Acoustic measurements and psychoacoustic analyses of ventilation diffusers

Lara Stürenburg [a,1]
Philipp Ostmann [b,2]
Lukas Aspöck [a]
Dirk Müller [b]
Janina Fels [a]

[a] Institute for Hearing Technology and Acoustics, RWTH Aachen University
Kopernikusstraße 5, 52074 Aachen, Germany

[b] RWTH Aachen University, E.ON Energy Research Center,
Institute for Energy Efficient Buildings and Indoor Climate
Mathieustraße 10, 52074 Aachen, Germany

ABSTRACT

Since ventilation systems are not only used in industry but also increasingly in residential buildings, it is important to study its sound radiation and the consequences for our well-being. This research project aims to identify if geometric features of air diffusers affect the rated annoyance of ventilation systems. It is known that the A-weighted sound serves as a criterion to a limited extent. Therefore, psychoacoustic analyses and evaluations need to be included to find out if there are correlations between psychoacoustic features and flow phenomena caused by the geometric features of the air diffusers. Several air diffusers were acoustically measured in a hemi-anechoic room using a developed mobile ventilation unit that supplied the necessary air volume flow. The ventilation unit could be operated in both supply and extract air configuration of the diffusers. With the measured data, the acoustic directivity of the air diffusers can be distinguished, and psychoacoustic features can be evaluated. Future listening experiments will also be extended to audio-visual experiments in virtual reality to increase ecological validity and study the role of the environment.

1. INTRODUCTION

The thermodynamic performance of air diffusers is often limited by the emitted A-weighted sound pressure level. But the A-weighted sound pressure level serves as a criterion to a limited extent when assessing ventilation noise on annoyance and pleasantness. Therefore, psychoacoustic analyses and evaluations need to be included in the assessment process. Susini et al. [1] conducted a psychoacoustic study where unpleasant sound emissions from air-conditioning units were identified with the help of

[1] lara.stuerenburg@akustik.rwth-aachen.de

[2] philipp.ostmann@eonerc.rwth-aachen.de

listening experiments. However, the results were not linked to flow phenomena, which is an important factor when investigating air diffusers and not rotating machines such as air-conditioning units or fans. During an investigation of the acoustic quality of fans by Töpken and van de Par [2] [3], the three most important noise groups were “unpleasant”, “humming”, and “shrill”. The fan noises could be separated into these adjective groups regarding their perception, although they had the same A-weighted sound pressure level. This shows the importance of psychoacoustic parameters when investing in ventilation noises. Despite the great offered information based on test person studies and psychoacoustic parameters, the results do not provide design recommendations. However, numerical simulation of two exhaust valves by Saarinen and Koskela [4] showed that even minimal changes in the geometrics could result in significant flow noise changes. Therefore, this research project aims to identify if geometric design features of air diffusers enhance specific psychoacoustic features and flow phenomena. In this paper, the acoustic measurements of air diffusers are described, and the first results of the psychoacoustic evaluation are shown. Small deviations in loudness and sharpness between the different air diffusers can be detected.

2. MEASUREMENT SETUP

Several air diffusers were acoustically measured in a hemi-anechoic room. A developed mobile ventilation unit controllably supplies the necessary air volume flow to the air diffusers.

2.1. Fluid Mechanics

The ventilation unit of the investigated system is equipped with a backwards-curved radial fan which is mounted inside an isolated housing to prevent noise radiation. Using a flexible hose, the fan is connected to a calibrated measurement section, which is then connected to the air diffuser. The ventilation unit is placed outside a hemi-anechoic room with only the hose entering it. The hose is guided through a small hole, which was thoroughly insulated to prevent noise from entering the hemi-anechoic room. If necessary, the hose is widened up smoothly to allow the connection to the investigated air diffuser. Depending on the configuration, the diffusers are operated in *supply air* direction or *extract air* direction. The volume flow $\dot{V}$ is measured with an orifice that was calibrated using a reference orifice that meets the standards of *DIN EN ISO 5167-2*. By measuring the pressure drop Δp the volume flow $\dot{V}$ can be calculated by using the following expression, where ξ is the pressure loss coefficient of the orifice and A the section’s cross-sectional area.

