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Specification of component sound quality applied to automobile power windows

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ABSTRACT

As cars become quieter the sound quality of components with electric motors becomes more important in the customer perception of vehicle quality. This has created a need to develop methods for the specification of component sounds. The objectives of this study were to identify perceptually important aspects, link them to acoustic metrics and, based on this, develop guidelines for the determination of requirements for power window sound. Seven prominent attributes were identified: *dull*, *loud*, *annoying*, *steady*, *powerful*, *overall product quality* and *under-dimensioned*. Effects of auditory stream segregation influenced the results. Power window sounds mainly consist of two sources: motor and window seal scratching. Subjects tended to judge only motor sound. Prediction models developed on isolated motor sound correlated well with judgements. Low loudness, sharpness and motor speed fluctuations led to perceived high product quality. The results emphasise the importance of handling auditory stream segregation and temporal variations in the sound design process.

1. Introduction

As car manufacturers design quieter cars to reduce wind, road and power train noise, the sound quality of systems with electric motors becomes more and more important for improving customer perception of overall vehicle quality [1]. Electric motors are commonly used in cars for applications such as power windows, seat adjustment, sun roofs, windshield wipers, etc. [2]. Power window sound is one of the component sounds which can be generated in a showroom and is consequently one of the components important in forming the initial impression of the car together with, for example, the door closing sound [3]. The increased focus on the sound of electric components has created a need to develop methods for specification of requirements for component sounds. To facilitate simple development processes, the requirements should contain physically measurable details which should be easily interpreted as descriptions of perceptions. The objectives of this experiment were to identify perceptually important aspects of power window sound, link descriptions of perception to acoustic quantities and to develop guidelines for determining power window sound requirements. The experiments were conducted in three steps: (1) interviews for elicitation of verbal attributes suitable for the description of perceived sound quality of power windows, (2) a listening test based on Verbal Attribute Magnitude Estimation [4] for the development of models for prediction of perceived sound quality based on acoustic metrics and (3) development of guidelines for determination of requirements for sound quality of power windows based on acoustic metrics.

Sound quality of power windows has previously been studied by Lim [5]. Seven technical attributes having a significant effect on the perception of annoyance were identified: seal separation noise, abrupt stopping sensation, motor tones, high pitch squeal/squeak, distinct transient impulses, quasi-periodic judder and time-varying character. Lim's study was restricted to the perception of annoyance. In the study reported upon here, the analysis was enhanced to include perceived overall product quality. Models based on acoustic quantities and subjectively measured qualities were developed. Models based on acoustic quantities facilitate simple requirement specification while models based on subjectively measured qualities increase the knowledge of underlying factors causing perceived annoyance and overall product quality. When the two are used together, the chances for finding suitable acoustic and psychoacoustic metrics for prediction of perceived qualities increase.

The human ability to, consciously or unconsciously, listen to parts of sounds will, in some applications, require knowledge about which parts of the sound field are actually being judged. Power window sounds mainly consist of two sources: the motor sound and the scratching sound of the window as it slides over the seal (also called weatherstripping). The experimental results were analysed to yield information about which of the two sources that were perceptually most prominent.

In the analysis of the experimental data special attention was paid to the influence of the temporal variations of the sounds. Most psychoacoustic metrics are originally designed to be used for steady-state sound [6]. Measures have to be taken to include effects of

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temporal variations when these metrics are used with time-varying sound. Since most laboratory experiments involve retrospective judgements this requires special handling. Kahneman et al. found that when judgements are made retrospectively subjects tend to judge peaks and ends of episodes rather than averaging their perceptions over an entire episode [7]. Västfjäll et al. demonstrated the same peak-and-end effect in sound applications [8]. Susini et al. showed that global retrospective judgements of loudness are influenced by the level at the end of the judged signal [9]. Therefore, it is important to evaluate the temporal character of samples with respect to peaks and ends.

2. Method

2.1. Recording of test sounds

Power window sounds from nine vehicles of several different brands were recorded. Binaural recordings were made in a semi-anechoic room at Volvo Car Corporation, Torslanda using Head Acoustics Noise Book and an artificial head (Head Acoustics HMS III) placed on front passenger seats. The artificial head was adjusted until its microphones were in ear positions for an average male passenger. Due to different voltages the speed of the power windows differed depending on whether the car engine was on or off. The voltage supplied with the engine at idle was chosen for the experiment. To avoid engine sound contamination of the recordings, the operating speed of the power window was first measured with the car at idle. Then the car engine was turned off and the battery replaced with an external power supply. The power supply was adjusted until the power window had the same speed as the speed measured with the car at idle. Measurements of the sound were made for both down and up travel of the window. The auto up/down function was used if existing.

