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"Humming" or "Hissing"? - Psychoacoustical investigation of sounds from heat pumps

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ABSTRACT

Heat pumps, which become increasingly popular as heating systems for houses, with the build-in fan as main acoustic source could be annoying for the neighborhood.

Previous jury tests with a semantic differential reveal that besides the psychoacoustic loudness and sharpness, temporal structures in a sound signal have a significant impact on the quality evaluation of fan noise. In this context, the blade passing frequency (BPF) and its harmonics play an important role. It emerges, that distinctive sound patterns rated "helicopter-like" by acoustic experts especially when tonal signatures in the signal are amplitude modulated with BPF. From a further jury test based on synthetic generated sounds, which were derived from measured fan sounds in heat pump applications, two different evaluation clusters with opposing assessments were determined: one major group, which prefers the "hissing of the fan" and a smaller group, which favors the "humming of the electric motor". In an attached interview some participants of the test describe a "harmonic balance" of the two mentioned sensations as ideal. By changing the blade shape of an axial fan, design optimizations should be investigated psychoacoustically. Therefore the annoyance will be predicted based on the previous results and directly measured in a jury test.

Keywords: Jury test, Annoyance, Blade passing frequency, Modulation, Temporal structures

1. INTRODUCTION

Heat pumps are according to the German Association *Bundesverband Wärmepumpe e.V.* in the meantime the second often requested heating technology for private households. In consequence the noise emission from these devices constantly increases. Especially the flow noise of the build-in fan often leads to complaints. Jury tests with the method of the semantic differential showed that besides the psychoacoustic perception variables loudness and sharpness temporal structures in a noise signal, characterized by "restiveness" (German: "Unruhe") or "irregularity" (German: "Ungleichmäßigkeit"), have a significant impact on quality judgement. Acoustic experts describe a prominent time structure appearing especially for axial fans with a blade passing frequency $f_{BPF} < 100$ Hz often as "helicopter-like". Modulation analysis show that these "helicopter-like" sensations occur when tonal signatures in a sound sample are amplitude modulated with the blade passing frequency f_{BPF}, cp. Figure 1. The perception of an amplitude modulation or a tone depends on the characteristics of the dominant tonal component levels.

According to Terhardt (1) integer ratios of tones lead to a hardly or even not at all noticeable temporal structure. This contradicts in the first instance the apparent amplitude modulation of multiples of the blade passing frequency with this modulation frequency.

In contrast to the theories of von Helmholtz (2) and Terhardt (1), according to which a well-tempered scale leads to a higher consonance, Miskiewicz et al. (3) and Vencovsky and Rund (4) show by investigating complex tone pairs, that integer frequency ratios can produce a higher subjective perceived roughness than tone pairs in equal temperament.

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The method of paired-comparison is used to examine the influence of integer tone ratios under variation of the tone levels and the basic frequency on the preference judgement.

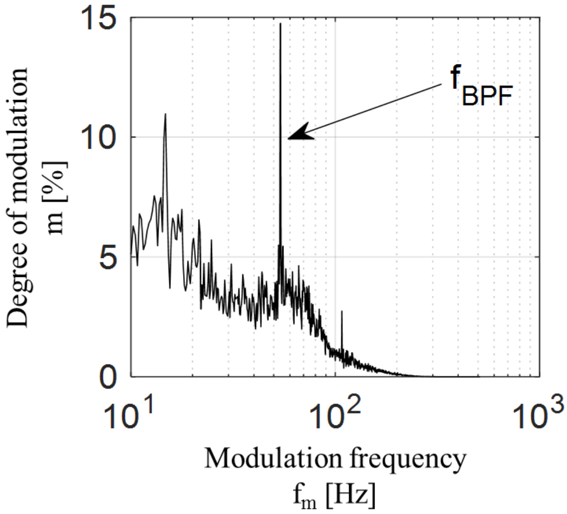

Figure 1 – Degree of modulation over modulation frequency of a “helicopter-like” flow noise signal. The dominant modulation frequency is equivalent to the blade passing frequency f_{BPF}, which results from the rotational number times the blade number of the used fan.

2. METHOD

For the investigation of integer tone component ratios under variation of the tone levels and the basic frequency the fan flow noise is reproduced by a filtered pink noise $x_n(t)$ (Butterworth low-pass filter at f = 1,2 kHz) and eight tone components in integer frequency ratios $x_t(t)$ according to

$$\begin{aligned} x(t) &= x_n(t) + x_t(t) \\ &= x_n(t) + \sum_{i=1}^{8} A_i \sin(2\pi i f_{tone} t + \varphi_i) \end{aligned} \quad (1)$$

where the phases φ_i of the tones are extracted from a “helicopter-like” fan noise signal.

