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Christian H. Kasess, Christoph Reichl, Holger Waubke, Piotr Majdak. Perception Rating of the Acoustic Emissions of Heat Pumps. Forum Acusticum, Dec 2020, Lyon, France. pp.2453-2458, 10.48465/fa.2020.0363 . hal-03234210

HAL Id: hal-03234210
https://hal.science/hal-03234210

Submitted on 26 May 2021

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PERCEPTION RATING OF THE ACOUSTIC EMISSIONS OF HEAT PUMPS

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ABSTRACT

Heat pumps are a versatile technology which becomes ever more popular. Thus, consideration as well as reduction of the sound emissions of such devices becomes increasingly important. The aim of this study presented is to perceptually evaluate the noise emission of an air-to-water heat pump in different directions using several, potentially noise reducing, measures. Four variants of a heat pump were under investigation, the emissions of which were recorded in a climate chamber equipped with sound absorbing walls. Four directions around the heat pump were investigated: near the fan inlet, the outlet and two directions perpendicular to the fan axis. 20 listeners performed an evaluation of these recordings. The listeners were asked to judge the annoyance of the sounds using a free magnitude estimation. Results show an effect of direction which is dependent on the variant of the heat pump. The differences in the annoyance can be explained by the A-level and the loudness level. By including the psychoacoustic sharpness and roughness the explained variance of the perceptual data is increased, albeit by a smaller degree.

1. INTRODUCTION

Heat pumps can be used for the heating or cooling of rooms or buildings as well as for the heating of water. As a consequence, heat pumps are an important part of the restructuring of the energy system. Clearly, the number one priority in the development of heat pumps is the energy efficiency. However, heat pumps also produce noise which is radiated into the surroundings. Due to the increased popularity the sound emissions of heat pumps become an increasingly important factor in heat pump design. Noise mitigation measures that only by a small degree affect energy efficiency are thus an active field of research, e.g. [1, 2]. Similar to other environmental noise sources such as traffic noise, a proper way to assess and quantify the changes in sound caused by such measures and to understand the relation to noise perception is vital. The most common descriptor is the A-weighted level. From numerous studies on traffic noise, e.g. [3–5], it seems clear that other noise descriptors more related to human perception such as loudness can provide a better description of the annoyance experienced by environmental noise. The aim of the study presented here was to perceptually evaluate the noise emission of an air-to-water heat pump for four directions using four variants. The variants under investigation comprised the heat pump without any modifications, a diffuser attached to the fan outlet and an acoustic deflection with and without a splitter-type silencer. Using emission recordings from four different directions the effect of the variant and the directivity were investigated by means of various acoustic quantities and a perception experiment in the lab.

2. METHODS

2.1 Measurements

Measurements were performed in a climate chamber with absorbing walls and a reflecting ground. A total of 61 microphones was placed around an air-to-water heat pump (Fig. 1). Microphones were arranged on an hexagonal prism. Signals were recorded at 96 kHz and later downsampled to 48 kHz for the acoustic analysis testing. During the measurements in the climate chamber temperature and humidity as well as inlet and return temperature were kept constant. Stationary noise samples were extracted from the recordings and investigated as a function of different heat pump variants comprising the original state, a diffuser attached to the fan, an acoustic deflection, and the heat pump with an acoustic deflection and a splitter-type silencer.

Four microphone positions were chosen around the head pump in a height of 127 cm above the floor. One recording position was located at the fan axis inlet (0 °). The second position was located at the fan outlet (180 °). Two further positions were located along an axis perpendicular to the fan axis on either side of the head pump. To guarantee comparable operating states for the different mitigation measures, sound samples were extracted about 60 seconds after the end of a defrosting cycle. The duration of the audio segments used for analysis and psychoacoustical testing was chosen to be 5 s to allow the listeners to properly assess the sound and at the same time avoid a lengthy investigation that might impact on the listeners focus. All 16 conditions (four variants, four directions) were used in the test. Furthermore, 8 samples containing pink noise at different A-levels within the range of the heat pump noise were included. The pink noise allows to compare the results with those from other studies (cf. [6]).

