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SOUND LABEL FOR HOUSEHOLD APPLIANCES

M.E. Altinsoy and S. Atamer
Chair of Acoustic and Haptic Engineering,
Technische Universität Dresden
Helmholtzstr. 18, 01069
Dresden, Saxony, Germany

ABSTRACT

Household appliances and their sound quality are important for our daily life quality. However the appropriate characterization of their sound is a difficult task. Not only product users but also manufacturers can profit from a sound label which characterize the perception of the customers. The purchase decision-making process according to acoustic criteria will be supported by such kind of label. In addition, a label and its components give orientation to the manufacturers during their product development process. Essential aspect for such kind of label is that it should represent the perception of the customers. Therefore psychoacoustical properties, e.g., loudness, sharpness, roughness, tonality, etc., are advantageous for characterization purposes. It would be beneficial to combine these psychoacoustical descriptors into a sound quality label, which is easy to understand. The authors have developed several sound labels for household appliances based on psychoacoustic properties. These sound labels are the result of the listening experiments which were conducted with potential customers. In this paper, various aspects of these investigations are summarized, extended and discussed.

INTRODUCTION

In our daily life, household appliances play an important role. Dishwasher or vacuum cleaner, for example, make our lives much easier by doing important amount of work and let us spare a lot of time. However, during their operation, they generate noise, which can cause annoyance. The sound quality of household appliances has direct influence on our life quality.

In most electronics shop, the customer doesn't have the possibility to listen the noise of the appliance during operation. Most of the regulations take into account only the sound power level of devices. The EU energy label, which is compulsory for white goods and based on the EU Directive 2017/1369 [1], includes the sound power level of the devices. Apart from that, there are several international and national ecolabels. For example the Blue Angel from Germany, the NF Environnement ecolabel from France or the TCO label from Sweden [2, 3, 4]. Most of these labels define upper limits for the sound power level of the products (a detailed overview can be found in [5]). It has been known for a long time that the sound power level or sound pressure level are important acoustical parameters, although they do not characterize the customers' perception of product sound sufficiently [6]. As early as 1990's, the first indexes/labels for the sound quality of refrigerators and vacuum cleaners were developed [7, 8]. These studies defined the basic steps for the development of indexes. These steps are the sound recording/data acquisition, subjective evaluation (listening test), signal and psychoacoustical analysis of the noises and the correlation of the results of the subjective evaluations and objective parameters. Furthermore there are commercial attempts from UK and Germany to define perception compliant labels. Quiet mark and SLG are two testing institutions are working in this area [9, 10]. However there are few publications about the details of the scientific background of these labels. Currently, there isn't any established EU, USA, Japanese, Korean, Chinese or other national directive, which defines a sound label to characterize the customers' annoyance perception of product sound.

For the characterization of annoyance perception, as well as sound pressure/power levels, loudness, high frequency content, timbre, steadiness, impulsiveness, amplitude variations and prominence of the tones are important parameters.

In this paper, we introduce the psychoacoustical parameters and evaluate their suitability for the labeling. One fundamental issue of the prospective sound labeling is the measurement setup. One of the questions of this paper to answer is: Where is the optimal measurement environment? Based on the answers given posing the following questions: Which (omnidirectional microphone or artificial head) and how many sensors are required for the labeling measurement? Where to place the sensors? Following these discussions, finally a sound label for dishwasher noise will be introduced.

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SUITABILITY OF THE PSYCHOACOUSTICAL PROPERTIES FOR LABELING

Several psychoacoustical properties are useful to describe the perceptual aspects of the household appliance noises. In this paper, we discuss about the loudness, the sharpness, the tonality, and the roughness.

Loudness

Cooker hood, vacuum cleaners, coffee machines and tumble dryers are loudest machines between the household appliances. Therefore their loudness play a very important role on their perceived annoyance and quality. Most of our previous studies show that the loudness have better correlation with the annoyance ratings rather than sound pressure level [11, 12, 13]. In most cases, quieter machine sounds obtain higher pleasantness ratings. In comparison to the above explained loud machines, refrigerators, dish washers, washing machines (except of spin), etc. are quite machines. Although they are quiet, the loudness also plays a role on their perceived quality. The results of the previous studies show that most of the users feel very annoyed, if their communication with partners or other residents will be disturbed by appliance sounds. Similarly, they are annoyed, when vacuum cleaner sound disturbs television watching or phone call. If the loudness of the household appliances is very high, the phone call or television program will be masked by the background noise and the user will suffer from reduced speech intelligibility. Therefore the intelligibility of speech, which can be predicted using the articulation index (AI) or speech intelligibility index (SII), is an important threshold for pleasantness and can be used for labelling.

