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Psychoacoustic model for predicting wind turbine noise annoyance

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ABSTRACT
Noise annoyance caused by wind turbines is a critical issue for the societal acceptance of wind energy. Wind turbine noise exposure is typically assessed using conventional time–averaged metrics, however, the literature suggests that these metrics do not fully capture the sound properties responsible for the perceived noise annoyance. Therefore, it is questionable to assess wind turbine noise and its abatement strategies using only such metrics. This paper presents a novel psychoacoustic model for predicting wind turbine noise annoyance that combines perception–based sound quality metrics. To establish the psychoacoustic model, the synthetic sound signals of two different wind turbines equipped with four state–of–the–art noise reduction add–ons (two types of trailing–edge serrations and two types of trailing–edge permeable materials inserts) were studied. Using a parametric wind turbine noise generator, the simulated sound signals were auralized at different observer positions and their noise annoyance was evaluated in two laboratory listening experiments with 16 and 10 subjects, respectively. The psychoacoustic annoyance model proposed here provides a very close agreement with the results of the listening experiment and improved accuracy compared to conventional sound metrics.

Keywords: Wind turbine noise, Psychoacoustics, Noise annoyance

1 INTRODUCTION

Wind turbines are a promising source of sustainable energy but the noise they generate causes annoyance to the residents around wind farms and, therefore, poses an important hurdle to their social acceptance. The ever–increasing demand for wind energy further worsens this situation. Wind turbine noise regulations become stricter with time and the emitted noise levels may prevent wind turbines from operating at maximum power settings and even stop operating at night.

In practice, conventional sound indicators are typically employed to assess wind turbine noise, such as the equivalent continuous A-weighted sound pressure level ($L_{\mathrm{A,eq,T}}$). Such metrics describe the sound exposure in a general and highly averaged way [1]. However, previous studies (e.g. [2]) reported that wind turbine sounds with tonal components and a stronger high-frequency content were perceived as considerably more annoying than those without tonal components and a stronger low-frequency content, despite having the same $L_{\mathrm{A,eq,T}}$ value. Therefore, it is highly questionable to only use these conventional indicators to assess wind turbine noise and its abatement procedures, since they do not fully capture the sound properties responsible for the perceived annoyance [1,3].

In general, wind turbine noise consists of broadband noise and sometimes additional discrete tonal components. Furthermore, the motion of the blades causes a periodic amplitude modulation of the sound with the modulation frequency being equal to the blade passing frequency. This sound characteristic is usually described as an annoying *swishing*, *lapping*, or *thumping* hearing sensation. Within the typical operational envelope, the turbulent boundary layer trailing edge (TBL–TE) noise of the rotor blades is considered the main noise source of modern horizontal axis wind turbines [4]. TBL–TE noise is generated when the unsteady pressure surface fluctuations convected within the boundary layer arrive at the trailing edge of the rotor blade, where they experience a sudden change in acoustic impedance and scatter as broadband noise. The blade sections near the tip

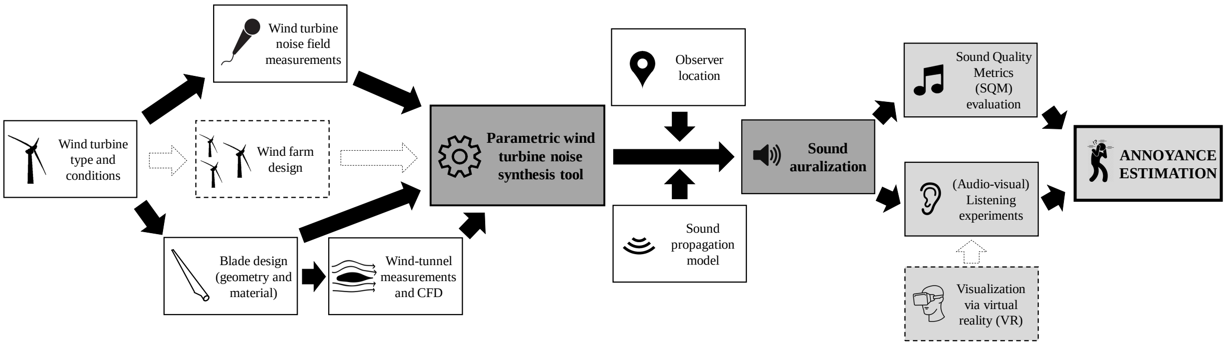


Figure 1. Block diagram illustrating the concept of perception–based evaluation of wind turbine noise reduction measures. The blocks with dashed lines were not employed in the current study but are considered as future extensions. Picture taken from [3] under CC BY 4.0 license.