$$\dot{V} = A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho \cdot \xi}} \quad \text{, with } A = \frac{\pi}{4} \cdot D^2$$

The ventilation unit can be equipped with different orifices to allow a wider volume flow range since a certain minimum pressure drop Δp is required for accurate measurements. For the targeted volume flow range, two orifices are used, with both using the same section diameter $D = 139.5\,\mathrm{mm}$. The bigger orifice was calibrated to $\xi_{\mathrm{high}} = 15.45$ and the smaller one to $\xi_{\mathrm{low}} = 56.13$. The air density ρ is calculated from the measured air temperature, relative humidity and absolute pressure by using the *Magnus formula* [5] and the ideal gas law. Due to the operating limits of the ventilation unit, the maximum achievable volume flow is at $600\,\mathrm{m^3/h}$.

In the following, the investigated air diffusers are briefly described. The diffusers cover a broad range of rated volume flows ($200\,\mathrm{m^3/h}$ - $800\,\mathrm{m^3/h}$) and are therefore suited for a wide range of possible applications or different room sizes. An overview of all diffusers is shown in Figure 1.

2.1.1. Swirl diffusers

The diffuser with the highest rated volume flow is a *TROX TDF 600* (see Figure 1a). It is rated at a volume flow of $800\,\mathrm{m^3/h}$ and its swirl vanes are manufactured by sheet punching. The vanes have a

swept shape.
The other swirl diffusers are rated at 700 m^3/h and are mainly distinguished by their vanes. The *Wildeboer DTQ* (see Figure 1b) is also manufactured by sheet punching, with small spacing between the vanes. The *Wildeboer DXQ* (see Figure 1c) has differently sized plastic vanes that are inserted into the main plate alternatingly.

2.1.2. Slot diffusers

As a rather simple slot diffuser, the *TROX TSD* (see Figure 1d) was selected with two slots. It is rated at 350 m^3/h at the selected length of 1 m. Its vanes can be rotated, allowing for either a ceiling-attached or ceiling-normal airflow.
A more complex slot diffuser with four slots is the *LTG LWmodule 12clean* (see Figure 1e). The flow is guided by rotatable cylinders. In addition to the main flow through the cylinders, an air curtain is produced by thin bypass channels over the whole length. The diffuser is rated at 400 m^3/h at the selected length of 1 m and fully opened cylinder position. Since only one of the two connection ducts is used, the effective rated volume flow reduces to 200 m^3/h. This setup was recommended for measurements by the manufacturer.