The calculation model of the loudness was standardized and there are three available standards, ISO 532, DIN 45631 and ANSI S3.4 for the calculation [14, 15, 16]. These standards are based on Steven's, Zwicker's and Moore's loudness models. These models deliver very good loudness predictions for steady state sounds. There are also research for calculating the loudness of nonstationary sounds, and even some of them is standardized. Most of the household appliance noises have very complex character. Some of them have tonal character. In a previous study, we noticed that the above mentioned models underestimate the loudness of the machine sounds, which have tonal character [17]. Therefore the model results can be corrected using a weighting which is based on the tonality to obtain better predictions.

Sharpness

In most cases, the high frequency content of the household appliance noises is annoying. Sound signals that consist of spectral components mainly at high frequencies perceived as sharp. There are two different sharpness models, one of them was developed by Aures and another by von Bismarck [18, 19]. The difference of the both algorithms is the weighting (g(z)) and both algorithms are presented below:

$$S = 0.11 \frac{\int_0^{24\,Bark} n'(z).\,g(z).\,z\,dz}{N} \tag{1}$$

$$g_{Aures}(z) = 0.078\,\frac{e^{0.171.z}}{z}\cdot\frac{N}{ln\,(0.05\cdot N+1)} \tag{2}$$

$$g_{von\ Bismarck}(z) = \begin{cases} 1 & for\ z \le 15\ Bark \\ 0.2\,\cdot\,e^{0.308\,\cdot(z-15)} + 0.8 & for\ z > 15\ Bark \end{cases} \tag{3}$$

In these formula, n'(z) is the specific loudness, which means that, g(z) is the weighting factor, z is Bark, N is the total loudness. The algorithm of Aures considers the total loudness of the stimuli with higher weighting than von Bismarck. Both algorithms calculate different sharpness values for same signal, therefore it is important to give reference to the used algorithm for the comparison purposes.

Vacuum cleaners and tumble dryers have mostly a broad band noise because of the airflow [11, 13]. If the upper cut-off frequency of the broad band noise shifts towards higher frequencies, the tumble dryer or vacuum cleaner sound is perceived sharper and more annoying. In our previous study, we noticed that some vacuum cleaners in the market have extremely strong high frequency components which cause high annoyance (e.g. A1, A4 and A5 in Figure 1).

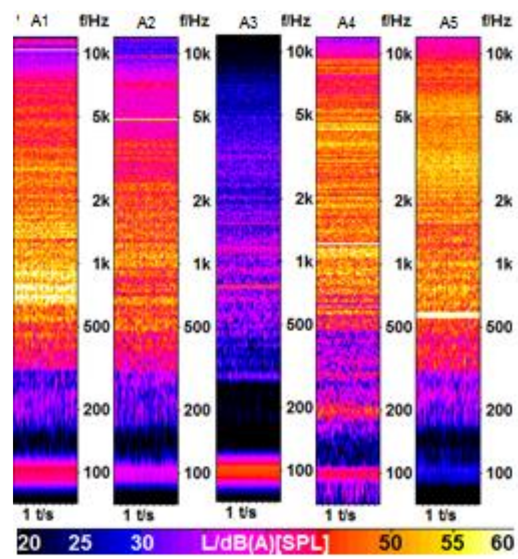

FIGURE 1: THE SPECTROGRAMS OF VACUUM CLEANER SOUNDS.

In some cases the splashing water causes high frequency sounds at dishwashers. Particularly if these high frequency

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dishwasher sounds are repeated with the rotation of the spray arm, their annoyance are higher.