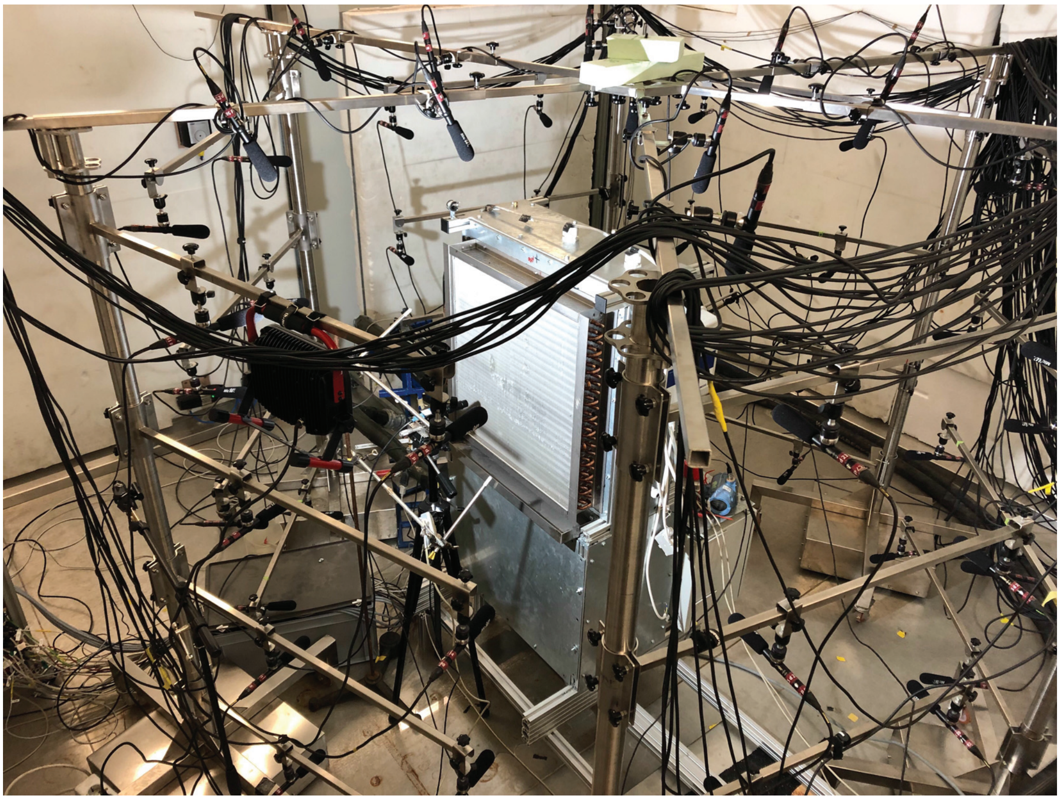

Figure 1. Measurement setup of the acoustic recordings in the climate chamber.

Samples were arranged in three runs with each run containing each stimulus three times resulting in a total of 9 repetitions. Between the runs a break of at least five minutes was enforced.

2.2 Listeners

20 normal hearing listeners (10 female) were tested. The mean age was 28.6±6.6 years. All but one listener had hearing thresholds less than 20 dB higher than normal thresholds for all frequencies tested. A single listener had a single sided increase in hearing threshold of 30 dB at 8000 Hz but had otherwise normal hearing.

2.3 Annoyance ratings

A free magnitude estimation was performed to determine the annoyance ratings of the different heat pump noises [3, 5]. After listening to the stimulus, listeners were asked to input a numerical rating corresponding to the perceived annoyance. While listeners were free in choosing their starting value, they were instructed to avoid extremely high or low starting values in order to stay within a comfortable range of numbers. Listeners were asked to perform a proportional rating, i.e. double the annoyance should result in doubling the value. Listeners were also instructed not to use 0 or negative numbers. They were also explicitly told to keep their rating scale constant within and across all runs. Once the rating was entered, listeners continued by pressing a key.

Before the main test, subjects received written instructions containing the definition of annoyance and a description of the procedure in German. Annoyance was defined as a feeling of discomfort, caused by noise or a feeling of aversion, discomfort, or irritation if the current activity is disturbed or affected by noise. Subjects were also asked to base their annoyance rating on imagining how annoying and distracting they would find the noise, if they were subjected to it on a regular basis [7, 8]. After reading the instructions, listeners performed a training covering a wide range of stimuli. The training consisted of a few trials, after which listeners were allowed to adapt their rating range in the case they felt uncomfortable with their initial choice. After the training, subjects had the opportunity to clarify open issues.

2.4 Psychoacoustical and acoustical parameters

The acoustical and psychoacoustical parameters for the 5 s long stimuli were calculated using the Matlab-Toolbox psysound3 [9]. The following psychoacoustical parameters were calculated: loudness N [10], roughness R [11], tonality T [12], sharpness S, and loudness fluctuation ΔN [13], as well as A and C-weighted levels (time weighting fast) were calculated. Of these quantities the median and the value that was exceeded 5% of the time were determined, (e.g. S_{50} and S_5 for median and 5% sharpness). The loudness level was also determined.

