VIBRO-ACOUSTICAL SOUND REPRODUCTION IN CARS

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Usually, headphones are used for seat-related entertainment systems in passenger vehicles. The goal of this project is the individual multi-seat audio reproduction using only loudspeakers. The main challenge is the crosstalk between different positions at low frequencies. One approach to solve this problem is the substitution of airborne sound by seat vibrations. Previous studies have shown, that such vibrations can improve the perceived quality of the music experience [1, 2, 3, 4]. Additionally, vibrations do influence the perceived intensity of a sound at low frequencies - the so-called auditory-tactile loudness illusion [5, 6]. This article discusses if the individual acoustic bass level can be reduced by excitation of seat vibrations. A car seat equipped with multiple vibration actuators was developed for the experiments. Different perceptually optimized algorithms were applied to generate vibrations from audio signals, taking into account the transfer characteristics of the exciters. Several music sequences were selected as test stimuli. The influence of different vibration levels was also investigated.

Introduction

It has been shown in a previous study that vibrations (mechanical stimuli, which excite the surface of the body and stimulate the tactile sense) are able to influence the perceived loudness of a sound at low frequencies [6]. Sinusoidal tones were perceived to be louder when vibrations were reproduced simultaneously via a seat. Because of this cross-modal loudness illusion, it might be possible that the ideal low-frequency audio equalization might change under the influence of additional vibrations in a music reproduction scenario. Therefore, this study investigated if the bass level can be reduced under the influence of seat vibrations. Several music sequences were selected as test sequences. The influence of different vibration levels was also investigated.

Setup

To investigate the coupled perception of vibrations and sound, a reproduction system was developed. Vibrations were generated via a car seat equipped with multiple vibration actuators. A first shaker was attached to the bottom of the seat and a second shaker behind the backrest. Figure 1 shows the seat and the position of the actuators. The transfer characteristic of the vibrating chair (acceleration at the surface of the seat versus voltage input) was measured for multiple subjects. A vibration pad (Brüel & Kjær Type 4515B) was used. The averaged transfer function (15 measurements: 3 subjects and 5 repetitions) at the seating is plotted in Figure 2. The characteristic at the backrest is comparable. A distinct resonance behavior can be seen. Inverse filters were designed in MATLAB to equalize the amplitude response. For real-time implementation in Pure Data, the resulting FIR filters (40th order) were divided into 20 biquad sections. Vibration generation was also implemented in Pure Data by simply low-pass filtering the mono sum of the audio signal. A 200 Hz Butterworth filter of 10th order was used. More advanced perceptually optimized algorithms, which will not be described here, were developed to generate vibrations from audio signals. For a discussion of the influence of various algorithms on the perceived concert quality in a music reproduction scenario please refer to [4].

Figure 1: Car seat with the position of electro-dynamic shakers.

For audio reproduction a conventional stereo setup was placed in a sound studio. Two Genelec 8050A loudspeakers and a Genelec 7060B subwoofer were used. The loudspeakers were placed in ear height with a distance of 2.5 m. The system was equalized to a flat frequency response at the listener position in the center of the room.

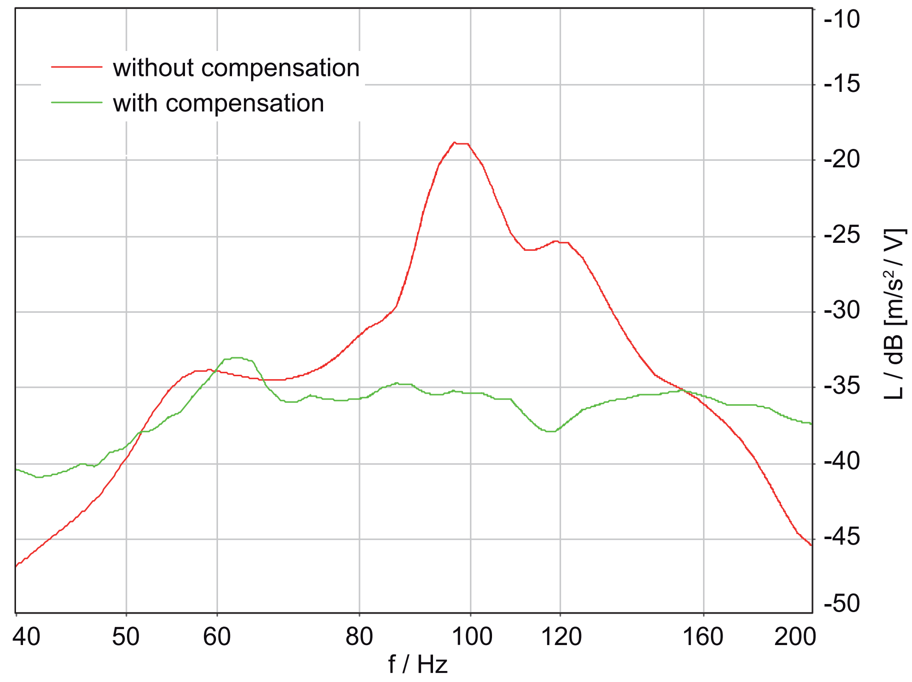

Figure 2: Averaged transfer function (FFT 65536, 1/24th octave intensity averaging) measured at the seat surface of the vibration chair, with and without compensation.

