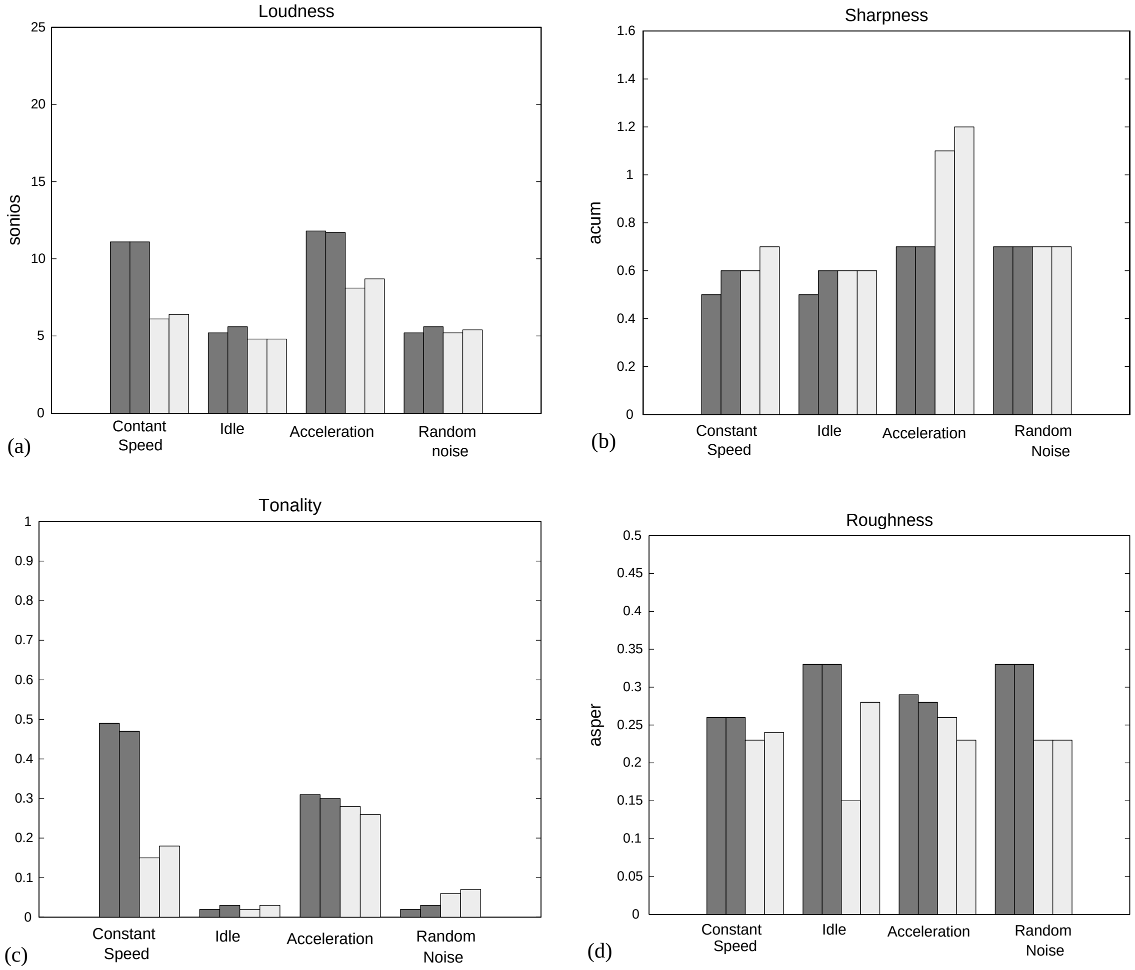


Fig. 8. Psychoacoustic parameters for real engine signals and random noise before (dark bars) and after (light bars) ANC. Bars refer to right canal (initial dark and light bars at each frequency) and left canal (second bar at each frequency): (a) loudness, (b) sharpness, (c) tonality and (d) roughness.

that is, whenever ANC decreases sound levels. ANC would almost always reduce the loudness level because this parameter depends on the sound power level. This parameter presents a significant influence in sound pleasantness as reported in Ref. [23]. Roughness also decreases; mainly due to a reduction of the inter-modulation effects. The tendency to smooth the power spectral density decreases the tonality and eventually, the sharpness parameter decreases when the original sound was rich in high-frequency components.