2.5 Annoyance

Three subjects reported a total of four input typos all of which were reproducible and could be corrected. As the magnitude estimation leads to a ratio scale, we applied the

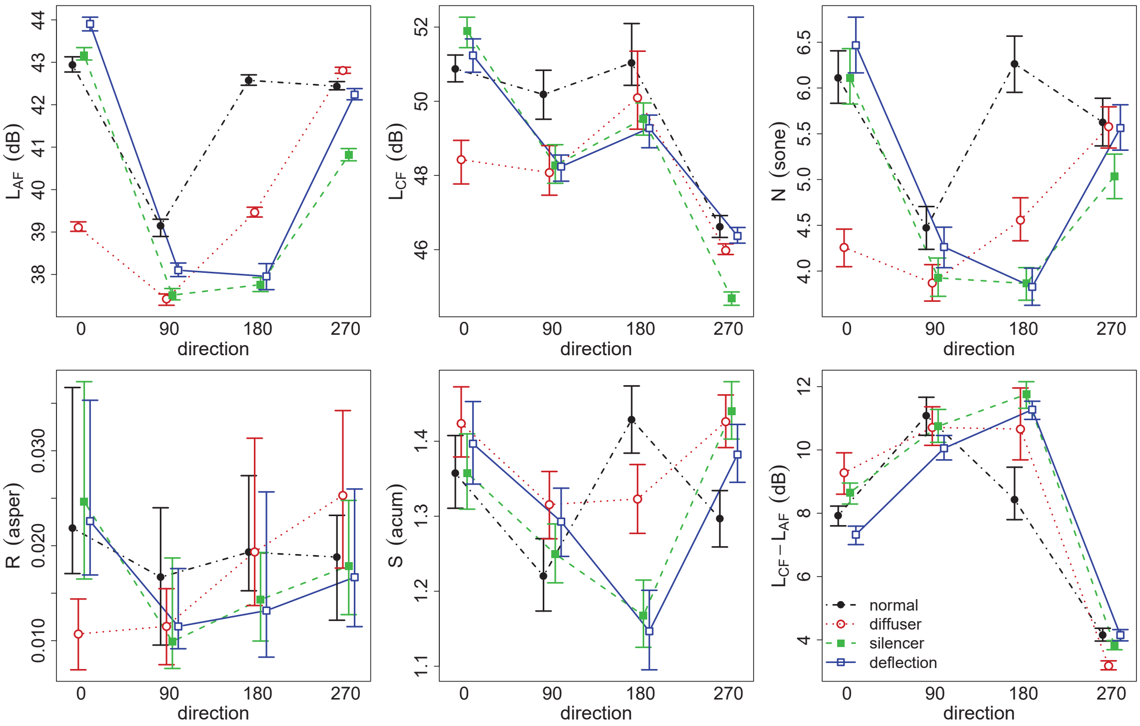

Figure 2. Acoustic parameters: The median and the inter-quartile range of the distribution calculated over the 5 s segments. Colors and symbols denote the heat pump variant.

logarithm of base 2 on the data [3]. Thus an increase by 1 in the log-ratings implies a doubling of the perceived annoyance. No outliers were detected outside the 3-fold standard deviation across the subject data. The overall consistency of the ratings was good. The correlation of the average log-ratings of each person with the group was for most listeners around 0.9. For one listener the correlation coefficient was slightly below 0.7, for another listener it was just below 0.6

2.6 Statistical analysis

Statistical analysis was performed using the software *R* [14]. The mean log-ratings per listener and condition were the input for a repeated-measures-analysis-of variance (RM-ANOVA) with condition and position as factors. The *R*-package *ez* was used for this purpose [15]. For significant effects omnibus post-hoc-Tests were performed using paired t-tests [16, 17]. Furthermore, the relation between acoustical properties and the annoyance rating was investigated using a stepwise linear regression. For this the function *stepAIC* (*R*-package *MASS* [18]) was used which allows for both, adding and removing parameters. To determine the model quality, the Bayes Information Criterion (BIC [19]) was used that allows us to take into account model fit and complexity.