2.2. Identification of prominent features in power window sound and elicitation of verbal attributes

To identify prominent features of power window sounds, seven subjects were interviewed. There were four men and three women. The average age was 37.9 years. All subjects were employees at Volvo Car Corporation, Torslanda. None worked with noise and vibration. For the test, three power window sounds deemed by the experiment leader to be considerably different in character were chosen. The interviews were carried out in the Sound Car at Volvo Car Corporation. The Sound Car is a rebuilt passenger car placed in a semi-anechoic room. The reproduction of sound in the Sound Car was controlled with a Head Acoustics SQlab system. Airborne sound was represented through subwoofers and headphones. The subject was sitting in the passenger seat and the interviewer in the driver's seat. The purpose of the interviews was to find which aspects of sound potential customers may focus on when listening to a power window and to elicit suitable verbal attributes to describe these aspects. The complete opening and closing events were judged including the starting and stopping events. The subjects were asked to state their opinions about the sounds. There was a special focus on the following aspects: What makes this sound good? What makes this sound bad? Does the sound contain annoying details? When in time do you find the sound good, bad or annoying? Spontaneous impressions and the use of similes were encouraged. At the end of the interview the subjects were asked to rank the power windows based on preference. The subjects were allowed to listen to the sounds as many times as they wanted. They were given no information about the origin of the sounds. The sounds were played in different random orders to each subject and were named A, B and C. The interview lasted for approximately 20 min.

2.3. Judgements of verbal attributes in a listening test

All nine sounds recorded as described in Section 2.1 were evaluated in a listening test. The listening test took place in the Sound Car (see Section 2.2). A total of 35 subjects participated – 17 women and 18 men. The average age was 34.6 years. All subjects were employees at Volvo Car Corporation, Torslanda. 18 of the participants worked with acoustics. The test was based on Verbal Attribute Magnitude Estimation [4]. The verbal attributes were selected from the interviews described above. Those interviews had shown that the travelling phase is more important than starting and stopping transients in the assessment of power window sound quality. This is consistent with the findings of Bernard et al. [10] who stated that it is important to differentiate between travel sounds and transient sounds because they induce different perception problems from a sound quality and tactile point of view. Similarly, Lim [5] found window opening slightly more important in estimates of overall sound quality than window closing. From a slightly different perspective, Zhang and Vértiz [11] found customer expectations of power window sounds to be essentially the same for window opening and window closing. Based on this, window opening with the starting and stopping transients excluded was chosen for further investigation. To avoid losing the realistic feeling the Sound Car provides, the starting and stopping transients were not excluded from the sounds presented to the subjects. Before the test it was emphasized to the subjects that the starting and stopping transients were not to be assessed. In addition to the nine recorded power window sounds, one of the sounds was played twice in order to check subject consistency. The subjects received instructions and a questionnaire written in Swedish. The native language of all subjects was Swedish. The subjects were asked to judge how well the verbal attributes *dull, loud, annoying* and *steady* described the sound of the power windows. The questionnaire also contained the questions: Does the power window sound powerful? Does it sound like a high quality power window? and Does it sound like the power window motor is under-powered? The judgements were assessed using nine point unipolar scales ranging from 0 to 8 with 0 representing "not at all" and 8 representing "much". First, the subjects listened to all sounds included in the test to get a feeling of the range covered. The sounds were then assessed sequentially in individually randomised orders. Each sound was repeated with a three second pause between repetitions until the subjects had answered the questionnaire. The subjects were given no information about the origin of the sounds. Tests lasted approximately 20 min.

2.4. Modelling annoyance and perceived product quality as functions of subjectively measured sound qualities

The main reason for modelling annoyance and overall product quality as functions of subjectively measured sound qualities was to understand which qualities are important for making a sound annoying or giving the impression of high overall product quality. The models were based on judgements of verbal attributes and were developed using linear regressions. As dependent variables, the means of all subject judgements of *annoying* and *overall product quality* for each power window were used. The means of all subject judgements of the attributes *dull*, *loud*, *steady*, *powerful* and *under-powered* were tested as independent variables.