The aim of this work is to try and establish the influence of ANC techniques over the sound quality, but for the moment only the relationship between ANC and the psychoacoustic parameters has been analyzed. Although some meaningful results have been obtained, there is insufficient information to assess the effects of ANC on sound quality. However, psychoacoustic parameters can be a good tool for estimating the pleasantness of noise, see Ref. [11].

4. Empirical comfort evaluation

A widespread method of sound quality evaluation is based on the use of mathematical models that were developed experimentally by means of tests [30]. These models try to supply a quantitative value for some subjective characteristic of noise, such as acoustic comfort. This quantitative value is related to some objective variables. In this case, psychoacoustic parameters [6,12,14] are used to evaluate acoustic comfort. By means of predictive mathematical models based on psychoacoustic parameters, changes of acoustic comfort after using ANC can be estimated.

Studies about sound quality [31] and predictive mathematical models have already been dealt with in some other papers [5,18,32]. In particular, the predictor model used in the present experiment has been described in Ref. [13], and it was developed for diesel engine noise, supplying an estimator of acoustic comfort. This model is based on only two psychoacoustic parameters: loudness and roughness. As indicated in Section 3, loudness is mainly affected by ANC, and roughness and tonality also exhibit comparable behaviors for engine signals. Therefore, it seems a good choice to use an objective metric based on just two psychoacoustic parameters providing loudness is one of them. Moreover, the metric presented below has already been tested to objectively evaluate comfort improvements after ANC operation in Ref. [18].

The model is expressed as

$$Y = -7.5395 - 0.2995N - 3.1451R, \tag{1}$$

where N is the mean value of the loudness, R is the mean value of the roughness, and Y is the comfort descriptor which increases when estimated comfort improves. It must be said that different comfort estimators were developed by the authors in a preliminary study [33]. One of the topics presented was the performance comparison of the comfort model proposed (1), and a comfort model developed by the present authors which depended on loudness, sharpness and roughness.

Not only an improvement of comfort for car engine noise is achieved using the descriptor in Eq. (1), see Fig. 9(a) and (b), but an improvement is seen for all analyzed noises. In spite of the fact that the proposed estimator was initially developed for car engine noise, results obtained for other noises could also be meaningful, especially for sounds similar to engine noise. Those sounds similar to engine noise show a remarkable comfort improvement, see Fig. 9(a). Fig. 9(b) shows comfort results for engine and random noises. Whereas comfort improves for engine noise in all cases, the comfort descriptor, Eq. (1), for random noise yields lower comfort improvements.

5. Jury test

As shown in the previous section, predictive comfort models provide valuable information about sound quality and the tested model reinforced the fact that ANC systems improve subjective comfort. However, it is necessary to contrast those conclusions with the human subjective point of view. For this reason, a set of jury tests were carried out by a set of 26 subjects randomly selected, mainly males, whose age ranged from 20 to 45 years.