Subjects

A total of 19 subjects participated in the experiment (13 male and 6 female). They were between 23 and 28 years old (mean 25 years). All participants stated that they had no known hearing or spine damage. Most of the test subjects had never participated in a listening experiment before. In general, the listeners can be regarded as naive, with no background in audio engineering or sound evaluation.

Stimuli and Experimental Design

Four music sequences were selected that include low-frequency content:

– BRADLEY, Charles - You Put The Flame On It, from: Victim Of Love, Daptone / Dunham Records, 2013
– BEATSTEAKS - Hand In Hand, from: Smack Smash, Epitaph / Warner, 2004
– MODERAT - Bad Kingdom, from: II, Monkeytown Records, 2013
– Wir sind HELDEN - Gekommen um zu bleiben, from: Von hier an blind, EMI Music, 2005

The sequences from different genres varied in speed and type of the bass content. The sequence MODERAT contained synthetic electronic sounds. The other sequences were recorded with electric and acoustic bass instruments. Also the temporal structure of the bass line varied between stimuli. There were long bass notes (BEATSTEAKS) and fast bass lines (HELDEN). The loudness of the four sequences was equalized in a pilot experiment using two subjects. The resulting equivalent continuous sound pressure level was measured; for instance, a value of approximately 73 dB(A) was obtained for the sequence BRADLEY. The first seconds were removed from two sequences, because not much bass was contained in the audio signal (BEATSTEAKS - ca. 10 s, HELDEN - ca. 9 s). To ensure that the participants had sufficient time for their evaluations, the stimulus length was not limited.

A diagram of a sample trial is shown in Figure 3. The *reference* interval without vibration and the test *test* interval with vibration were played back in turns. The participants were allowed to switch individually between both intervals at any time and as often as wanted. A computer screen provided feedback about the currently activated interval for better orientation. The reference interval contained the original unmodified music signal with fixed bass level (flat frequency response). In contrast, the bass level in the test interval was adjustable. The listeners were asked to adjust the bass level during the test interval, until the bass intensity in the reference and the test interval felt the same. The vibration in the test interval remained the same throughout each trial. Adjacent intervals were separated by 0.75 s breaks. The music sequence was continued at the same position at which it ended in the last interval.

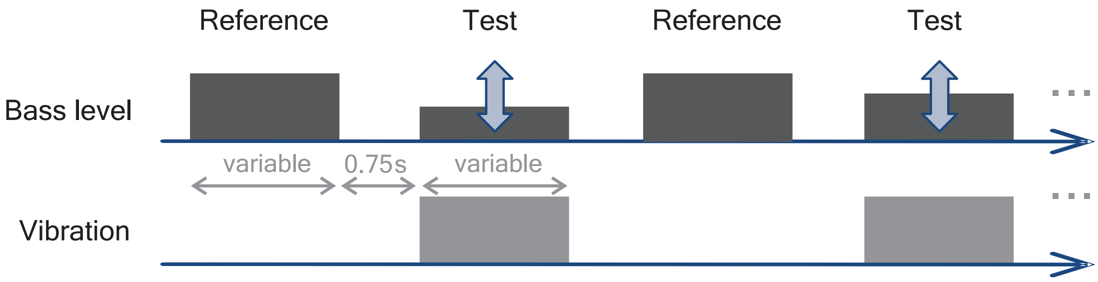

Figure 3: Experimental procedure: The test participant was allowed to switch between the reference and test interval until she/he was satisfied with her/his adjustment of the bass level. Throughout each trial, the vibration amplitude remained constant at a 0 dB, 3 dB, 6 dB, 9 dB or 12 dB sensation level.

A shelving filter at 200 Hz was implemented in Pure Data for adjusting the bass level in real time. An infinite rotary knob with no visible marks was applied (PowerMate, Griffin Technology). Intensity increments were possible in 0.5 dB steps over a $\pm$6 dB range. The initial bass level in each trial was randomly varied over the complete dynamic range.