3. RESULTS

3.1 Acoustics

At the fan outlet, the highest values for A-level as well as loudness (Fig. 2) were observed in the the reference variant (i.e. no measures applied) as compared to all other variants whereas at the fan inlet only the diffuser caused a difference in level. At the sides the different variants only resulted in minor changes, however, at 90 ° the A-weighted levels and loudness were much lower than at 270 °. The smaller difference between C- and A-level at 270 ° indicates a small low-frequency contribution for that direction. At the fan outlet a change in sharpness was observed with the reference variant and the diffuser exhibiting higher values. Differences for the roughness were mostly minor at 0 ° for the variant with the diffuser. Overall, the effect of the condition seems smaller for the side positions than for the positions at the fan inlet and outlet.

3.2 Annoyance ratings

Fig. 3 shows the dependence of the annoyance ratings on the variant and the direction. The RM-ANOVA yielded a significant main effect of direction ($p<0.0001$) as well as a significant interaction for variant and direction ($p<0.0001$). Mauchlys Test showed a deviation from sphericity for both effects. After applying the Greenhouse-Geisser correction [20] both effects were significant ($p<0.0001$). Only the heat pump variant showed no significant overall main effect. In an omnibus test 36 pairwise interaction contrasts were defined.

In the reference variant versus the diffuser variant, the significant interaction effects with the direction seem to originate from a decreased annoyance along the fan axis and a trend towards increased annoyance perpendicular to the fan axis. In the reference variant versus the acoustic deflection with and without a silencer, only the log-ratings

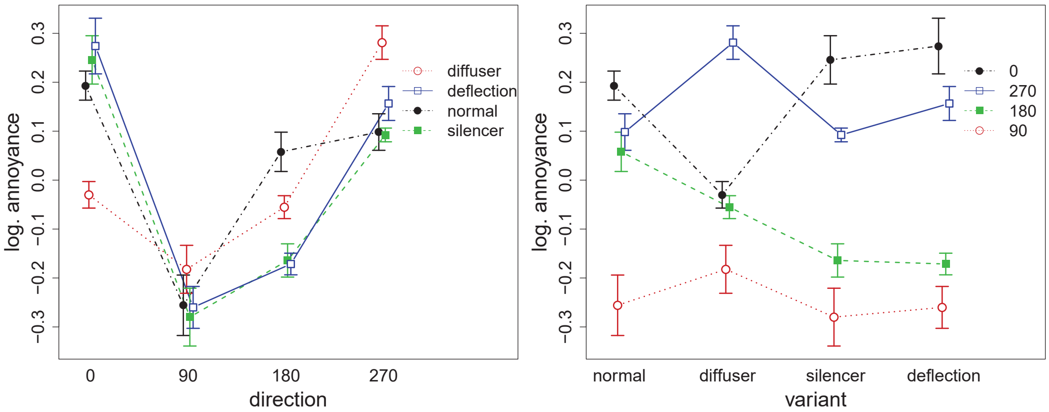

Figure 3. Annoyance vs. direction and condition: The mean and standard error of the annoyance log-ratings across the group of listeners as a function of direction and variant. Colors and symbols denote variant(left panel) or direction (right panel)

of the annoyance at the fan outlet seem to decrease in the deflection variant.

In the diffuser variant vs. the deflection variants the annoyance of the fan inlet increases for the deflection variant whereas every other direction seems to exhibit a decrease in annoyance for the deflection. The silencer had essentially no additional effect to the acoustic deflection.

For the significant main effect of the direction, a post-hoc test yielded all directions pairs to be significantly different except 0 and 270 °, i.e. the fan inlet and one of the heat pump sides. Due to the significant interaction effects, care has to be taken when interpreting the main effect of direction. As all relevant interactions are quantitative, meaning that all differences for different variants compared across directions have the same sign, an interpretation of the main effect is, however, reasonable.

The 90 ° direction was rated as less annoying than any other direction whereas the fan inlet (0 °) was rated as more annoying than the directions 90 and 180 °.

The question that remains is, which acoustical quantities explain the differences in ratings. A stepwise linear regression yielded the model considering the median A-level L_{AF50}, the peak loudness level L_{N5}, the peak sharpness S_5, the peak loudness N_5, and the peak psychoacoustic roughness R_5 (Fig. 4, lower right panel). The different panels in Fig. 4 illustrate how the prediction (gray lines and dots) changes when using the different models. The L_{AF50} was the single best descriptor with about 87% explained variance (Fig. 4, upper left panel). L_{N5} and S_5 explain an additional 5% and 3% of the total variance, respectively. The last two parameters only added around 2% together. All loudness related quantities (N_5, N_{50}, L_{N5}, L_{N50}) explain between 75% and 78% of the variance.

