

A psychoacoustical evaluation of active and passive methods for noise reduction in automotive engineering

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Introduction

In our everyday life we are often surrounded by road traffic noise. One important noise source is the engine, especially in the case of vehicles driven by combustion engines. Automotive engineering provides different active and passive techniques to reduce this noise. The success of these techniques is commonly quantified on the basis of physical measures such as the attenuation of the sound pressure level. However, the results of this approach may not always correlate with perception, e.g., at the same sound pressure level a sound may be less acceptable if it has a higher roughness or it has salient tonal components. Thus, the present study investigates the benefit of the noise reduction perceptually. The experiment uses sounds radiated from a stripped car engine as stimuli. The engine includes a cylinder block and an oil pan. For an active control of the sound radiation, piezoelectric actuators and sensors are attached on the surface of the oil pan. The sounds are evaluated in three psychoacoustical experiments. The first focuses the attention on the tonal portion of the sound and how this is affected by the active method to reduce the noise. The second experiment investigates how the overall loudness is affected by the active noise reduction method. Finally, we assess the change in acceptance of the sound in the third experiment.

Oil pan sound

The experiments used the sound emitted by an oil pan in a stripped car engine, consisting of a crankcase and an oil pan. In Figure 1 the setup of the stripped car engine is shown. Since the oil pan is a major noise emitting structure this study focusses on the oil pan sounds. The vibrations of the oil pan were altered using actuators attached to it [1, 2]. For the optimal position of the piezoelectric actuators, the most dominant mode shapes were analyzed by means of harmonic FE simulations. The actuators were placed to significantly influence the shape of the structural modes. The first, third and fourth eigenmodes were considered. A velocity feedback control approach was used. A collocated design was chosen with sensors and actuators at the same position. This is important to guarantee control stability. Using a separate patch sensor for each patch actuator leads to a decentralized feedback control strategy. Thus, for our setup with two actuator positions, we had two independent local feedback loops.

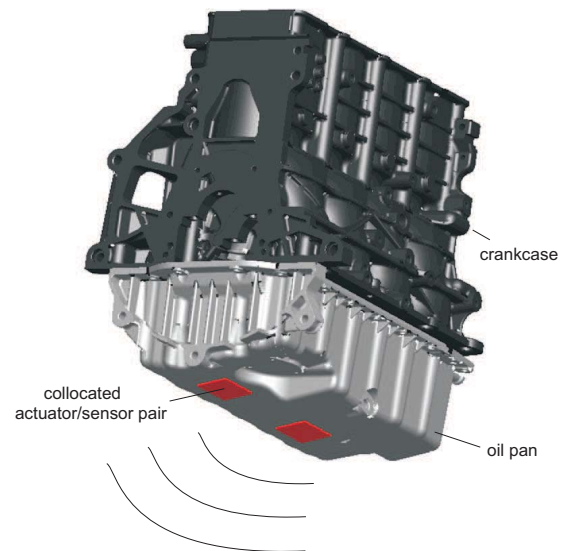


Figure 1: Test Setup of stripped car engine.

The stripped car engine was excited by a shaker mounted to the oil pan with real engine spectra. More precisely, energetically averaged cylinder pressure signals of a four-cylinder diesel engine at 1500 revolutions per minute were used. It should be noted that the amplitudes of the excitation are smaller than under real operating conditions. The structural vibrations were measured by further patches mounted on the inner surface of the oil pan bottom. The vibrations recorded by these patches were filtered using a butterworth low-pass filter with a cut-off frequency of 1900 Hz. The spectra of the sounds emitted from the uncontrolled and controlled stripped car engine are shown in the top panel and middle panel of Figure 2, respectively.

In addition to the controlled condition with full gain, three other controlled conditions were considered: one condition where the actuators were driven with half of the gain and two conditions where only one of the two patches was active.

Experiment 1: Partial loudness of tonal portion

One prominent characteristic of the oil pan sounds is that they contain tonal components. This experiment investigates how the tonal portion of the noise is changed with the active noise control.