usually generate the highest noise levels, because of their comparably higher velocity due to the rotation [3]. In the last years, multiple noise reduction measures have been suggested to alleviate the aforementioned acoustic impedance mismatch. The most promising concepts involve trailing–edge serrations add–ons [4–6] and permeable inserts [7–9], presenting sound pressure level reductions up to about 10 dB in certain frequency bands, with respect to the baseline configuration with a straight, solid trailing–edge [3]. Nevertheless, there is a lack of research evaluating how these sound pressure level reductions are perceived by the population in terms of noise annoyance reduction.

The overarching objective of the study reported here was to develop an accurate psychoacoustic model to estimate wind turbine noise annoyance (and its potential reduction when using noise abatement measures) more accurately than current "classical" assessment methods. A holistic approach is proposed to obtain a perception–based evaluation of wind turbine noise. The interested reader is referred to the original open–access publication [3] for more detailed information.

2 METHODOLOGY

2.1 Overview of the approach

Figure 1 depicts a block diagram that describes the perception–based evaluation of wind turbine noise proposed in [3]. A parametric wind turbine noise synthesis tool was first developed based on wind turbine noise field measurements [10]. This parametric tool can synthesize the sound signals that a virtual observer in a given location would hear, considering also sound propagation effects, based on the concept of auralization. Auralization consists of artificially making an acoustical situation audible, which can be considered the acoustical counterpart to visualization. Further details about the auralization process employed can be found in [3, 10]. The associated noise annoyance for each generated sound signal can then be estimated in listening experiments and/or with psychoacoustic sound quality metrics (SQMs).

2.2 Sound stimuli

Using this auralization approach, the synthetic sound signals of two different wind turbines were simulated (based on the field measurements of [10]): a Vestas V90–2.0 MW (henceforth *WT I*) and an Enercon E82–2.0 MW (*WT II*), considering the three different observer positions. The location henceforth denoted as "*norm*" replicates the recording position on the ground of the field measurements and follows the IEC 61400–11 standard for noise certification of wind turbines. This location corresponds to a distance from the tower equal to the sum of one wind turbine blade radius and one wind turbine hub height, which is 140 m for *WT I* and 119 m for *WT II*. Two additional observer positions (at 400 m and 600 m from the tower) were considered at a height of 1.7 m (approximate ear level of an average standing person) to represent an observer in residential areas close to a wind farm.

