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Sound quality of small electric motors

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ABSTRACT

The usage of electric motors at cars and household appliances increases and the sound quality of them is becoming more and more important. Their noise contains various tonal components at low and high frequencies and in some cases these tonal components are modulated. Mostly the frequency of tonal components are rotational speed dependent. Therefore psychoacoustical parameters, such as tonality, sharpness, fluctuation strength, roughness and loudness, can be used to describe their perceptual characteristics of electric motor sounds. Whining, rattling, roaring, booming and hum are some verbal descriptors of various kind of electric motor sounds. The aims of this study are to evaluate the perceived annoyance of small electric motor sounds and to identify the perceptually important features which are relevant to the quality impression. To systematically approach to these aims, first the electric motor sounds were recorded and the recorded stimuli were modified via digital filtering in frequency and time domains. Then the recorded signals were analyzed and their psychoacoustical metrics were calculated, in parallel a listening test to evaluate the sound quality was conducted. The results of the psychoacoustic analyses and the jury test were correlated.

Keywords: Electric motor, Sound quality, Annoyance
I-INCE Classification of Subject Number: 61

1. INTRODUCTION

Electric motors are widely used in different products, such as cars, bikes, airplanes, household appliances, shutters, elevators, fans, robotic applications, etc. Therefore their sound quality plays an important role for our daily life quality. Although most of the electric motors are silent, their sound can be heard and annoying in quiet environments. For a very long time until today, the reduction of the level of motor vibration and noise transmission is an important research topic (1-6). There are mechanical and electrical noise sources at electric motors, such as shaft bearings, brushes, arcing, cogging torque, etc. Mostly modelling of 3D magnetic field (electric circuit and magnetic field shape, the interaction of armature and field flux) and structural aspects of motor is necessary to define necessary noise and vibration reduction measures. There are several studies on the sound quality of powered seat adjusters and car window motors (6-9). These studies show that the psychoacoustical properties, such as loudness, sharpness, roughness, and fluctuation strength can describe the perceptual impression of the motor sound. The weightings of the properties and their number vary from one study to another study. This point is similar also for recent sound quality investigations on electric motors

(10-12). The quality of electric motor sounds as a part of household appliances was also research topic of various studies (13-16).

The small electric motors can generate sounds, which can be described as whining, rattling, roaring, booming and hum, etc. In an investigation, we conducted perceptual annoyance experiments with electric motor sounds which have whining, rattling, roaring, booming and humming characters. In this paper, we report the results of the perceptual annoyance experiments with electric motor sounds which has clatter character.

2. EXPERIMENTS

2.1 Stimuli

The sound of an electric motor with rattling problem was recorded using a binaural headset (HEAD acoustics). The recorded sound was analysed and then additional sound stimuli were generated by filtering important frequency components (e.g. tonal components using band pass filters, high or low frequency ranges using high or low pass filters). Short-time Fourier transform (STFT)-based original noise spectrogram and filtered versions are shown in Figure 1. The original sound has strong modulated tonal components at app. 2300 Hz, 3550 Hz, 5300 Hz and 6800 Hz. These modulations cause the clatter perception. Additionally, the sound has a very sharp character, because of strong high frequency components. Using the analysis results, the band stop filters at above mentioned tonal components and low pass filters with various cut off frequencies (1000 Hz, 2000 Hz, 4000 Hz and 6800 Hz) were used to generate the additional stimuli (Figure 1 b, c, d, e, f, g, h, i).

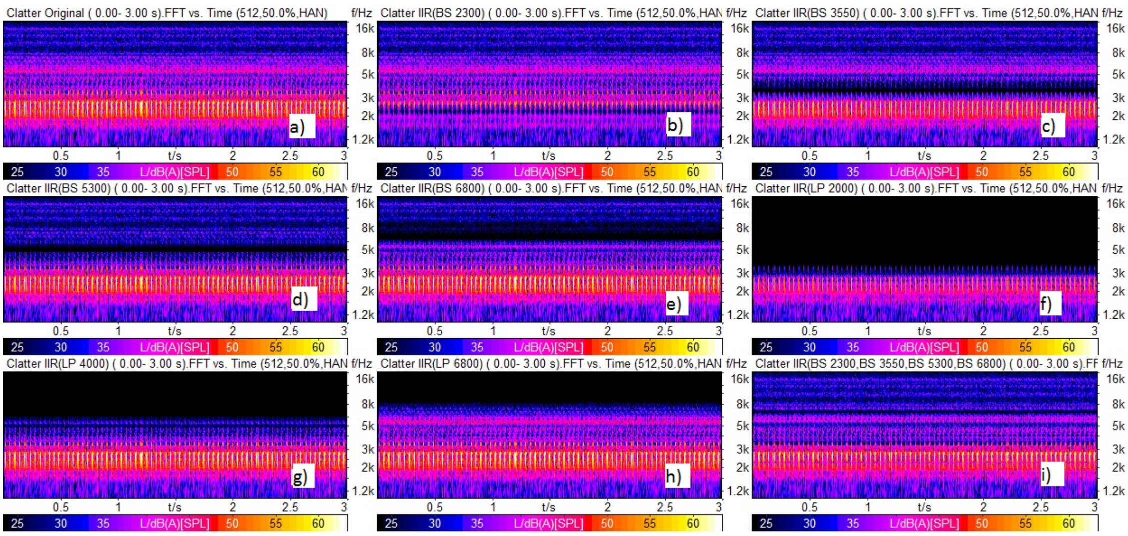

Figure 1 - The STFT-based spectrograms of original recording (a) and various variations, which are bandstop filtered signals at 2300 Hz (b), 3550 Hz(c), 5300 Hz (d) and 6800 Hz (e), low pass filtered signals with cut off frequencies 2000 Hz (f), 4000 Hz (g) and 6800 Hz (h). FFT length: 4,096, hanning window.