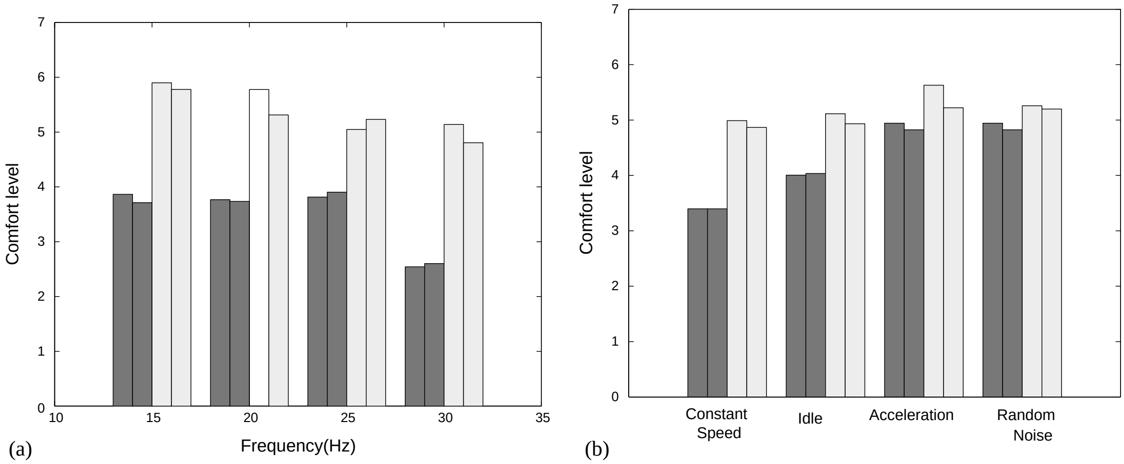


Fig. 9. Comfort estimation obtained with mathematical model for (a) repetitive noise and, (b) random noise and real engine noise (constant speed, idle and acceleration noises), before (dark bars) and after (light bars) ANC.

Six different noises were tested: two synthesized repetitive noise whose fundamental frequencies were 20 and 25 Hz, random noise, and real car engine noise (idling, constant speed and acceleration). Jury members heard the noise pairs, comprised of sound binaurally recorded before and after control. After listening to both signals, they expressed their impression by selecting a score. An improvement in comfort or quietness was marked between 1 and 5, otherwise when a subjective characteristic worsened, jury members assessed the change between -1 and -5. The first sound presented was set as the reference sound, and the second sound was compared with this reference. Both sounds, the sound before ANC and the residual sound, could have been considered as the reference in each noise pair, but this information was not provided to the jury.

In analyzing the test results, it should be pointed out that they express the subjective point of view of the jury, which is related to their likes and dislikes, or sensations perceived. Therefore, it is not uncommon to find a few contradictory opinions. However, attention will be focused on the opinions of the majority.

Results of subjective evaluation using the jury tests are illustrated in Fig. 10 for all of the signal. Both subjective sensations, quietness and comfort are evaluated. From the histogram, it can be seen that most of the jury people positively scores both characteristics. Comfort improves after ANC operation in more than 65% of cases and most people have decided that the sound was more pleasant after ANC, and so they scored between 1 and 3. It is also important to note that in the 92.47% of cases where noise quietened, comfort also improved. This fact was expected and it leads one to remark that ANC systems produce a more pleasant psychological sensation by means of reducing sound pressure levels.

Test results are qualitatively shown in Table 1. The effect of ANC on the sensation of quietness, or comfort, is indicated. Columns labeled as *much worse* and *worse* indicate that control has been considered harmful in nearly 25% of cases. Although sound amplitude reduction is objectively achieved in all cases, it does not seem to always have had the expected positive impact on human subjectivity.

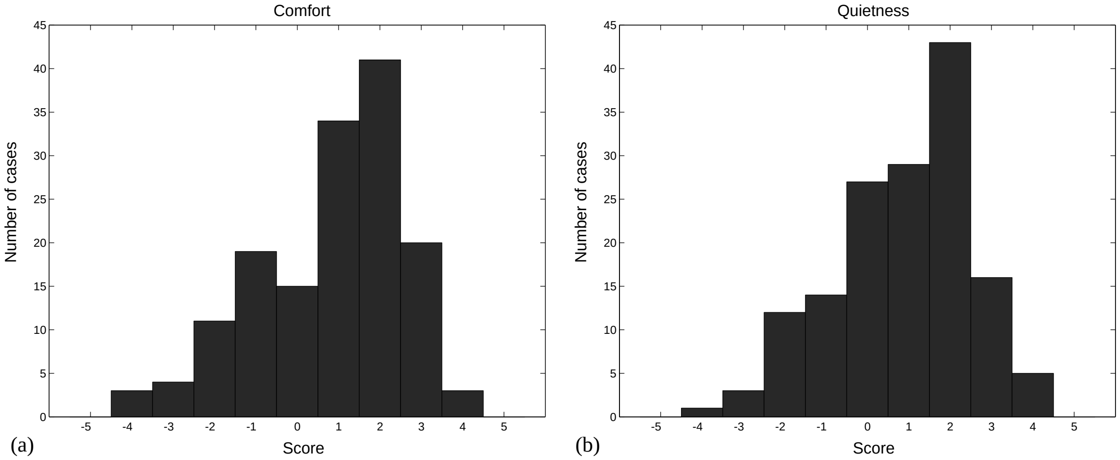


Fig. 10. Histogram of jury test result for sense of comfort (a) and sense of quietness (b).