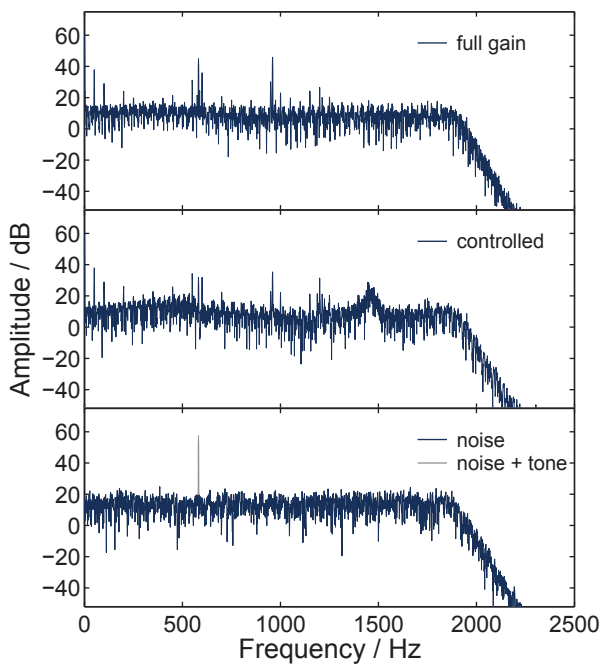


Figure 2: Spectra of stimuli: Top panel: Oil pan sound without noise reduction. Middle panel: Oil pan sound with active noise reduction (full gain). Bottom panel: Comparison noise (blue) with added tone (gray).

Methods

The loudness of the tonal content of the oil pan sounds was measured using an adaptive two-alternative, forced-choice procedure with a 1-up 1-down rule [5]. Each trial consisted of one interval with an oil pan sound and one interval with a comparison stimulus. This comparison stimulus consisted of a low-pass filtered noise with a matched spectrum and a tone. To generate the noise of the comparison noise, a broadband white noise was filtered with a butterworth low-pass filter with a cut-off frequency of 1900 Hz, i.e., the same filter that was used for the oil pan sounds. The noise level was 60 dB SPL. The frequency of the tone was 582 Hz which was a prominent tonal component in the uncontrolled oil pan sound. The noise and the tone are shown in the bottom panel of Figure 2 with dark and light colours, respectively. The level of the uncontrolled oil pan sound without the tonal components was chosen to match the level of the comparison noise. The other oil pan sounds were amplified preserving the relation of the levels of the different oil pan sounds. In general, the stimuli were 1 s long and were gated on and off with 50 ms cosine square windows.

Within the adaptive run, the level of the tone of the comparison stimulus was varied. The order of the intervals was randomized for each interval. After the presentation of the two intervals of the trial, participants were asked in which of the intervals the tonal portion of the sound was louder (German: “In welchem Signal ist die tonale Komponente lauter?”). Participants had to indicate the interval with the higher magnitude of tonal content by pressing the corresponding button on the keyboard. For each adaptive track, the starting level

was either 50 or 65 dB SPL. The tone level was initially adjusted in steps of 8 dB. The step size was halved at each upper reversal until the minimum step size of 2 dB was reached. The run continued for four reversals with the minimum step size. The mean of these four last reversals was taken as an estimate of the level of equal loudness. The average of the estimates of the two runs with the different starting levels was then taken as the final estimate of the level at equal loudness of the tonal portion of the sound. To reduce potential bias effects, all ten adaptive tracks (5 oil pan sounds x 2 starting levels) were interleaved (e.g., [6]).

Stimuli were generated digitally at a sampling rate of 44.1 kHz. A standard personal computer controlled stimulus generation and presentation and recorded results using MATLAB. Stimuli were D/A converted and amplified by a RME Fireface 400 and presented via Sennheiser HD 650 headphones. The participants were seated in a sound-insulated booth. Fifteen listeners (10 female, 5 male) participated in the experiments. The age ranged from 22 to 43 years. All listeners showed a normal audiogram in the relevant frequency range, i.e., thresholds were 15 dB HL or lower for all audiometric frequencies in the relevant frequency range.