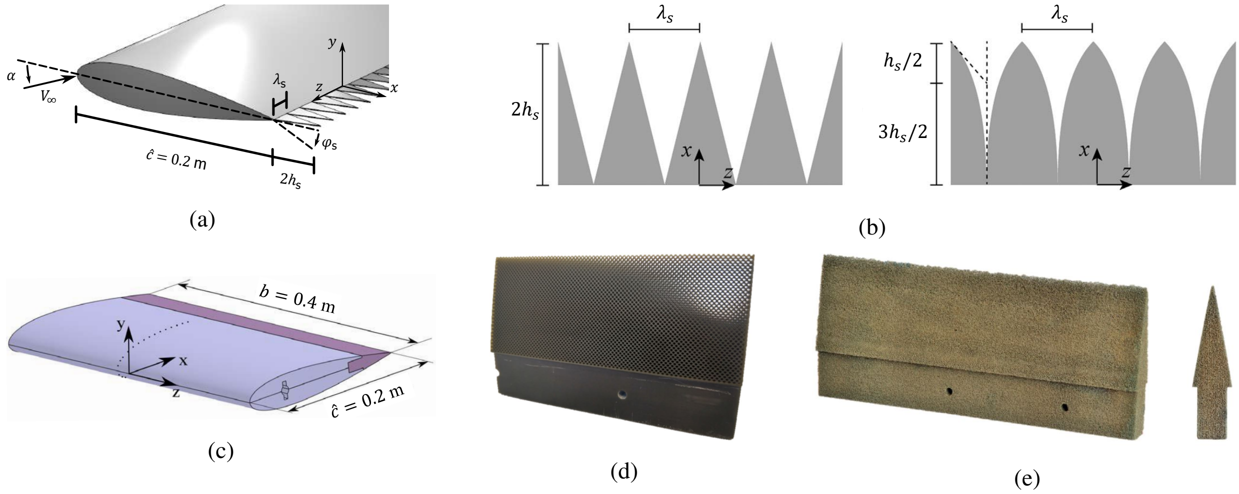


Figure 2. (a) Illustration of a wind turbine blade with retrofitted sawtooth serrations. Adapted from [5]. (b) Sketch showing the difference between the sawtooth serrations (left) and concave serrations (right). Adapted from [6]. (c) Illustration of a wind turbine blade equipped with a permeable trailing–edge insert (in dark purple) [9]. (d) Detail of the 3D–printed permeable insert [7]. (e) Detail of metal foam insert [8]. Picture taken from [3] under CC BY 4.0 license.

Apart from the baseline case (with no add–ons implemented), four state–of–the–art TBL–TE noise abatement measures were considered: sawtooth serrations [4, 5], concave serrations [6], 3D–printed permeable inserts [7], and metal foam inserts [8, 9], see Fig. 2. Their respective noise reductions were directly obtained from recent publications in the literature [4–9] and upscaled to the full–scale wind turbine geometries [3]. A detailed explanation of the physical mechanisms involved in these noise reduction measures and the assumptions made for the upscaling of the noise reductions (and the consequent limitations) can be found, respectively, in [3] and [4–9].

The total number of sound stimuli auralized was 30, i.e. 2 wind turbine types × 3 observer locations × 5 configurations (baseline + 4 noise reduction measures).

2.3 Listening experiments

Two listening experiments were performed to assess the short–term noise annoyance reactions to the wind turbines in the different trailing-edge configurations.

2.3.1 Experiment 1

Listening Experiment 1 [3] was performed in the AuraLab at Empa. Sixteen subjects (8 females, 8 males), all employees of Empa, with self–reported normal hearing, who felt healthy and well, and who were not tired at the time of the experiment, participated in the study. They had a mean age of 41.2 years with a standard deviation of 11.0 years. The subjects performed the experiments individually, one at a time, in which they listened to and rated the stimuli regarding annoyance. To that aim, they used the ICBEN 11–point scale to answer the following question during or after the playback of each stimulus (in German): "*When you imagine that this is the sound situation in your garden, what number from 0 to 10 best shows how much you would be bothered, disturbed or annoyed by it?*". Here, 0 represents the lowest and 10 the highest annoyance rating. This experiment did not consider the sound stimuli corresponding to an observer distance of 600 m. Further details about Experiment 1, such as the playback order of the stimuli, can be found in [3].

2.3.2 Experiment 2

Experiment 2 aimed at replicating the conditions of Experiment 1 and was performed in a quiet room at Delft University of Technology. Experiment 2 evaluates the comparability of the results obtained from a different, independent listening experiment and, in addition, it complements Experiment 1 with the sound stimuli for an observer distance of 600 m. The 10 subjects (2 females, 8 males) were all aerospace engineering bachelor students with a mean age of 20.1 years with a standard deviation of 1.1 years. As in Experiment 1, all participants had self–reported normal hearing and felt healthy and well during the experiment. The same annoyance question was used as in Experiment 1 but in English instead of German. All participants listened to two repetitions of each stimulus in a randomized order.