Table 1
Qualitative results of ANC effects from jury test regarding subjective sense of quietness and comfort

	Much worse (%)	Worse (%)	Same (%)	Better (%)	Much better (%)
Quietness	0	20	18	58.7	3.3
Comfort	1.3	23.3	10	63.4	2

Percentage of opinions when all studied sounds are considered.

Table 2
Qualitative results regarding subjective sense of comfort for synthesized sounds

	Much less pleasant (%)	Less pleasant (%)	Same pleasant (%)	More pleasant (%)	Very much pleasant (%)
Signal ff = 20 Hz	0	4	0	88	8
Signal ff = 25 Hz	0	0	4	92	4

Attention is now turned to the evaluation results obtained for particular subsets of signals. Table 2 shows the results of the jury test for the synthesized repetitive noise with harmonics of 20 and 25 Hz. From them it can be concluded that ANC operation is overwhelmingly positive in improving the sense of comfort. The predictive comfort model has determined an improvement in comfort for this kind of noise, which completely agrees with the respective jury test results (see Fig. 11). Moreover, Table 3 shows the subjective sense of quietness for these synthesized sounds, being their results very similar to the comfort sensation.

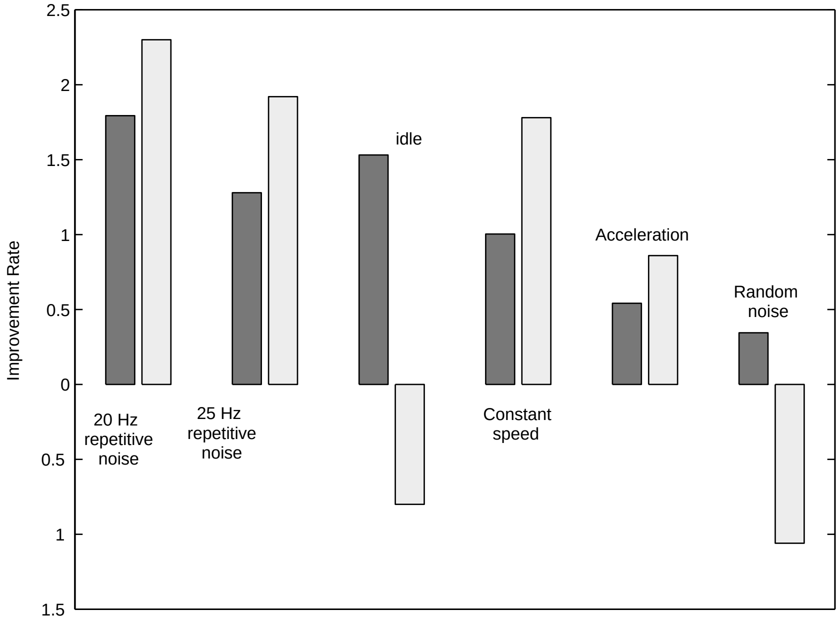


Fig. 11. Improvement achieved by mean of ANC system according to jury test (light bars) and predictor comfort model (dark bars).

Table 3
Qualitative results regarding subjective sense of quietness for synthesized sounds

	Much less quiet (%)	Less quiet (%)	Same quiet (%)	More quiet (%)	Very much quiet (%)
Signal ff = 20 Hz	0	4	4	84	8
Signal ff = 25 Hz	0	12	0	80	8

Jury test results for real and random noises are shown in Tables 4 and 5. Idling and random noise obtain the worst scores. It seems that both noises are considered quiet enough before ANC operation, since they exhibit low loudness levels as can be seen in Fig. 8. Therefore, the ANC effects are not well appreciated, especially at low frequencies. Moreover, these noises have a smooth spectrum that is affected by the ANC system depending on practical and physical considerations [27]. These changes in the original regular spectrum negatively influence the studied psychoacoustical impression. This fact does not occur for other noises with more complex spectrum, such as constant speed and acceleration.