The levels $L_{T,i}$ of the first three tone components were varied in three steps of 6 dB each. As basis the Tone-to-Noise Ratio TNR_0 of the BPF from the previously selected “helicopter-like” fan noise signal is taken and plotted as reference line indicated with „0 dB“ in Figure 2. The tones 4 – 8 are only be used to make the noise signal sound more voluminous and fuller in order to achieve a high similarity to real flow noise signals.

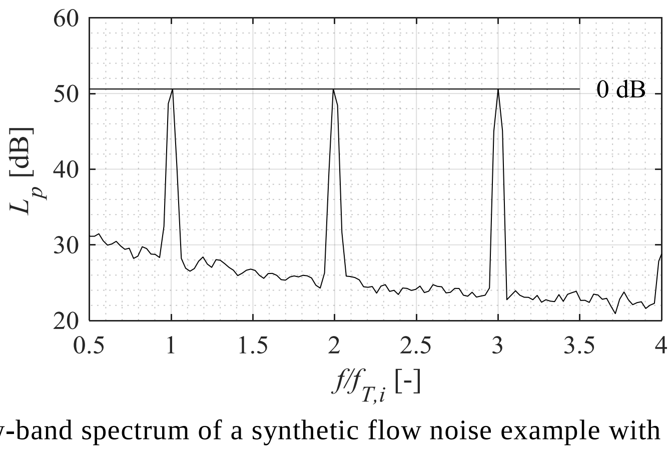

Figure 2 – Narrow-band spectrum of a synthetic flow noise example with maximal chosen Tone-to-Noise Ratio (TNR) of the first three harmonics of BPF. These three harmonics were decreased in three steps of 6 dB respectively (band width Δf = 2 Hz, Hanning window with overlap 50 %).

Two jury tests were performed with the basic tone frequencies f_A = 48,5 Hz resp. f_B = 76,5 Hz. The test language is German – therefore the original used adjectives are indicated in brackets behind the most suitable English translation in this paper (German: “x”). Since the noise signals within one listening test differ just by the tone levels $L_{T,i}$, the method of paired-comparison is chosen. This method allows for the detection of small differences of the tested characteristic – in this case the adjective “unpleasant” (German: “unangenehm”). The three steps of three tones result in 27 possible combinations. The number of test signals is reduced by the Latin-square method to nine combinations because a full comparison of all possibilities would exceed the power of concentration of the test persons, cp. Bortz and Schuster (5).

The tested combinations of the tone levels are shown in Table 1. All sound pairs are queried twice within the jury test and named “Test” (comparison of sound 1 with 2) resp. “Retest” (comparison of sound 2 with 1). That leads to 72 comparisons all together.

Table 1 – Selection of the nine chosen TNR combinations for the jury tests with basic frequency f_A = 48,5 Hz resp. f_B = 76,5 Hz.

Sound No.	$L_{T,1}$**-TNR$_0$**	$L_{T,2}$**-TNR$_0$**	$L_{T,3}$**-TNR$_0$**
1	0 dB	0 dB	0dB
2	0 dB	-6 dB	-6 dB
3	0 dB	-12 dB	-12 dB
4	-6 dB	0 dB	-6 dB
5	-6 dB	-6 dB	-12 dB
6	-6 dB	-12 dB	0 dB
7	-12 dB	0 dB	-12 dB
8	-12 dB	-6 dB	0 dB
9	-12 dB	-12 dB	-6 dB

For the jury tests all sounds were adjusted to an equal A-weighted sound pressure level of 55 dB(A) and presented to the test persons for a duration of 10 s. The test was controlled by a graphical interface in Matlab®. 20 probands each took part in listening test A (50 % male, ⌀ 28 years) resp. B (45 % male, ⌀ 25 years). Seven test persons attended both studies. Here it has been taken care, that approximately half of the probands started with jury test A and the other half with jury test B. The participants were instructed in written form. They were requested to choose in each paired comparison the more unpleasant sound via a button in the GUI. In addition the test persons were asked to state at least one word in an implemented comment line why this signal is rated more unpleasant. The sounds were presented individual in a random order to avoid rank order effects. The first test part was completed after 36 of the total number of 72 comparisons. Because of the random arrangement of the signals the two test parts are not synonymous with “Test” and “Retest”. The second test part was conducted after a longer interruption (generally at least one day). After completion of the second test part the participans were questioned in an interview. They were asked to name pleasant and unpleasant properties of the sound signal.

3. RESULTS

Whereas the participants in jury test A (f_A = 48,5 Hz) judge significant consistent, an equivalent concordance for jury test B (f_B = 76,5 Hz) can’t be found. A hierarchical cluster analysis according to WARD’s method reveal two clusters B_1 (60 % of the probands) and B_2 (40 % of the probands). The test persons of the clusters B_1 as well as jury test A evaluate sound no. 1 and no. 4 as most unpleasant, whereas the probands from cluster B_2 on the contrary evaluate these sounds as most pleasant. Participants who attended both jury tests show a consistent judgement behaviour, despite the change in basis frequency.

