Investigation into the human perception of separate and combined air- and structure-borne excitation of the ABS/ESP system

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Introduction

This paper addresses the human perception of ABS-excited sound and vibration. It tries to find an answer for the question which excitation is more important for the ABS evaluation, air- or structure-borne. Therefore the annoyance of sound and vibration are evaluated separately as well as combined.

Antilock braking systems cause fluctuations of the hydraulic brake pressure and thereby excite vibrations on the brake pedal and noise inside the cabin. Such noise and vibrations affect the comfort feeling of the driver, especially if they exceed certain limits. The perception thresholds for foot-transmitted vibration are presented in recent studies [1, 2]. Additional auditory stimuli are shown to have negligible effect on the vibration perception threshold [3, 4] while mutual effects for combined noise and vibration are reported for comfort evaluations for several applications, e.g. railways [5, 6] or vehicles [7, 8]. With regard to the partially very different results in studies on vibration/noise perception it becomes clear that investigations should be done as close as possible to the field of application, since results cannot easily be transferred between different situations.

Experimental environment and procedure

Subjects are exposed to braking noise and pedal vibrations in a realistic vehicle simulator representing the particular posture and brake pedal forces during braking [2, 4]. Foot acceleration is measured directly at the plantar area [2, 4]. Noise-only evaluation is done in earlier hearing tests.

Stimuli are 35 different records of pedal acceleration and the corresponding cabin microphone, acquired during on-road tests on low-µ tracks. Signals are cut to 5 seconds duration. Previous to each test, vibration signals are corrected by the inverse of the individual transfer functions of the excitation path (shaker-pedal-foot). This results in a very good reproduction of the original vibration at the participant foot, as shown in Figure 1 as an example.

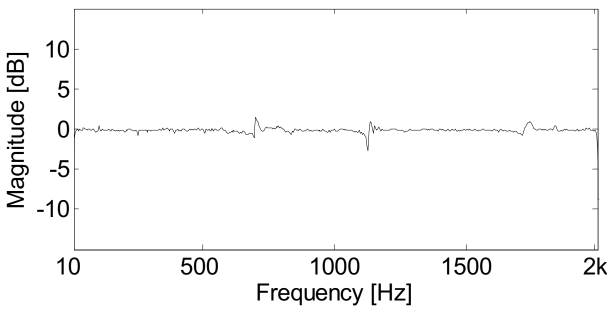

Figure 1: Magnitude of transfer function between desired acceleration signal (bandpass-filtered noise from 10 Hz to 2 kHz) and the actually measured foot acceleration for one participant.

Subjects have to evaluate the annoyance of each stimulus or combination of stimuli on a 10-segment scale, as widely used for comfort evaluations in the automotive industry. Rating 1 represents the worst rating and 10 means no annoyance. The 'individual test' procedure [9] is applied, allowing the arbitrary play back and repetition of each stimulus and changing of a given rating until subjects are sure to have given the appropriate ratings. Before the actual test, each participant attends a training session. The presented ratings are rounded median values.

Annoyance of combined noise and vibration

Figure 2 shows the ratings for sound and vibration alone as well as for both combined. In 88% of all cases investigated here the rating for combined noise and vibration is worse than the corresponding ratings for vibration or noise alone or equal to the worst of both. The changes in the evaluation of combined sound and vibration clearly indicate that both modalities contribute to the overall annoyance.

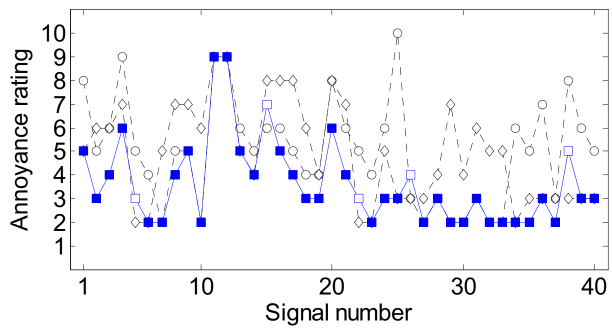

Figure 2: Ratings for vibration only (circles), sound only (diamonds) and combined sound and vibration (squares). Filled squares indicate the signals for which the combined rating is worse than the single ratings.

When considering combined noise and vibration in comparison to the evaluation of vibration only, the ratings get worse in 68% of all cases (see Figure 3).

