Sound Quality Evaluation of Power Seat Adjusters

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Introduction

The sound quality of electric adjusters in the car interior has become more and more important. Increasing customer requirements and cost pressure have led to a strong demand for reliable and efficient testing methods. Usually, the psychoacoustic modelling of auditory attributes requires a large amount of empirical data from listening experiments. However, experimental labour can be saved if the design of experiments (DoE) approach is used where a fractional factorial design is applied by means of a response surface (RS). The latter can be regarded as a systematic structure of parameter combinations, the dimensionality of which is given by the number of selected parameters. In contrast to a full factorial design, a small number of stimuli representative of all relevant parameter combinations is employed, and the number of experimental runs is decreased too a large extent.

This paper addresses the question as to whether the DoE method is suitable for the investigation of psychophysical functions of auditory sensations relevant in the evaluation of the sound quality of power seat adjusters. It is intended to derive psychophysical functions from annoyance ratings of synthetically-produced stimuli and to use the DoE approach for a critical monitoring of the results.

Method

Selection of Parameters

In the first step, the dimensionality of the RS design was determined through the selection of relevant physical parameters. The idea was to explore annoying noise components of power seat adjusters by means of a survey with acoustic experts. It was shown that the sound quality of power seat adjusters is strongly related to loudness, short-term disturbances and temporal fluctuations of the tonal components (see also [1]). The latter were subjected to further investigation in the present study while the well-known loudness factor should be eliminated through equalization. The tonal components and their temporal fluctuations are dependent on the rotational frequency, respective orders of the electric motors and fast periodic changes of the load [2]. Primarily, this is equivalent to a frequency modulation of sinusoids and therefore relatable to investigations of the psychoacoustic sensation fluctuation strength [3][4][5][6][7]. For the experiment, the modulation frequency (f_{mod}) and the modulation depth (m) were considered as primary factors. Further, the relative change of the carrier frequency (f_c) over time was added as a third factor describing the long-term behaviour of the tonal components ($\Delta f_c(t)$). The latter is caused by a slow and continuous load change.

In the second step, a representative sample of parameter values was specified for each dimension defining individual ranges and centre points. The parameters f_{mod}, m and $\Delta f_c(t)$ were varied so as to be representative of the observed operating area of power seat adjusters. While f_{mod} and m were each varied from the observed minimum to the maximum, $\Delta f_c(t)$ was altered symmetrically to the range centre with negative and positive values.

Response Surface Design

Figure 1 shows the three dimensional RS comprising a symmetric structure with 16 nodes. The nodes represent the stimulus configurations based on five graduations for each parameter (see [8][9]). The latter manifest themselves in a structure of a 2-nodes centre, a surrounding 8-nodes cube and a 6-nodes star. The centre nodes, which mark the focus of each parameter, are applied twice to allow for an estimation of the measurement error. The star data estimates the shape of the psychophysical function associated with each dimension. Three nodes thus may be indicative of either a linear, a quadratic or a constant function. Generally, parameters should be spaced in a way that the presumed types of the functions can be proved and alias effects are avoided at the same time.

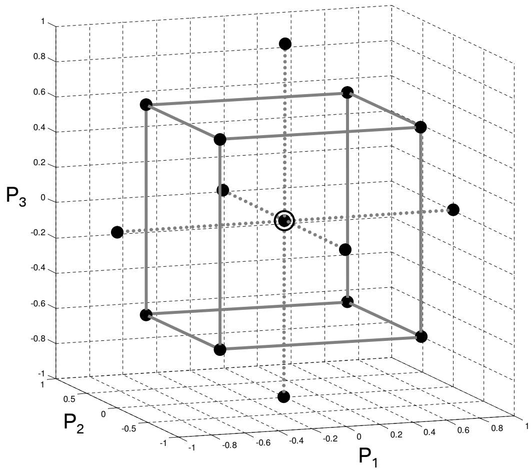

Figure 1: Response surface with three parameters (P)

The cube nodes allow for a confirmation of the presumed functions by means of other parameter constellations (see Fig. 1). A geometric shape of the function based on linked node pairs of the cube indicates the independence of the parameters from the observed annoyance data in the respective parameter range.

Figure 2 reflects subspace diagrams with exemplary annoyance data to demonstrate the rationale of the DoE method. The following geometric criteria are assumed

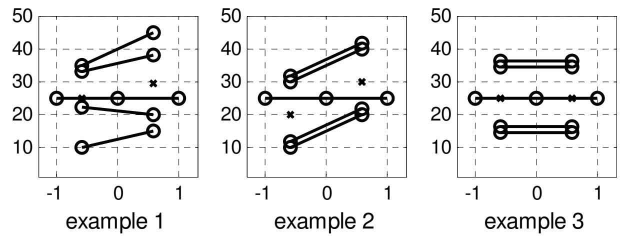

Figure 2: Examplary subspace diagrams of annoyance (A)

to account for parameter independence: parallel lines of the linked pairs (example 2 & 3), coincident positions of related nodes (example 2 & 3), coincident positions of the arithmetic means (cross indicator) of related nodes data with the estimated star characteristic (example 3). If all of the three criteria are fulfilled, the parameters in the observed range can be assumed to be independent of each other and the RS approach can be expected to yield valid results.