In conclusion, some differences between jury test results and the predictive comfort model have come to light. Fig. 11 shows quantitative improvement indexes calculated from both methods of sound quality evaluation. Improvement rate from the jury test results have been calculated by averaging all the jury opinions, so it is bounded between ±5. On the other hand, the improvement rate for the predictive model shows the difference between the comfort indexes obtained before

Table 4
Subjective evaluation of real engine noise and random noise with respect to the subjective sense of comfort

	Much less pleasant (%)	Less pleasant (%)	Same pleasant (%)	More pleasant (%)	Very much pleasant (%)
Idle	4	68	4	24	0
Constant speed	0	4	4	92	0
Acceleration	0	8	24	68	0
Random noise	4	56	24	16	0

Table 5
Subjective evaluation of real engine noise and random noise with respect to the subjective sense of quietness

	Much less quiet (%)	Less quiet (%)	Same quiet (%)	More quiet (%)	Very much quiet (%)
Idle	0	48	32	20	0
Constant speed	0	0	16	84	0
Acceleration	0	4	24	68	4
Random noise	0	52	32	16	0

and after control, and averaged between both ears. Although both indexes cannot be quantitatively compared, Fig. 11 qualitatively shows, as previously commented, that the predictive model fails to predict the comfort of those signals which present low loudness levels before control (idle and random noise). That is, those signals which can be subjectively considered sufficiently quiet before control.

6. Conclusions

The ability of ANC systems to achieve a more pleasant sound has been evaluated. A multi-channel local ANC system which minimizes the acoustic power of low-frequency acoustic fields at different positions in the listening space has been used. Synthesized and real car engine noises were used to test the performance of the local ANC system in an enclosed room. Recordings were carried out using a *Head acoustics*^{TM} head and torso simulator, seated on a typical car seat, and with calibrated microphones in the ear canals. In previous works [25,34], a similar ANC system was experimentally tested and 10 dB zones of quiet around the headrest of a car seat placed inside the room were successfully achieved.

The analysis has focused on the estimation of noise quality changes through the evaluation of the sense of comfort after active control operation. Two methods have been developed: firstly an empirical method based on the psychoacoustic parameters; and secondly, a subjective method by means of a jury test.

There can be no doubt that ANC positively affects the acoustic comfort as can be concluded from both analysis. The mathematical comfort predictor developed by Ingham et al. [13] for engine noise has satisfactorily predicted the improvements of sound pleasantness because it is based on two psychoacoustic parameters influenced by ANC. As far as the subjective evaluation method is concerned, the jury test results showed that acoustic comfort is, in most cases, directly related with the subjective sense of quietness except for rare cases when psychological elements like insecurity could be associated with quietness. It is obvious that a subjective evaluation always obtains answers from an individual viewpoint, and therefore there is no completely general rule.

ANC can be considered a useful tool to reduce the sound pressure level of low-frequency noises and it leads, in most cases, to an improvement in acoustic comfort. When ANC does not work as expected (it does not achieve sufficient attenuation) worse scores can be seen in the jury test (see Tables 4 and 5 for idle sound and random noise). In these cases, the developed ANC controller has been incapable of reducing the loudness of these sounds perhaps because of the low level of the sounds before control. Reduction of loudness is insignificant, as we can observe in Fig. 8. Consequently, the variation of other psychoacoustic parameters (see Fig. 8) could result in ANC being unable to improve the sound quality of these signals, according to the jury test results. A more pleasant subjective sensation could be achieved retaining some residual noise by means of an active noise equalizer. This technique, which was reported in Refs. [1,35] is currently being researched.

Finally, it is clear that subjective improvement strongly depends on the nature of the controlled sound, mainly its power spectrum before and after control, and not just the attenuation level achieved. Note that, in this experiment, those signals which were considered sufficiently quiet before control and boasting a smoother spectrum (idle sound and random noise) were not positively assessed after control, despite showing noticeable amplitude reductions. Moreover, the predictive comfort model failed to predict the jury test result for these signals.

Acknowledgements

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