Results and Discussion

Figure 3 shows the level of the 582-Hz tone in the comparison noise relative to the noise level which had, on average across all participants, the same loudness of the tonal component as the tonal portion of the oil pan sounds. On the far left the result for the uncontrolled noise are shown while the other data points are for the four controlled oil pan sounds with active noise reduction. For all oil pan sounds, the level of the tonal component

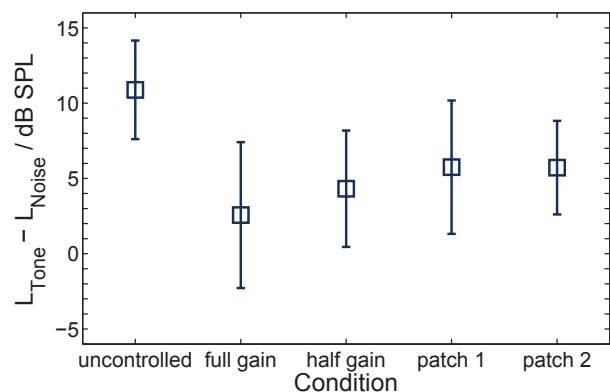


Figure 3: Level of the 582-Hz tone relative to the noise level eliciting the same sensation of loudness of the tonal component as the tonal portion of the oil pan sound. Mean data of 15 participants and interindividual standard deviations are shown.

in the comparison sound was well above the noise level indicating that all oil pan sounds had a clearly audible tonal characteristic. However, the controlled oil pan sound with full gain largely reduced the loudness of tonal content. The loudness reduction corresponded to a reduction of the tone level by 8 dB in the reference sound

for full gain. If the active noise reduction was driven with half gain or only one of the patches was used in the active noise reduction method, the reduction of the loudness was equivalent to a reduction of the level of the tonal component in the reference sound by about 6 dB.

Recently, Verhey and Heise [8] measured the partial loudness of the tonal component in noise and the magnitude of tonal content for the same sounds and within the same participants. Based on the high correlation between the results for these two sensations they argued that the partial loudness of the tonal component may be used to assess the magnitude of tonal content. The magnitude of tonal content, sometimes also referred to as tonalness or tonality [7], is an important sensation to characterize the noise of environmental sounds. Sounds which include a tonal part are considered more annoying because of their more intrusive character and several national and international standards attempt to quantify this effect [3, 4].

In the light of this line of arguments, the present data show that the active noise reduction methods reduces the annoyance of the sound (see also Experiment 3).

Experiment 2: Overall loudness

Methods

Apparatus and procedure were the same as used in the previous experiment. However, the comparison stimulus was now the 60-dB noise only (i.e., without the tone) and the level of the oil pan sounds were varied in level to match the overall loudness of the comparison noise. After each trial the participants (the same as in Experiment 1) were asked which of the two signals was louder (in German “Welches der beiden Signale war lauter?”). The uncontrolled noise and the oil pan sound with an active control on full gain were used as test stimuli. The starting levels were 50, 60, or 70 dB SPL. As in Experiment 1, all tracks were interleaved, in this case six tracks (2 noises x 3 starting levels).

Results and Discussion

Circles in Figure 4 indicate the level difference between the equally loud oil pan sounds and the comparison noise. This level difference is slightly negative (about -2 dB), i.e., the oil pan sound was slightly louder than the equal-level comparison noise. Note that the level difference is almost the same for the two oil pan sounds. Thus the active noise reduction method hardly changed the loudness of the sound.

Experiment 3: Preference

Methods

The general procedure, stimuli and participants were the same as in Experiment 2 but the participants were now asked to choose the interval which they preferred.

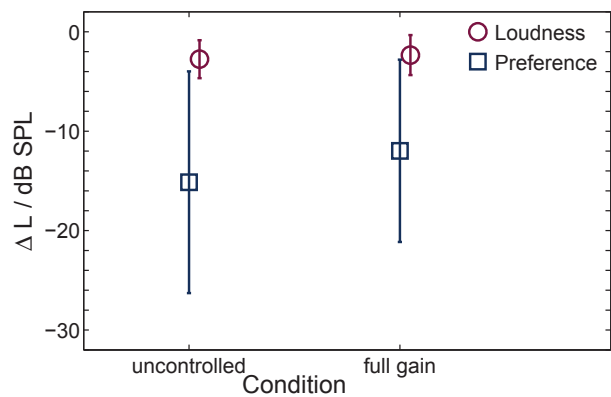


Figure 4: Level difference at equal loudness (circles) and equal preference (squares) of the oil pan sound and the comparison noise for the uncontrolled noise (left) and noise with an active noise reduction method on full gain (right). Mean data of 15 participants and interindividual standard deviations are shown.