Listening Experiment

Apparatus and Stimuli

Synthetic sounds were produced which primarily consisted of a prominent tonal component (f_c) at 500 Hz with respective orders. In addition, a frequency modulation (f_{mod}, m) and a time-dependent change of f_c were implemented. The loudness of all sounds was equalized which involved to restrict the frequency shift of the tonal components to a range within critical bands. In order to achieve a realistic sound character of the signals, a dummy-head recorded noise was superimposed on all synthetic sounds. This sequence consisted of the starting and ending of a power seat adjuster and had a sound character that reflects a realistic impression of the car interior [10]. Furthermore, striking tonal components were removed from the recorded signal to avoid the interference with synthetic components.

In the intention of a reliability analysis 8 randomly picked sounds were represented twice in the stimulus set which thus comprised a total of 24 signals. The duration was 4,1 seconds equivalent to the duration of the superimposed noise sequence. Signals were presented diotically.

Participants and Procedure

A total of 47 test subjects (39 males, 8 females), mostly consisting of staff members, participated in the experiment. They were required to provide annoyance ratings of the stimuli according to the method of category-subdivision scaling (50-points scale). In this method, subjects are instructed to first select one of the five verbal categories ranging from *almost not annoying* to *very strongly annoying*, and afterwards to fine-tune the rating according to the 10-point numeral scale within the category [11]. Stimulus sequences were randomized for each subject [12][13]. On average, the experiment took the participants about 15 minutes to complete the task.

Results

Mean annoyance ratings are plotted against the parameters under investigation as shown in Figure 3. The

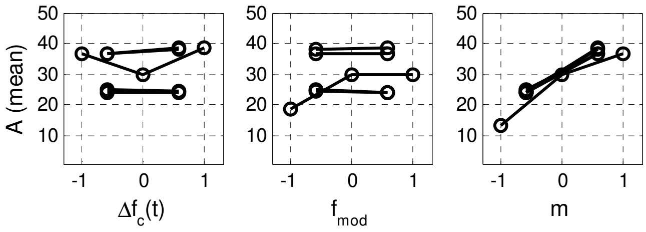

Figure 3: Subspace diagrams of annoyance (A)

subspace diagrams depict orthogonal views on the RS response data each focusing on the isolated behaviour of one parameter. The geometric positions of the paired cube nodes can be used to evaluate the curve fit according to the criteria mentioned above.

Figure 3 shows that there are only small deviations from an ideal fit, which are due to the dispersion of the ratings, hence the assumption of independent parameters can be accepted. Consequently, the original data were transformed as shown in Figure 4. While the annoyance

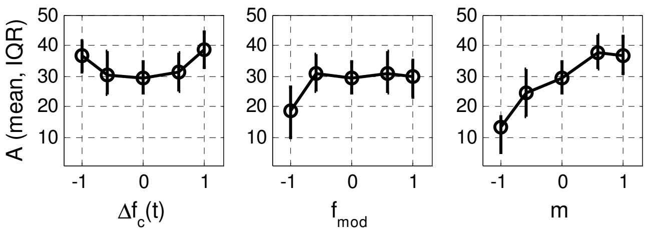

Figure 4: Transformed subspace diagrams of annoyance (A)

values represented by the data points #1, #3 and #5 is given directly by the RS star nodes, the data points #2 and #4 are calculated from the nodes of the RS cube because they were not measured directly. A good approximation for the subspace points #2 and #4 is the arithmetic mean of the annoyance ratings of the corresponding 4 nodes of the 8-node RS cube.

All of the three centre points (#3) in Figure 4 reflect the centre node of the RS. It can be interpreted as an anchor for all annoyance characteristics. The data shows an approximately quadratic function for the first parameter $\Delta f_c(t)$. As expected, a change of the carrier frequency over time has a direct influence to annoyance, regardless of this change being positive or negative. The second parameter f_{mod} mainly shows a constant behaviour except for the lowest modulation frequency of 0,5 Hz. The influence of the third parameter m is linear. The larger the modulation depth, the larger is the annoyance of a technical sound, independent from the modulation frequency.

Summary and Conclusions

The present study utilized the DoE method to derive psychophysical functions for a selection of parameters strongly related to the noise annoyance of power seat adjusters. A listening experiment was performed based on the experimental variations of three parameters (f_{mod}, m, $\Delta f_c(t)$). As opposed to a full-factorial design that would have resulted in a total of 125 stimuli, the DoE method required to prepare only 15 noises for the auditory assessment. Subspace diagrams were derived from mean annoyance ratings according to the DoE standards which allowed for an estimation of the underlying psychophysical functions.

Thus, the DoE method demonstrated to yield meaningful results by means of a minimum of experimental labour. Further research is needed to validate the presumed functions and determine the accuracy of the method.

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