Tonality

Most of the household appliances, such as vacuum cleaners, cooker hoods, refrigerators, shavers, etc. have tonal sounds. In most cases tonal components are mainly caused by electric motor (supply frequency, rotation speed and pole number-dependent) or fan (rotation speed and blade number dependent). The prominence and the incidence of the tonal components vary between sounds. Mostly 100 Hz or its harmonics are observable at washing machines, dishwashers or tumble dryers. These low frequency components can be amplified by room in daily use.

Our auditory system is very sensitive to the tonal components of a signal rather than the broadband components. The tonality describes the audibility of tonal components in a sound signal. DIN-45681 describes a tonality model, which is based on the difference between the sound pressure level of the tone and the background noise [20]. The unit of tonality is the tu, and 1 tu (tonality unit) corresponds to the tonality of a 1 kHz, 60 dB sine tone. Other models are the prominence ratio (ANSI S1.13 and Nobile/Bienvenue [21]) and the tone-to-noise ratio (ANSI S1.13). The prominence ratio model does not provide quantitative data.

Fluctuation Strength and Roughness

Amplitude or frequency modulated sounds elicit two different kinds of auditory sensations, such as fluctuation strength and roughness. At low modulation frequencies up to a modulation frequency of about 25 Hz, the "fluctuation strength" is perceived. At higher modulation frequencies, the auditory sensation of "roughness" is observed. At about 20 Hz, roughness starts to increase, and reaches its maximum near a modulation frequency of 70 Hz and decreases at higher modulation frequencies.

Roughness is influenced by the speed of change, i.e. it is proportional to the frequency of modulation and modulation depth. 3 tones within a critical band of human auditory system can cause a roughness perception. Until now, there is no any standard for the roughness calculation, but there are attempts to define a standard, which will be available soon.

The roughness phenomenon is observed at vacuum cleaners, washing machines, tumble dryers, shavers and particularly refrigerators. A very rough refrigerator sound was shown in Figure 2.

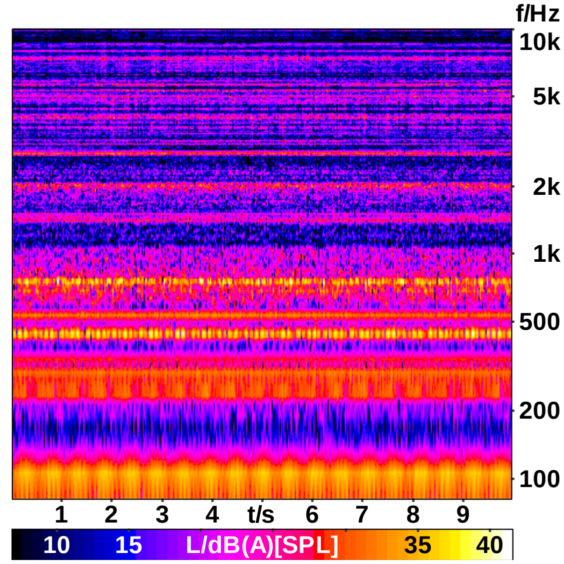

FIGURE 2: THE SPECTROGRAM OF AN EXAMPLE REFRIGERATOR SOUND.

OPTIMAL MEASUREMENT ENVIRONMENT, SENSORS, AND SETUP

Most of the household appliances are used in kitchens, bathrooms or in living rooms. The size and the acoustical parameters of these rooms differ from each other strongly. However in most cases, they have a hard floor or a carpet on it. Moreover to that, most of the dishwashers, washing machines or refrigerators are placed in front of a hard wall. All these aspects are taken into account in the current sound power level directives. Therefore typically the sound power level of household appliances are measured in the semi-anechoic chambers, which has a reflective floor. Additionally a back wall is used to simulate the kitchen or bathroom environment. These measurement conditions realize the minimum of common ground based on the room acoustical aspects. Same measurement environment conditions can be applied for sound label measurements. Most of the household appliances are integrated to the built-in kitchen. Therefore it is meaningful to use a housing/an enclosure according to the CEI IEC International Standard 60704-2-3 for the fully or semi integrated dishwasher, refrigerator, and washing machine measurements (except of free standing machines).