The listeners were asked to adjust the bass level for five levels of vibration. Additionally, a condition without vibration was investigated. The acceleration levels referred to the individual perception threshold to ensure that the perceived vibration magnitude was comparable between subjects. The threshold was measured for each participant in a short test. Supra-threshold white noise was used as vibration signal. Masking white noise was reproduced throughout the experiment at 74 dB via headphones to reduce the influence of possible sound radiation of the seat. The subject was asked to use the rotary knob described above, to reduce the vibration intensity until the vibrations were just perceivable. Subsequently, the threshold was tested again. The experimenter raised the intensity slowly until the subject raised her/his hand to indicate that she/he felt the vibration. An averaged perception threshold was calculated from the two measurements for each participant.

The five acceleration levels were then adjusted relative to the individual thresholds and were further labeled as relative vibration levels: 0 dB (just perceivable vibration) , 3 dB, 6 dB (medium vibration), 9 dB, 12 dB (strong vibration). A relative vibration level of 0 dB means that the *averaged* RMS acceleration level of a music sequence was equal to the acceleration level at the perception threshold. However, the *peak* acceleration level is slightly above this threshold - depending on the music sequence.

To test the reliability of each subject, there were two repetitions of each sequence. This process resulted in a total of 48 trials (four sequences $\times$ six vibration levels $\times$ two repetitions). The listeners were allowed to stop a trial as soon as they were satisfied with their adjustment. Before the experimental session, the listeners were familiarized with the procedure and all of the music sequences. The overall test time varied between subjects and took up to 1:30 h including a break.

Results and Discussion

Figure 4 presents the mean adjusted bass levels, for which the perceived bass intensity was judged as equal in both intervals. The adjusted bass level corresponds to an increase or decrease of the bass level in the test interval compared to the reference interval.

For the condition without vibration, the adjusted bass level is approximately 0 dB as expected. This case is marked with a horizontal line. With increasing vibration level, the adjusted bass level decreases. This effect is significant for vibration levels ≤ 9 dB (repeated-measures ANOVA). The difference between 9 dB and 12 dB is not significant. The subjects reported perceiving the highest vibration level as too strong.

The mean standard deviation for the two individual repetitions of the same stimuli was below 1 dB, which suggests reliable results. No significant effect was found for differences between music sequences. Furthermore, no preference groups were observed.

Figure 5 shows the mean values from this study in comparison with results from other studies. In contrast to this study, no influence of seat vibrations on the perceived bass intensity of music was found in an earlier experiment of the author [7]. The main difference seems to be the applied experimental method: The task of the subjects was to adjust the intensity of the bass to their *preferred* level. *No reference* stimulus was reproduced helping the subject to orient. The participant had to rely on her/his internal reference. Naive listeners, with no background in audio engineering or sound evaluation took part in the experiment. Therefore, it can be assumed that this internal reference was not very stable. In comparison to the current study, a much stronger variance was found in the results. Additionally, the internal reference might have changed because of the vibration signal: The subject might have expected an amplified bass in the presence of stronger vibration. This theory could explain the missing influence of the vibration level on the bass equalization preferences in the previous study. However, this effect might have been reduced in the current experiment. The reason for this could be the direct A-B comparison (with and without vibration) and the task to *match* the bass intensity and not to adjust the intensity of the bass to a *preferred* level.

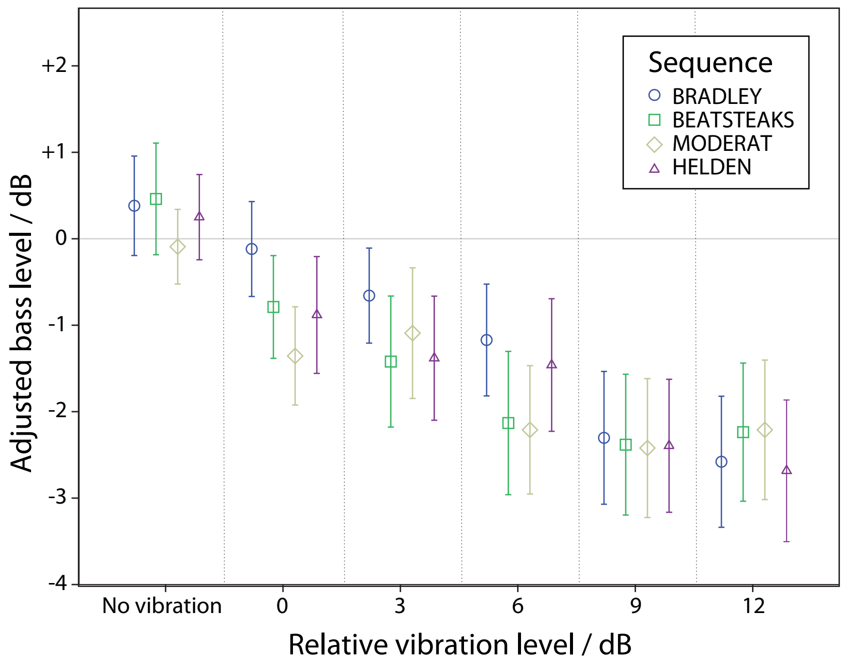

Figure 4: Mean of the adjusted bass levels with 95 % confidence intervals for different vibration levels. The adjusted bass level (in the test interval) is plotted relative to the bass level in the reference interval (flat frequency response). The vibration level is plotted relative to the individual threshold.