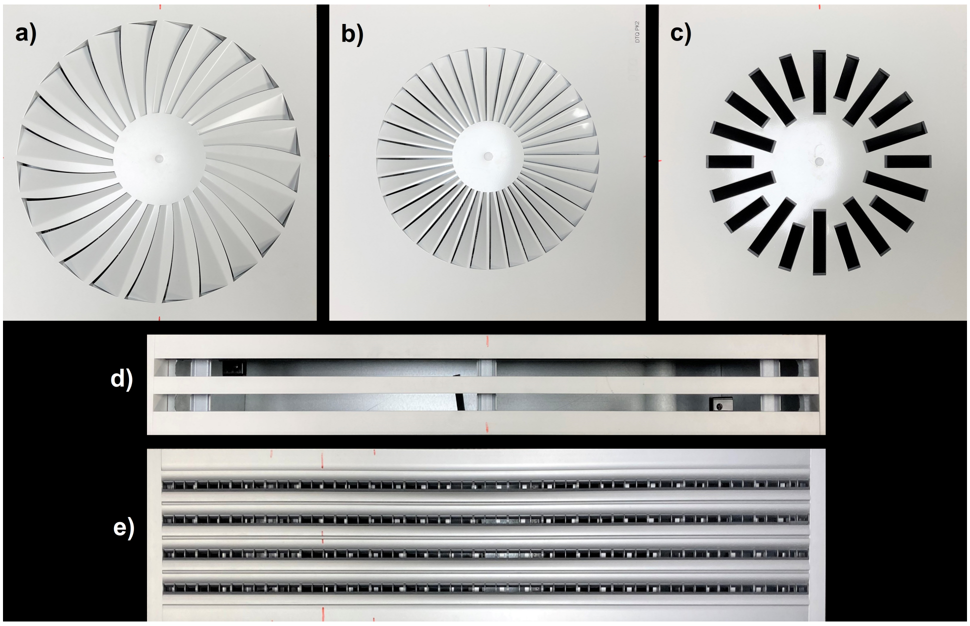


Figure 1: Selected air diffusers: a) swirl diffuser from TROX, b) swirl diffuser DTQ from Wildeboer, c) swirl diffuser DXQ from Wildeboer, d) slot diffuser from TROX, and e) slot diffuser from LTG.

2.2. Acoustics

The measurements took place in a hemi-anechoic room (see Figure 2) with a lower limiting frequency of 100 Hz. To reconstruct the environment, the air diffusers were integrated into a ceiling tile construction of 2.4 x 2.4 m^2. A microphone arc with a radius of 195 cm measured the acoustic signals for each air diffuser at four different room positions, and three volume flows (200 m^3/h, 400 m^3/h and 600 m^3/h). The microphone arc contains 19 microphone capsules (Sennheiser KE 4-211-2) at a 5° distance from each other. The first microphone (No. 1) was placed parallel to the air diffuser, and the last microphone (No. 19) was centred directly above the air diffuser. To investigate the directional radiation patterns of the air diffusers without increasing the measurement effort considerably, four microphone arc positions were chosen at 45° intervals. The room positions were: *180* - as in Figure 2, opposite of the hose, at 180° to the hose; *135* - in the Figure at the left corner, at 135° to the hose; *90* - in the Figure at the front site, at 90° to the hose; and *45* - in the Figure at the front corner, at 45° to the hose.

Figure 2: Measurement setup with the microphone arc in a hemi-anechoic room. The air diffusers were integrated into a ceiling tile construction.

Further measurements were taken with a low noise microphone (G.R.A.S. 40HL ½”) positioned 195 cm above the air diffuser as microphone No. 19 of the microphone arc.
For all measurement setups and configurations, three recordings were conducted, each with a length of 11 seconds.