A F-Test shows statistically significant main effects over all three varied BPF tone levels for the jury test A with the basic frequency of 48,5 Hz, cp. Table 2. However, the residual sum of squares indicates possible interaction effects whereby a reasonable interpretation of the principal effects is not possible at this point (Bortz and Schuster (5)).

Table 2 – Results of F-test to determine significant main effects by varying the TNR of the three harmonics $L_{T,i}$ from Latin-square method for the jury test A.

	A(Test)	A (Retest)
$F(L_{T,1})$	$17{,}3^{**}$	$4{,}3^{*}$
$F(L_{T,2})$	$44{,}6^{**}$	$39{,}0^{**}$
$F(L_{T,3})$	$55{,}9^{**}$	$62{,}2^{**}$
F_{Resid}	$3{,}88^{*}$	$5{,}63^{**}$

$^{+}$ significant on 10 % level
* significant on 5 % level
** significant on 1 % level

The F-Test is applied to the results of both clusters B_1 und B_2 of jury test B, see Table 3. While for cluster B_1 a significant main effect for all tone levels $L_{T,i}$ can be found (in the Retest with significant residual sum of squares), the results of the second cluster B_2 show significant effects only for tone levels $L_{T,2}$ und $L_{T,3}$. Thus, the tone level $L_{T,1}$ of the basic frequency (f_B = 76,5 Hz) reveals no significant influence on the probands rating.

Table 3 – Results of F-test to determine significant main effects by varying the TNR of the three harmonics $L_{T,i}$ from Latin-square method for the clusters B_1 and B_2.

	B_1 (Test)	B_1 (Retest)	B_2 (Test)	B_2 (Retest)
$F(L_{T,1})$	$17{,}2^{**}$	$3{,}6^{*}$	0,7	0,2
$F(L_{T,2})$	$15{,}8^{**}$	$14{,}3^{**}$	$6{,}4^{**}$	$2{,}8^{+}$
$F(L_{T,3})$	$20{,}7^{**}$	$12{,}2^{**}$	$10{,}6^{**}$	$7{,}6^{**}$
F_{Resid}	2,25	$7{,}19^{**}$	0,10	0,47

$^{+}$ significant on 10 % level
* significant on 5 % level
** significant on 1 % level

The median of rank order *RO* from the paired-comparison is compared to the frequency of mention h_i of the statements in the comment line of the jury test GUI. Therein the highest rank order (1) corresponds to the most annoying sound sample in the test. Plotting the rank order *RO* over the most frequently mentioned term “humming” (German: “Brummen”) show in Figure 3 (left) that a linear correlation between the perceived “humming” and the evaluation “unpleasant” in the results from the clusters A ($r = -0.98$, $p < 0{,}01$) and B_1 ($r = -0.79$, $p < 0{,}05$) can be found. What is remarkable is that the adjective “humming” is used in jury test A four times as often as in test B_1. The sounds no. 3, 5 and 9 are rated less unpleasant by the proband clusters A and B_1 and were hardly described as “humming”. The found trend is confirmed in the subsequent interview, where the participants state that “humming”, which they assign to the component “motor” leads to a higher annoyance of the sound signal. On the other hand test persons of cluster B_2 state that they feel disturbed by the high frequency of a “hissing” (German: “Rauschen”) sound. The German “Rauschen” is translated by “hissing” here (another option would be “noisy”) because of the fact that the test persons mention explicitly the high frequency regime in connection with annoyance. This “hissing” is connected to the component “fan” and flow noise. The relation to the term “hissing” is depicted in Fig. 3 (right). Here only cluster B_2 shows a linear relationship ($r = -0.78$, $p < 0{,}05$). In the interview additional preferences emerge besides the two represented by clusters B_1 and B_2. While the participants in the jury test prefer either a “humming” or a “hissing” sound, the attached questionnaire reveals that some of them perceive definitely both phenomena as disturbing. These test persons describe a “harmonic balance” of the two mentioned sensations as ideal, which means that they merge both phenomena to one sound, so that two different single sounds are no longer existent.