2.2 Participants

6 participants (3 female, 3 male) took part in the listening experiment. Age of the participants varies between 20 and 47 years old. The participants are naïve and don't have any acoustic or electrical engineering background. They were paid for their participation on an hourly basis. All participants have normal hearing (self reported).

2.3 Experimental Setup and Procedure

To present the binaurall stimuli, HEAD acoustics HA II.1 headphones were used. An aurally-accurate reproduction was guaranteed using a PEQ IV equaliser. The experiments were conducted in a sound-attenuated room. Sounds were presented in a random order and four times. The participants were asked to evaluate the annoyance of the sounds on a quasi-continuous scale (not at all - 0, slightly - 25, moderately - 50, very - 75, and extremely - 100). A graphical user interface was used for the evaluation experiments. The duration of the experiment was 45 Minutes, which includes a training and instruction session. The familiarization with stimuli was a part of the training.

2.4 Results of the Experiment

The analysis of the electric motor sound and the annoyance judgments show that particularly the loudness, the modulated tonal components and high frequency components are important to describe the annoyance caused by clatter. Particularly roughness has a dominant influence on the annoyance judgments. An annoyance index was developed based on the psychoacoustic properties, such as loudness (ISO532B), the sharpness (Aures model) the roughness (Aures model), the tonality (Aures/Terhardt model).

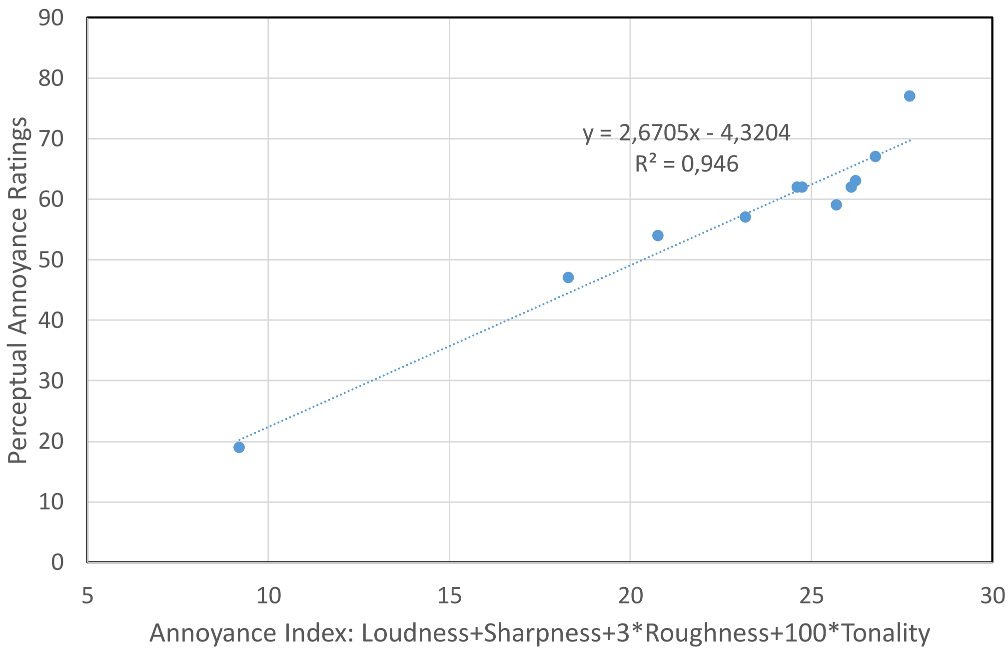

Figure 2 - The correlation between the annoyance ratings of the participants with the developed annoyance index.

The weightings of the individual psychoacoustic properties were determined based on the numerical values of the calculated properties, the trends of the annoyance judgments and the expert's opinion. The equation of the annoyance index is:

$$\text{Annoyance Index} = \text{Loudness} + \text{Sharpness} + 3 * \text{Roughness} + 100 * \text{Tonality}$$

A regression analysis between the developed index and perceived annoyance ratings resulted in a very high correlation coefficient of $r^2 = 0.94$ (Figure 2).

3. CONCLUSIONS

In this study, the sound quality of small electric motors regarding clatter was investigated. The results of the study show that roughness, loudness, sharpness and tonality are important psychoacoustical properties to describe the perceived annoyance. In this study, the number of participants was very limited, therefore the significance of the results is very limited. Future investigations are planned with more participants and other psychoacoustical analysis (like relative approach) will be taken into account.

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