2.4 Psychoacoustic sound quality metrics (SQMs)

Sound Quality Metrics (SQMs) from the field of psychoacoustics are currently being studied and considered for their application in wind turbine noise [3] and aircraft noise [11–13]. In general, SQMs provide sensation magnitudes instead of stimulus magnitudes, i.e. they describe the hearing sensation instead of a purely physical magnitude, such as the sound pressure or sound pressure level. Hence, these metrics are expected to better capture the human ear behavior and be more accurate in predicting annoyance compared to the conventional sound metrics normally employed for wind turbine noise assessment. The five most common SQMs [12], as also used here, are:

- Loudness (N) is the subjective perception of the magnitude of a sound and corresponds to the overall sound intensity. The calculation of loudness has been standardized within the ISO norm 532–1 using Zwicker's method [14].
- Tonality (K) measures the perceived strength of the unmasked tonal energy within a complex sound. In this work, Aures' method [15] was employed.
- Sharpness (S) describes the high–frequency content of a sound. The von Bismark's [16] method was used.
- Roughness (R) refers to the rapid amplitude fluctuations of some sounds in the frequency range between 50 Hz and 90 Hz. The method by Daniel and Weber [17] was used.
- Fluctuation strength (FS) assesses slow fluctuations in loudness, having its maximum value for fluctuations of approximately 4 Hz. The method by Fastl and Zwicker [18] was employed.

All SQMs were calculated with in–house software developed at TU Delft. Several authors have tried to combine these SQMs into global metrics, such as the Psychoacoustic Annoyance (PA) metric first introduced by Fastl and Zwicker [18] and later modified by More [12] and Di et al. [19] to also include the tonality metric. The general expression for the PA metric is:

$$\mathrm{PA} = N\left(1+\sqrt{C_0 + C_1\,\omega_S^2 + C_2\,\omega_{FR}^2 + C_3\,\omega_T^2}\right), \tag{1}$$

where the term ω_S contains the sharpness S (and loudness N) contribution:

$$\omega_S = \begin{cases} 0.25(S-1.75)\log_{10}(N+10), & \text{for } S \geq 1.75, \\ 0, & \text{for } S < 1.75. \end{cases} \tag{2}$$

The term ω_{FR} contains the contributions of the roughness R and fluctuation strength FS (and loudness N):

$$\omega_{FR} = \frac{2.18}{N^{0.4}}\left(0.4\,FS + 0.6\,R\right), \tag{3}$$

and the term ω_T contains the tonality K (and loudness N) contribution:

$$\omega_T = \begin{cases} 0, & \text{for the model by Fastl and Zwicker [18]}, \\ \left(1-e^{-0.29N}\right)\left(1-e^{-5.49K}\right), & \text{for the model by More [12]}, \\ \frac{6.41}{N^{0.52}}K, & \text{for the model by Di } et\ al.\ \text{[19]}. \end{cases} \tag{4}$$

Lastly, the coefficients C_0 to C_3 of Eq.(1) for each PA model are listed in Table 1.

Table 1. Coefficients for Eq.(1) for each of the PA models considered.

PA model	C_0	C_1	C_2	C_3
Fastl and Zwicker [18]	0	1	1	0
More [12]	-0.16	11.48	0.84	1.25
Di *et al.* [19]	0	1	1	1