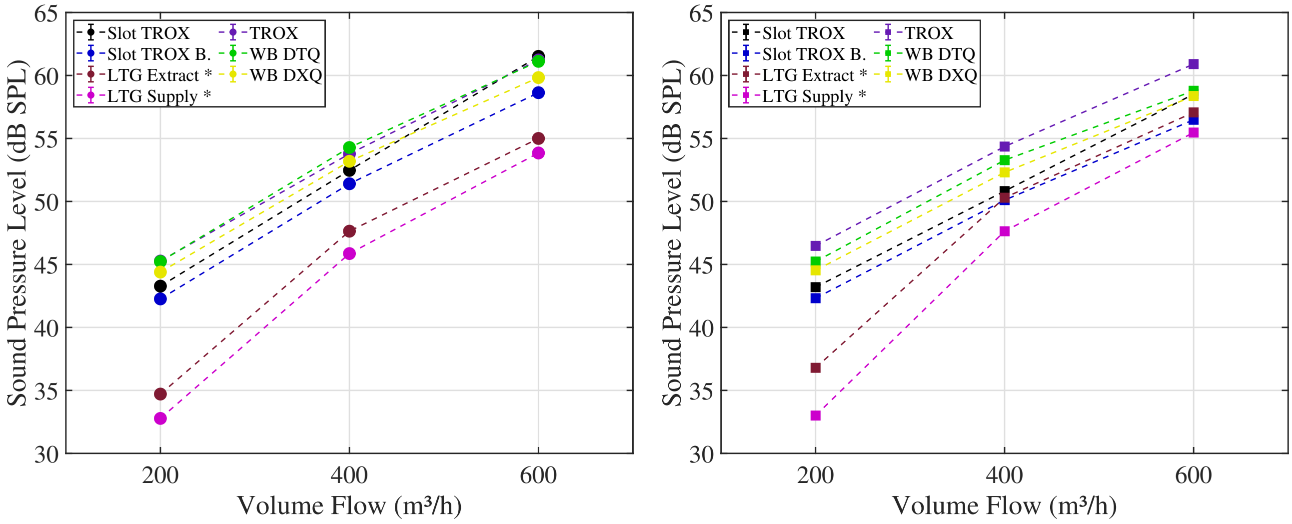
3. RESULTS

With the sound pressure levels of the 19 signals from the microphone arc at four room positions, the sound power levels were calculated according to the standard DIN EN ISO 3745. The results for all air diffusers and the three different volume flows are listed in Table 1.[3] The “B.” represent the second vane position of the slot diffuser from TROX, which emits ceiling-attached airflow, while the first vane position emits ceiling-normal airflow. The table shows that the sound power level increases for all air diffusers when the volume flow increases. The slot diffuser from LTG has the lowest sound

Table 1: The sound power level in dB of the air diffusers for different volume flows.[3]

Diffuser	Volume Flow (m^3/h)		
	200	400	600
Slot TROX	59.4	68.6	75.3
Slot TROX B.	58.6	67.9	74.4
LTG Extract *	53.5	62.3	68.8
LTG Supply *	53.3	60.8	68.1
Swirl TROX	60.9	70.1	75.8
WB DTQ	60.4	69.2	75.7
WB DXQ	60.0	68.1	74.4

[3]Only one half of the slot diffuser from LTG was measured. The volume flow was halved to compare it with the other air diffusers.



(a) Microphone No. 19

(b) Low noise microphone

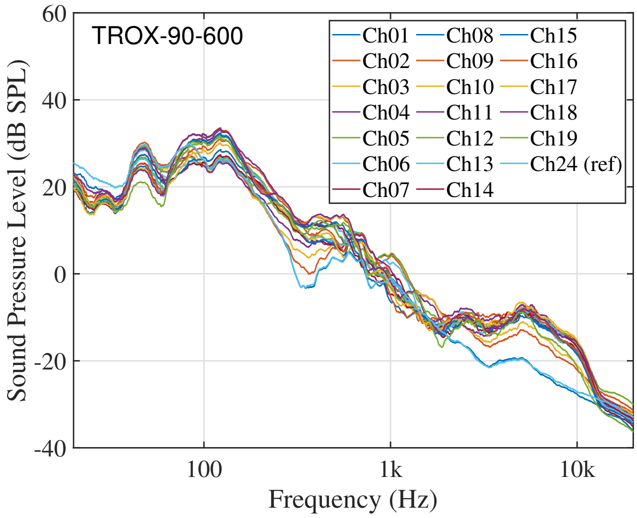
Figure 3: Comparison of the band-pass filtered sound pressure level in dB SPL between (a) the microphone No. 19 of the microphone arc and (b) the low noise microphone. They measured at the same position: centred 195 cm above the air diffusers.

power levels of all air diffusers for each volume flow.[3] The sound power levels of the slot diffuser from TROX in both vane positions are similar to the sound power levels of the swirl diffusers from TROX and Wildeboer.

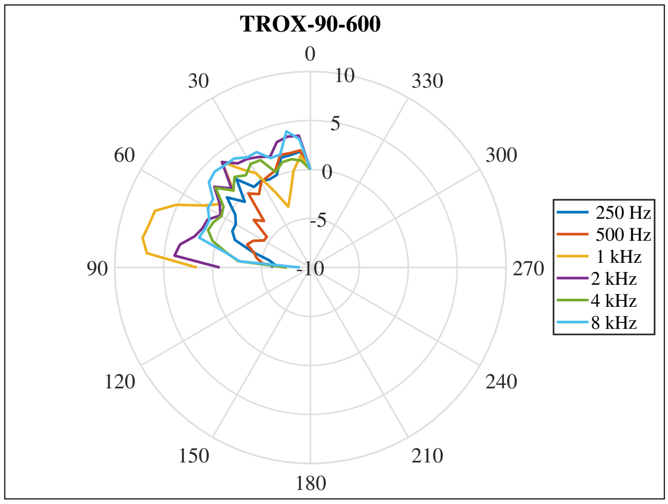
In Figure 3 the sound pressure level in dB SPL is shown over the volume flow for the microphone No. 19 of the microphone arc (Figure 3a) and the low noise microphone (Figure 3b). These two microphones were placed at the same position: centred 195 cm above the air diffusers. The signals were band-pass filtered between 100 Hz and 4 kHz. It can be seen that the sound pressure levels compared between these two microphones are very similar, and differ by a maximum of 3 dB for the measurements of the slot diffuser from TROX in the first vane position at a volume flow of 600 m^3/h.