An analysis of the log-ratings for the pink noise by means of the loudness levels L_{N5} and L_{N50} explained around 99.5% of the variance. An increase of 12 phon lead to a doubling of the log-ratings, i.e., a doubling of the loudness (10 Phon four loudness values greater 1 sone) lead to slightly less than double the annoyance. For the L_{AF50} (99,4%) an increase of 10 dB lead to a doubling of annoyance.

4. SUMMARY

Summarizing, a number of observations can be made. First, the effect of the different variants, i.e. noise mitigation measures, was heavily direction dependent. This dependency was observed in acoustical and psychoacoustical parameters, in particular in sound pressure levels, loudness, as well as sharpness. This interaction between variant and emission direction was, however, difficult to interpret. The directivity manifests itself also in a significant main effect for the annoyance, although caution is recommended when interpreting these differences due to the significant interaction with the factor variant.

Annoyance ratings were explained to a high degree by the A-level and the loudness level. In particular sharpness also improved the explained variance of the model significantly .

A final remark: we measured the acoustic effects close to the heat pump. The direction dependence will most likely be less pronounced, when considering a realistic setting with reflections from surrounding structures. Additional tests are necessary to investigate this issue in more detail.

5. ACKNOWLEDGEMENTS

This work was part of the project SilentAirHP. SilentAirHP was supported in the framework of the Energy research program of the Climate and Energy Fund (5148527) initiated by the Austrian Ministry for Transport,Innovation and Technology

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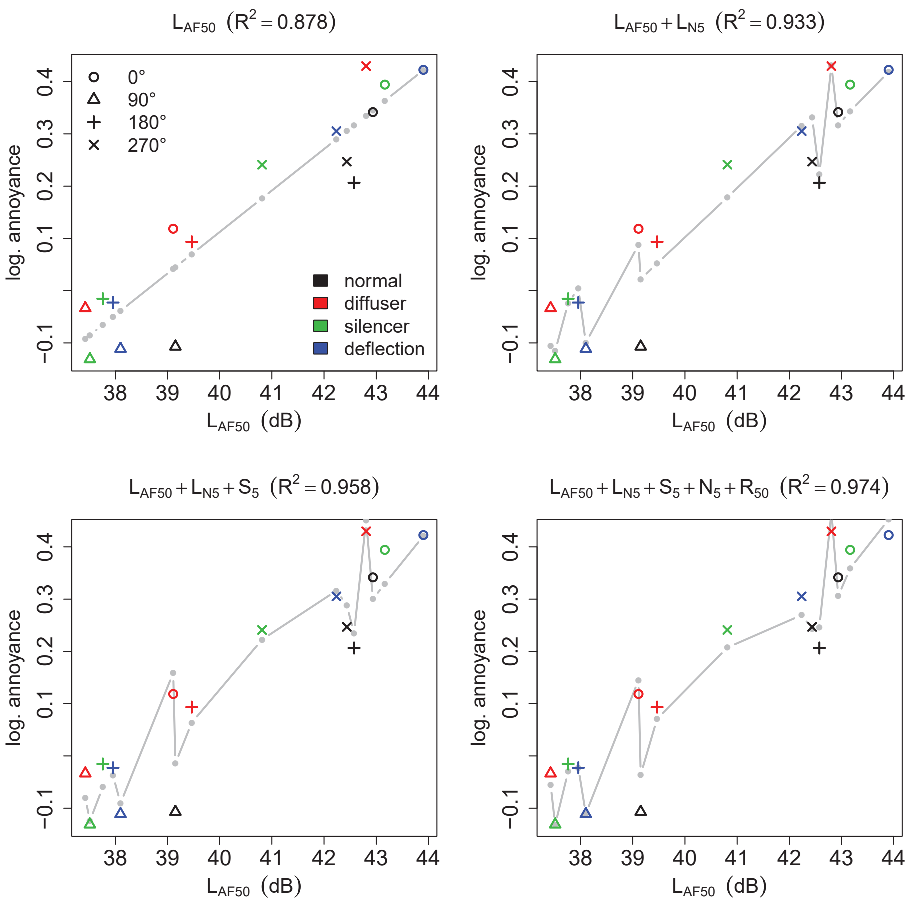

Figure 4. Stepwise model selection: Effects on the modeled annoyance when including various acoustic quantities to the linear model of the annoyance log-ratings. Group mean ratings are plotted as a function of the median L_{Af}
. Colors denote the variant. The gray symbols and lines show the prediction of the respective model denoted in the title.

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