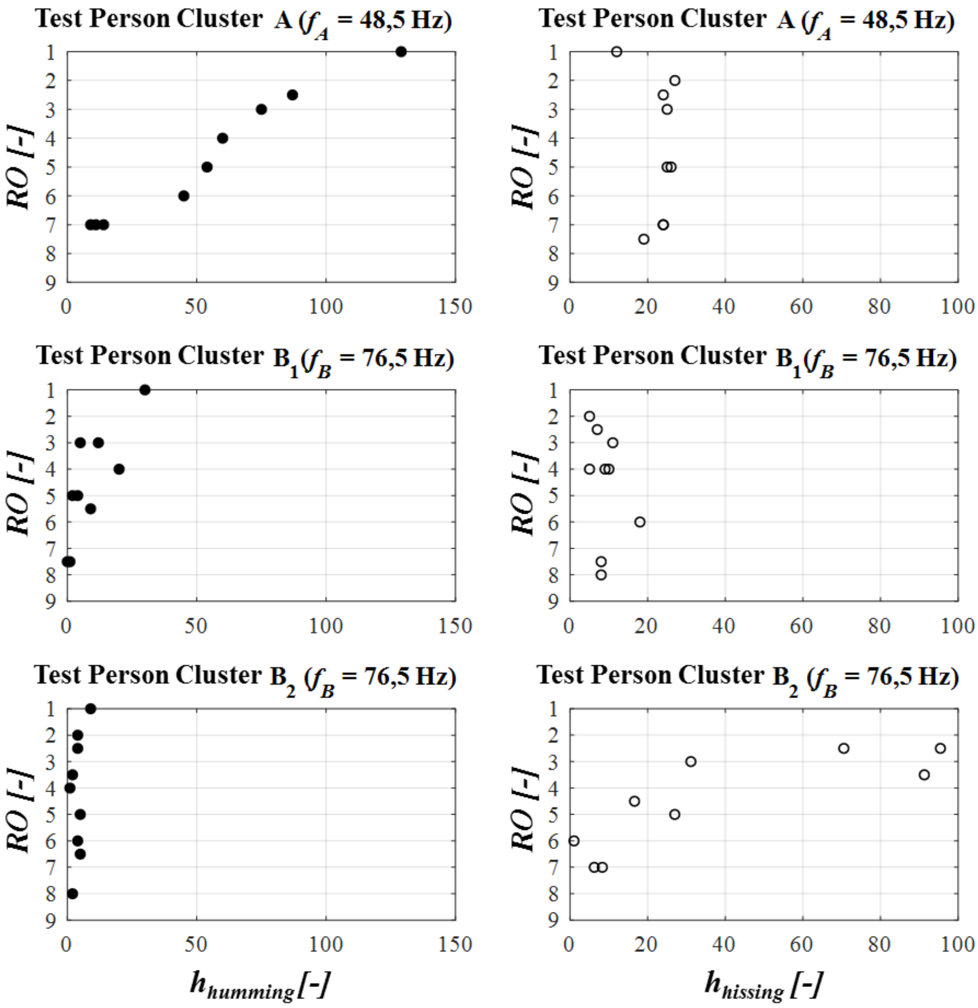

Figure 3 – Median of rank order *RO* from paired-comparison over the frequency of mention $h_{humming}$ (left) and $h_{hissing}$ (right) from the named interview statement „humming“ (left) and „hissing“ (right) for jury test A and the clusters B_1 and B_2 of jury test B. The highest rank order (*RO* = 1) corresponds to the most annoying sound sample in the test.

Besides the two mentioned terms “humming” and “hissing” the probands use the adjective “roaring” (German: “wummernd”) in jury test A (48,5 Hz) and “buzzing” (German: “summend” and “surrend”) in jury test B (76,5 Hz). The time structure of the signals is more often the reason for a lower preference in test A, expressed in adjectives like “restive” (German: “unruhig”) or “irregular” (German: “ungleichmäßig” and “unregelmäßig”). The “humming” and “roaring” is recognized as “moving around the head” from some participants.

4. CONCLUSIONS

In a jury test with the method of paired-comparison the influence of tones with integer frequency ratio embedded in a synthetic broadband noise signal is investigated with respect to preference. This is done by varying the levels of the first three BPF harmonics (derived from measured fan sounds) for two basic frequencies. While for a low frequency of 48,5 Hz all test persons state that “humming” (German: “Brummen”) leads to higher annoyance of the sound, two opposite judging proband clusters appear for the basic frequency of 76,5 Hz: 40 % of the test persons prefer humming noise, e.g. a combination of tone levels according to a classical amplitude modulation in comparison to hissing noise. The test persons associate the attributes “humming” (German: “Brummen”) and “hissing” (German: “Rauschen”) directly with the components “motor” and “fan”. In an attached interview some participants of the test describe a “harmonic balance” of the two mentioned sensations as ideal. Besides “humming” they use “roaring” (German: “Wummern”) for a frequency of 48,5 Hz, at the higher frequency of 76,5 Hz the term “buzzing” (German: “Summen” and “Surren”). It is notable, that terms with regard to time structure like “restive” (German: “unruhig”) or “irregular” (German: “ungleichmäßig”) are used more often for the lower basic frequency. The “humming” and “roaring” is recognized as “moving around the head” (German: „wandernd um den Kopf“) from some participants.

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