Results and Discussion

Squares in Figure 4 indicate the level difference at equal preference for the oil pan sound and the comparison noise. As in Experiment 2, the levels are negative. However, the level difference required to be perceived as equally preferred is considerably larger than the one for equal loudness. This indicates that the preference is not only determined by the loudness of the stimulus.

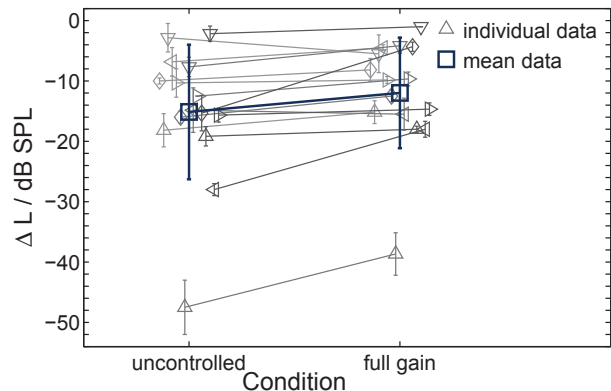


Figure 5: Levels at equal preference (squares) of the oil pan sound and the comparison noise for the uncontrolled oil pan sound (left) and the sound with an active noise reduction method on full gain (right). Individual results are shown with triangles. In addition, mean data of all 15 participants and interindividual standard deviations are redrawn from Figure 4.

The interindividual differences are more than four times larger than those for the overall loudness (9 vs. 2 dB). This is mainly due to large interindividual differences in the level difference at equal preference for both oil pan sounds, as shown in Figure 5. Note that a wider range of levels are shown than in Figure 4, since some participants measured level differences outside the previously chosen level range. In general, the level difference is reduced for the controlled oil pan sound, although there are individual differences in the magnitude of the effect. For

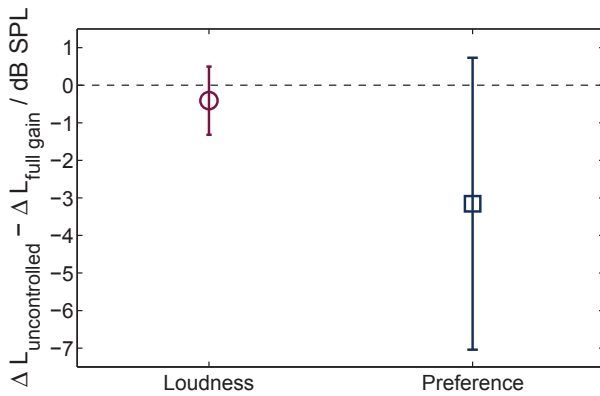


Figure 6: Difference in the results for equal loudness (circles, left) and for equal preference (squares, right) between the uncontrolled condition and the condition with an active noise reduction method on full gain. Mean data of 15 participants and interindividual standard deviations are shown.

one participant, the opposite effect is observed. The mean magnitude of the effect is shown in Figure 6. It is 3 dB for the preference experiment (right). This is considerably larger than that for the loudness judgement, which is close to zero and where the interindividual standard deviation is less than 1 dB (left). This indicates that the preference is not solely determined by the loudness but is also largely influenced by other factors such as the loudness of the tonal content of the sound.

Summary

The present study investigated the effect of active noise reduction on the perception of the sound emitted by a stripped car engine. Noises emitted by an oil pan from a car engine were compared to artificial sounds. The level at equal magnitude of sensation was measured for the partial loudness of the tonal content, the overall loudness and the preference. This approach allowed to quantitatively assess the reduction of the magnitude of tonal content, loudness and sound quality (preference) due to the active noise control. In our example, the tonal content was largely reduced and the acceptance of the sound increased while the loudness hardly changed.

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