Another interesting point is that there is already a small shift of the adjusted bass level for just perceivable vibration (0 dB relative vibration level). The reason for this could be different methods to estimate the threshold of vibration perception. Even small level differences can result in a strong perceived difference, because the perceived vibration magnitude grows rapidly in the proximity of the threshold [4].

Two other studies reported that vibrations associated with low-frequency reproduction of music in an audio system produced a decrease in the level of preferred bass equalization. Data from Simon et al. [8] and Martens et al. [9] are plotted in Figure 5 for comparison.

Both studies investigated the same automotive audio system via binaural reproduction using headphones. Vibrations were generated from the audio signal using a low-pass filter. Martens et al. [9] reproduced vibrations using a platform in a room. An adaptive staircase tracking procedure was applied for bass adjustment. Short audio segments were selected from four musical sequences. Simon et al. [8] simulated vibrations by mounting a low-frequency audio transducer under the seat of a car. Two looped audio sequences were chosen with lengths of 20–30 s. The test procedure was similar to that applied in the previous study of the author [7]. The task of the subjects was to adjust the bass equalization levels to taste. However, both studies used trained listeners with backgrounds in audio evaluation. Presumably, these experts have been familiar with the applied stimuli. This could have resulted in a more stable internal reference related to the sound of the audio examples.

The data from both studies agree with a 1.5–2 dB decrease in the preferred bass level for a 4 dB increase in vibration level. In comparison, a slightly weaker level dependency was found in this study. Other multimodal experiments with sinusoids have shown a weak or missing dependency on vibration level [5, 6]. Martens et al. reported that at higher vibration levels, the audio experts might have become annoyed and 'reduced the level of bass equalization, perhaps with the false hope that it might also reduce the vibration' [9]. This would have biased the effects, resulting in lower preferred bass levels.

The differences between the results cannot be conclusively explained. Further experiments with modified experimental methods are conducted at the moment.

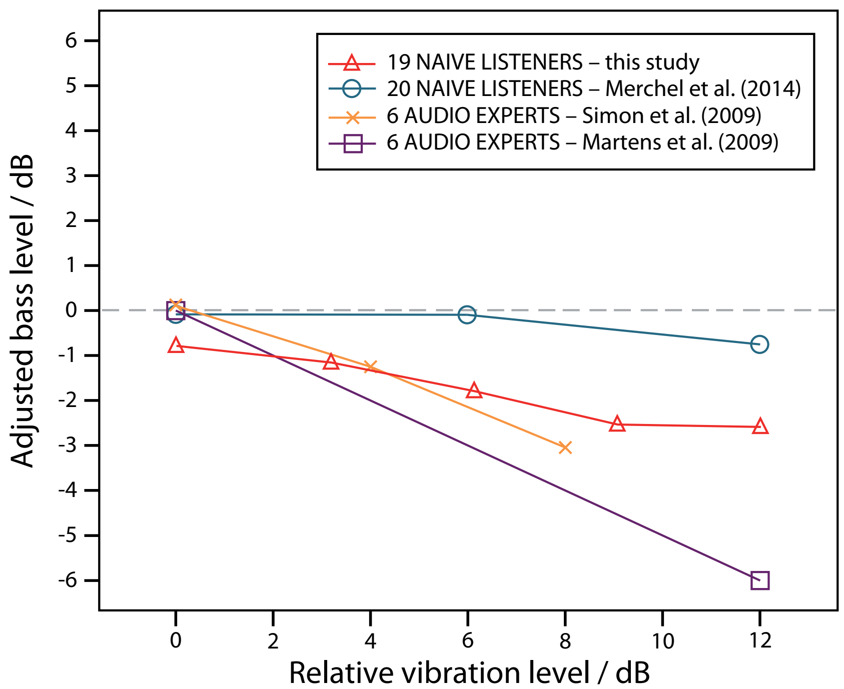

Figure 5: Comparison of the adjusted bass levels for simultaneous vibration reproduction from several studies [7, 8, 9]. The vibration level is plotted relative to the individual threshold.

Acknowledgement

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