In Figure 4a the sound pressure level in dB SPL is shown over the frequency in Hz for all 19 microphones of the microphone arc. The spectrum is shown for the swirl diffuser of TROX at a volume flow of 600 m^3/h and room position *90*. The highest sound pressure levels are between 75 Hz and 150 Hz. For frequencies above 150 Hz, the sound pressure levels decrease almost logarithmically with the frequency. In Figure 4b the directivity of the sound pressure level in dB SPL measured with the microphone arc can be seen. Shown is the measured deviation of the sound pressure level in reference to microphone No. 19 (at 0°) of the swirl diffuser from TROX at a volume flow of 600 m^3/h and room position *90*. The one-third octave bands 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz are plotted for all microphones of the microphone arc. Microphone No. 1 is marked at 90°, going down in 5°-steps to microphone No. 19 at 0°. It can be seen that the differences between the microphones are smaller than ±10 dB SPL. Parallel to the air diffuser (75°-90°; microphones No. 4-1) the frequency bands of 1 kHz and 2 kHz have higher sound pressure levels than at the more vertical microphone positions (0°-30°; microphones No. 19-13). For the frequency band 250 Hz the sound pressure level decrease in the parallel position (60°-90°), and also the sound pressure level of the frequency band 500 Hz is low from 45°-90° (microphones No. 10-1).

The psychoacoustic values in Figure 5 and 6 were evaluated with the software *ArtemiS Suite* by HEAD acoustics. The given values are the mean values of three conducted measurements in each condition. In Figure 5a the A-weighted sound pressure level in dB is shown over the volume flow in m^3/h for all