According to our previous investigations, artificial head recordings and diffuse-field high quality measurement microphone recordings deliver comparable results [11]. Because of the ease of use and availability, it is meaningful to use a single microphone for the labeling. However the position of the microphone is a critical issue. The sound radiation characteristic of the household appliances differs from each other strongly and is an important parameter, which we investigated in our previous studies. Most important position for the microphone measurement is of course the common or critical user place/position. This position differs between the

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vacuum cleaners and other household appliances. In most cases, the user of a vacuum cleaner is located between the brush and the vacuum cleaner. Therefore we recommend to use the microphone position, which is shown in the Figure 3. It should be noted that, this measurement set-up and defined recording position differs from the sound power level measurements of the vacuum cleaners.

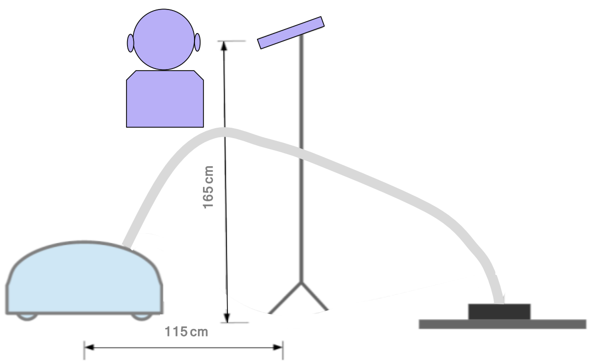

FIGURE 3: RECOMMENDED SETUP FOR RECORDING VACUUM CLEANER SOUNDS.

For the dishwashers, washing machines, refrigerators etc., we recommend to use a microphone position, which is in front of the machine, placed 1.5 m away to be in far field and the height of the microphone position can be 1.65 m (average ear height). In the future, more possible positions and the interaction between the sound radiation and room acoustics characteristics will be taken into account.

SOUND LABEL CALCULATION FOR WASHING MACHINES BASED ON PSYCHOACOUSTICAL PROPERTIES

We present, as an example, a sound label for washing machine sounds, which is based on psychoacoustical properties. The signal analysis of the washing machine sounds and listening test results show that loudness, sharpness, roughness and tonality are important psychoacoustical parameters to describe the perception of the washing machine sounds. Although wash cycle is very quiet, the spin cycle is very loud and annoying. Therefore the loudness is one of the important parameters. In some cases the sounds have dominant high frequency components which causes annoyance. These components can be described by sharpness. Washing machine sounds contain modulated and tonal sound components, which can be described using roughness and tonality.

Taking into account the results of the listening test and psychoacoustical analysis, an index was developed [12]. This index contains the above mentioned psychoacoustical parameters, such as loudness, sharpness, roughness and tonality.

$$\text{Sound Quality Index} = 2.5*N+4*R+S+T$$

The loudness (N) calculation is based on Zwicker model (ISO532B), the sharpness (S) and roughness (R) calculations are based on Aures models ([17], [22]), the tonality (T) calculation is based on Terhardt model. The developed index show high correlation with annoyance ratings.

SOUND LABEL FOR DISHWASHERS

A sound label for dishwashers was developed in our laboratory (Figure 4). It is important that the sound label can be clearly identifiable and differ from sound power labels. The usage of the letters and the colors allow the potential customer to easily identify the noise annoyance level of the appliance. Most of the psychoacoustical parameters are not known by potential customers, the indication of the psychoacoustical values of the appliance will make the label very complex and not be helpful.

FIGURE 4: SOUND LABEL FOR DISHWASHER SOUND.