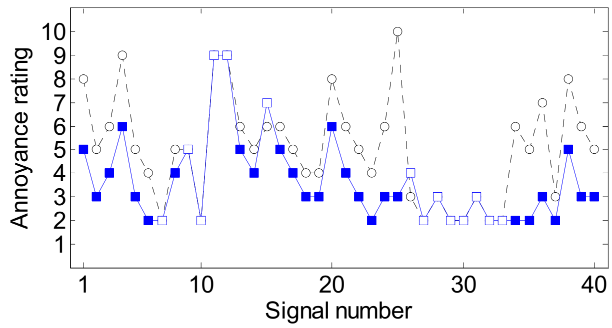

Figure 3: Ratings for vibration only (circles) and for combined sound and vibration (squares). Filled squares indicate the signals for which the combined rating is worse.

In comparison to evaluations for sound only, the combined ratings get worse in 60% of all cases (see Figure 4).

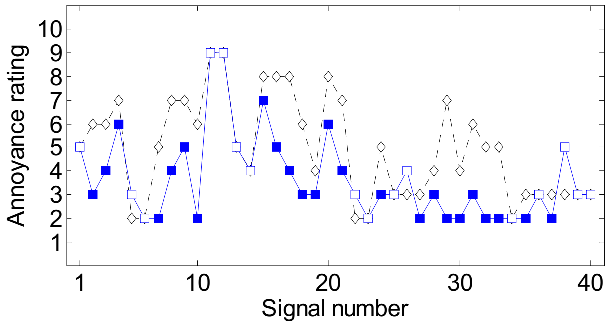

Figure 4: Ratings for sound only (diamonds) and for combined sound and vibration (squares). The filled squares indicate the signals for which the combined rating is worse than the rating for sound only.

The remaining cases, in which the combined ratings are better than the ratings of sound or vibration alone, show deviations about one. This is in the range of the individual rating repetition deviations. The repetition deviation is calculated as the absolute averaged deviation between the 1st and 2nd ratings of five repeated signals. For the evaluation of pedal vibration the rounded median deviation of ratings differences of the 15 participants is 1, which indicates consistent rating behavior. Also in case of combined evaluation of sound and vibration the rounded median of rating differences is 1.

In case of the strong stimulation of one modality (vibration or sound), this modality dominates the combined annoyance rating. For the signals investigated here, vibration became dominant in cases with stimulus levels causing vibration-only ratings around two. For sound no such relatively clear border can be said from the existing data. Further investigations are ongoing to clarify the observed effects.

A correlation analysis between instrumental signal parameters suggested in [5] for the evaluation of vibration and the median ratings showed the r.m.s. of foot acceleration to be a useful predictor for the perceived annoyance. The obtained linear relation, yielding a R^2 value of 0.76, is

$$\Psi = -0.41s + 8.9,$$

where Ψ is the vibration annoyance and s is the r.m.s. in ms^{-2} of the pedal vibration signal.

Ratings of experts vs. non-experts

All in all 15 persons participated in the experiments which are conducted in the simulator (vibration only and combined evaluation). Five of them were experts, working in the field of brake NVH. For the evaluation of vibration only, all inter-rater differences are found to be non-significant (Friedman, p=0.66). Thus also the rounded median ratings of the experts and non-experts groups do not differ significantly.

Concerning the evaluation of combined noise and vibration, the experts group showed no significant differences in the participants ratings (Friedman, p=0.69). The data of three participants are removed from the non-experts group leading to a homogenous data set with non-significant inter-rater differences (Friedman, p=0.64). There is also good agreement between the individual judgments of this group and the experts group (Friedman, p=0.7, see Figure 5). Median ratings from these two groups (N=12) are used in the previously presented analyses.

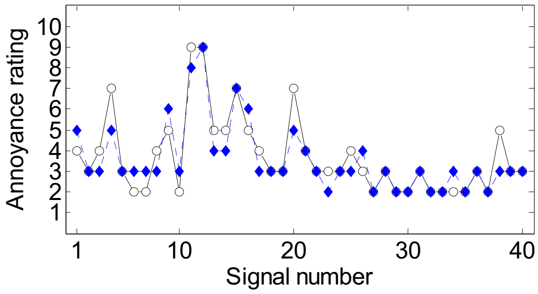

Figure 5: Rounded median ratings for combined evaluation of sound and vibration annoyance, given by experts (filled diamonds) and non-experts (circles).

In case of the evaluation of modulation noise the inter-rater differences are found to be not significant (Friedman, p=0.31). Four experts and 13 non-experts attended in the hearing tests for modulation noise. Summing up it can be said the experts do not show a different evaluation behavior compared to non-experts, even of the individual rating stability of experts is generally higher.

Summary

We have shown that both vibration and sound contribute to the overall annoyance of modulated sound and vibration due to ABS excitation. If one of them is dominant, then it determines the final rating of the system. A correlation analysis showed the r.m.s of pedal vibration to be a useful predictor for the perceived vibration annoyance. No significant differences are found between the ratings of brake system NVH experts and non-experts.

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