(a) Spectrum

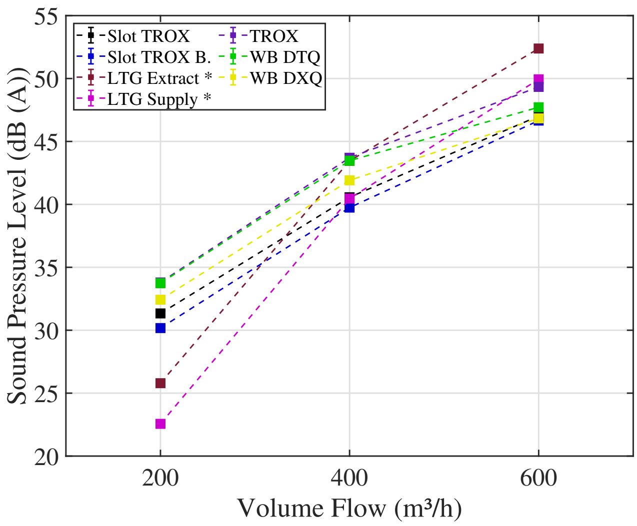


(b) Directivity

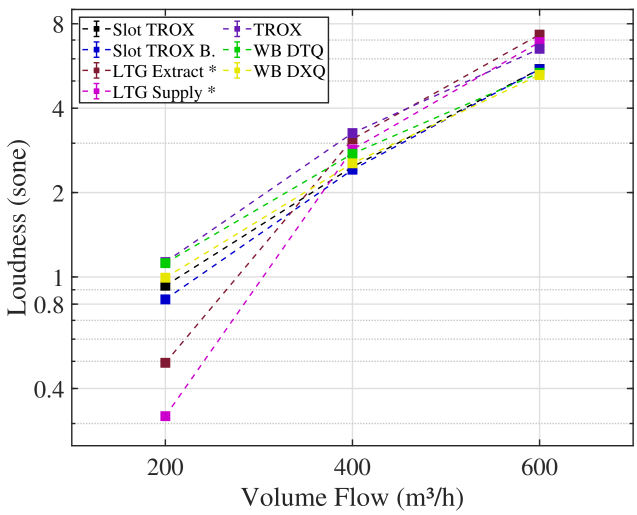
Figure 4: (a) Spectrum of the swirl diffuser from TROX measured with the 19 microphones of the microphone arc at a volume flow of 600 m^3/h and position *90*. (b) Directivity of the sound pressure level in dB SPL of the same air diffuser at the same room position as in (a), plotted for six one-third octave bands in reference to microphone No. 19 (at 0°).

measured air diffusers. For all air diffusers, except the slot diffuser from LTG, the A-weighted sound pressure level increases approximately linear with increasing volume flow. In Figure 5b the loudness in sone is shown over the volume flow in m^3/h for all air diffusers with a logarithmic ordinate. It was calculated according to the DIN 45631. The loudness increases approximately logarithmically when increasing the volume flow for all air diffusers, except the slot diffuser from LTG. It can be determined that the loudness for all air diffusers is approximately three times higher when doubling the volume flow from 200 m^3/h to 400 m^3/h. When increasing the volume flow from 400 m^3/h to 600 m^3/h, the loudness approximately doubles.

In Figure 6a the sharpness in acum is shown over the volume flow for all measured air diffusers. The sharpness is calculated according to the DIN 45692. With the logarithmic ordinate, a logarithmic

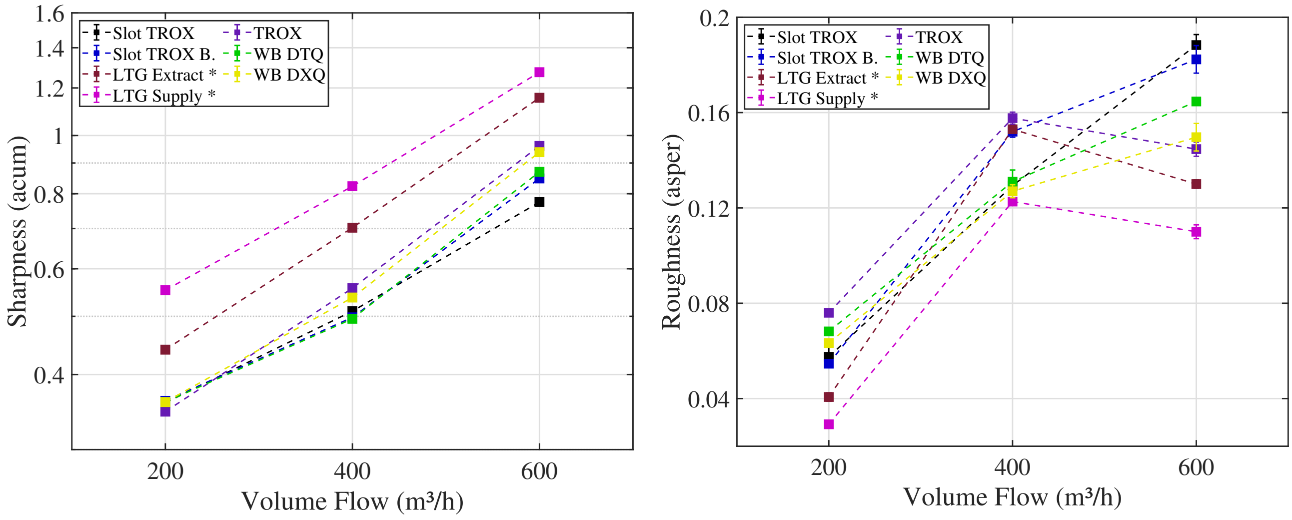


(a) A-weighted sound pressure level



(b) Loudness

Figure 5: (a) A-weighted sound pressure level in dB and (b) loudness in sone over the volume flow for all measured air diffusers.