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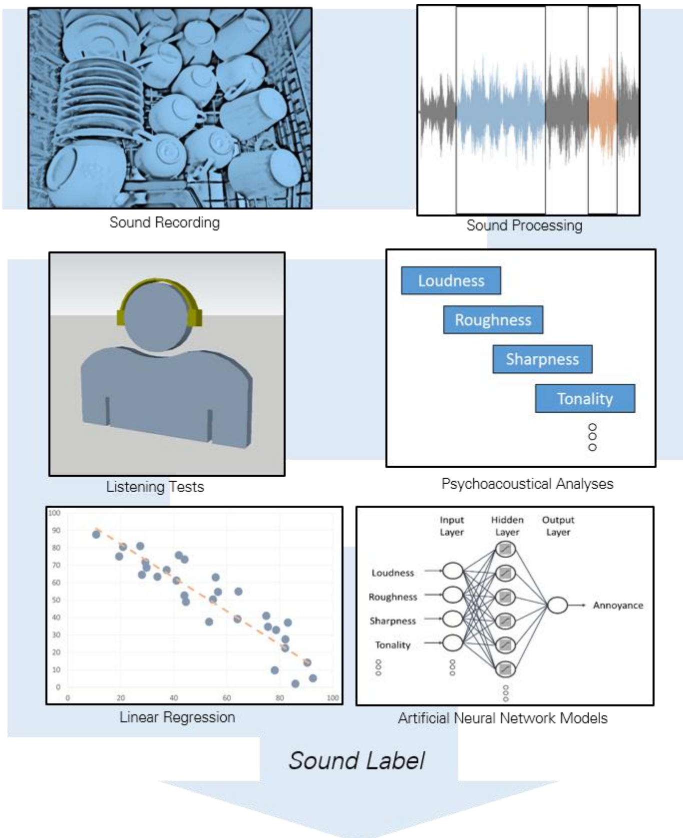

FIGURE 5: STEPS FOR SOUND LABEL CHARACTERIZATION.

For the preparation of the sound label, the above mentioned steps were conducted (Figure 5). Dishwashers from various brands having a broad band sound quality range were selected from the market. Their sounds were recorded in acoustic laboratory of TU Dresden, which fulfill the required environment conditions that were discussed in the section 'Optimal Measurement Environment'. During the recordings, microphone was placed 1.5 away from the front side of dishwashers, having a 1.65 m height.

The sound of dishwasher changes its character during the operation, depending on the selected washing algorithm. For the comparison, ECO washing algorithms of each device were used for recordings, which takes approximately 2.5 hours for almost all devices. From the recordings, characteristics time spans are selected, considering the phase of the device, including the upper and lower spray arm rotation and/or drying section. Applying a similarity analyses, representative stimuli is selected from the whole recordings, such that the selected real stimuli can represent most of the washing cycle of each device under test. Moreover, analysis of the original selected sounds was useful to generate virtual dishwasher sounds, which are possible variations of existing dishwasher sounds. 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) of these time spans, as the same procedure described in the former studies [12, 13]. The modified sounds are still perceived as usual dishwasher sounds. At the end, a stimuli data base is generated with real and synthesized stimuli of dishwashers.

In a listening experiment, the participants evaluated the annoyance of the recorded and generated dishwasher sounds. The experiments were conducted in a sound-attenuating room. Using headphones, the recorded sounds and their modifications were presented to the participants. The sound pressure level of the sound presentation was calibrated.

The procedure of the experiment was same as our former studies [12, 13, 17, 24]. The subjects were asked to evaluate the annoyance of the sounds, which is presented in a random order, on a quasi-continuous scale, for which Rohrmann had tested the equidistance of neighboring categories (not at all, slightly, moderately, very, and extremely). The length of the slider was 100 mm with a resolution of 1 mm. The score on this scale was equal to the distance (mm) from the left end of the bar. A graphical user interface in MATLAB was implemented for the evaluation experiments.

Lastly, dishwasher sounds were analyzed according to their psychoacoustical and signal based properties as objective parameters. The listening test results were correlated with objective parameters. According to the correlation, an index, which is based on psychoacoustical parameters, was developed similar to the washing machine study. The index results were translated to the letters, such as A, B, C, D …, which are easily understandable for the customers.

CONCLUSIONS

In this study, the importance of the sound labels, which characterize the perception of the sounds, for household appliances was discussed. The steps for the development of such a sound label and necessary psychoacoustical properties were introduced. The suitability of the psychoacoustical properties for labeling was discussed with examples. At the end a sound label for dishwasher sounds were introduced. The results show that an adaptation of the psychoacoustical properties for the complex household appliance sounds is necessary to achieve greater consistency between the labels and the perceived annoyance. Lastly, most of the existing sound quality indexes for household appliances are based on the regression model which considers the multiple linear regression between the subjective evaluation results and the psychoacoustical properties. However artificial neural networks (ANNs) can open up new opportunities for the sound labelling in the following future. [23, 24].

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