(a) Sharpness

(b) Roughness

Figure 6: (a) Sharpness in acum and (b) roughness in asper over the volume flow for all measured air diffusers.

sharpness increase can be seen for an increasing volume flow. The maximum sharpness is calculated for the slot diffuser from LTG in the supply air setting with 1.27 acum at 600 m^3/h, and the lowest sharpness is calculated for the swirl diffuser from TROX with 0.35 acum at 200 m^3/h. In Figure 6b the roughness in asper is shown over the volume flow for all measured air diffusers and is calculated according to the ECMA-418-2 [6]. The roughness is minimal for the slot diffuser from LTG in the supply air setting with 0.03 asper at 200 m^3/h and is maximal for the slot diffuser from TROX in both vane positions with 0.18 asper at 600 m^3/h. It is noticeable that with an increasing volume flow from 400 m^3/h to 600 m^3/h, the roughness does not increase strongly for any air diffusers.

4. DISCUSSION

The sound pressure level and the sound power level increase for all air diffusers with increasing volume flow. The differences in the sound pressure level between the air diffusers become smaller with increasing volume flow. It was shown that the measurements between microphone No. 19 of the microphone arc and the low noise microphone show little difference in the sound pressure levels. Therefore it can be inferred that the data of both measurement setups are suitable, and the recordings are reproducible. The directivity of the sound pressure level showed an angle difference divided into different frequencies. The angle difference can be explained due to the geometric structure of the air diffusers, which is often such that the airflow is ceiling-attached. In the shown Figure 4b, the one-third octave bands of 1 kHz and 2 kHz have an increased sound pressure level for the angles near the ceiling (75°-90°). Similar directivity patterns are given when looking at the other measured air diffusers. For the measurements without any air diffuser, only with the hose and the ceiling tile construction, the directivity pattern is similar. It even shows increased sound pressure levels for the 1 kHz and 2 kHz one-third octave bands. This would imply that the geometric design of the air diffusers reduces the sound pressure levels of these frequencies and that there is further potential to decrease these sound pressure levels by geometric modifications to the diffusers. The results of the A-weighted sound pressure level and the loudness are similar. It is noticeable that the loudness increases logarithmically. This could be an important factor when assessing the noises according to their pleasantness and annoyance. This must be further investigated through listening experiments with subjects. It is noteworthy to look at the results for the slot diffuser from LTG in the extract air setting and the supply air setting. Especially at a volume flow of 200 m^3/h, the sound power levels, loudness, and roughness differ significantly from the results of the other air diffusers. This can be due to the fact that only one half of the air diffuser was measured. The levels will add up in full operation, resulting in a minimum 3 dB increase in the sound power level. However, this air diffuser has increased sharpness compared to the other air diffusers. Nevertheless, the sharpness values are not high. This is due to the fact that the signals contain mainly frequencies below 1 kHz, and the calculation of sharpness includes a weighting that only takes effect above 16 Bark (≈3 kHz). Also, the perceived sharpness is less when there is a broad spectrum of low frequencies in signals [7]. The roughness values are relatively small, which can be expected for unmodulated broadband noise [8]. The threshold for roughness is at approximately 0.1 asper [7]. Therefore, the sounds of all air diffusers generated with a volume flow of 200 m^3/h might not be perceived as rough. For the sounds generated with higher volume flows of 400 m^3/h and 600 m^3/h, the roughness might be perceived but with values between 0.11 and 0.18 not as strongly.

5. CONCLUSION

In this study, acoustic signals from five different air diffusers were measured, two of them in different settings. The results of this study seem to indicate that there are differences between the manufacturers and types of air diffusers regarding the psychoacoustic parameters loudness, sharpness and roughness. These findings now need to be confirmed with the help of listening experiments with subjects. Based on the results of the psychoacoustic analyses, numerical simulations and upcoming listening experiments, the air diffusers will be modified in their geometric design to avoid unpleasant sound features.

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