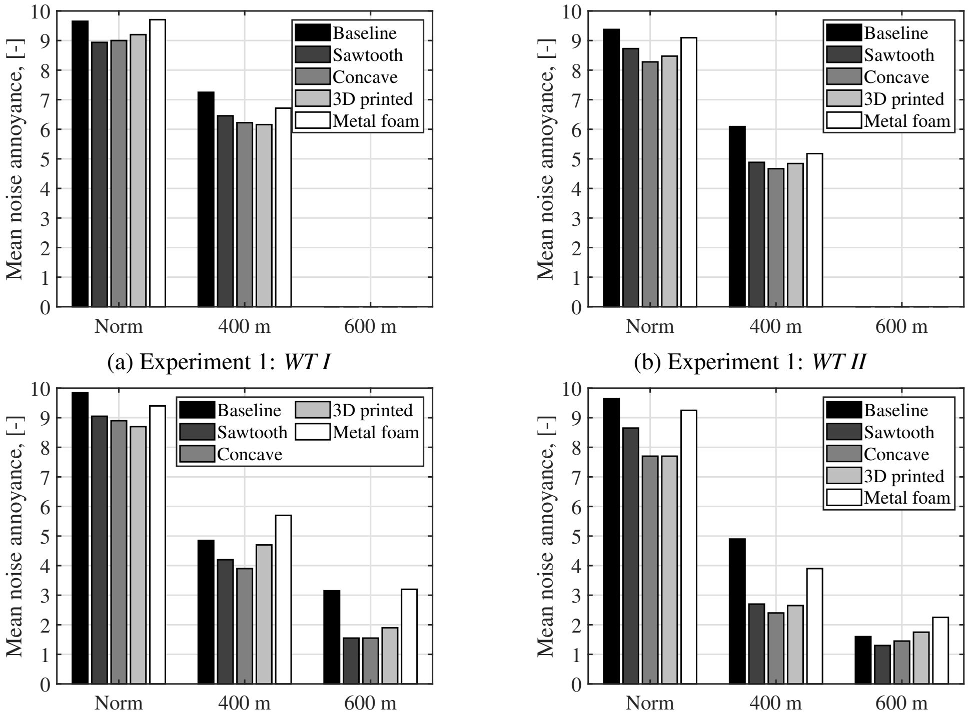
3 RESULTS

The mean observed annoyance reactions in both listening experiments as a function of the wind turbine type, observer distance, and trailing–edge configuration are presented in Fig. 3. Most noise reduction add–ons result in clearly reduced annoyance ratings compared to the baseline, except for the metal foam which does not achieve significant improvements. This is most likely due to the increase in high–frequency noise caused by this measure [3, 8]. This difference is particularly noticeable in Experiment 2, where the metal foam is sometimes even perceived as more annoying than the baseline. It should be noted that the participants of Experiment 2 have a considerably lower mean age than those of Experiment 1 and, hence, they are expected to be more sensitive to higher frequencies [18]. Overall, in this case study, the concave serrations showed the best performance in reducing noise annoyance.

Furthermore, the observed annoyance to the *WT I* is somewhat higher than to the *WT II*, and the annoyance reactions to the latter decrease in a stronger way with increasing distance than to the former. On the other hand, the effectiveness of the measures was quite similar for both wind turbines and listening experiments and did not change between the distances significantly either. Similar performance can, therefore, also be expected for other observer positions, although this claim would have to be experimentally verified.

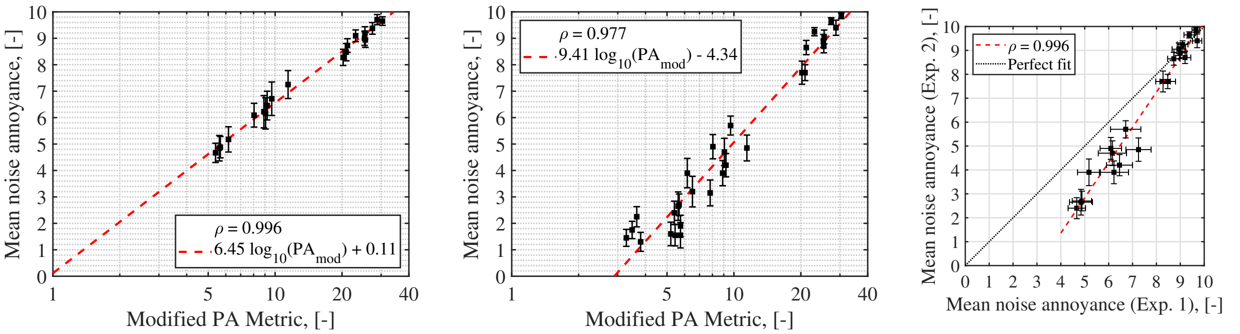
Table 2 contains the correlation coefficients (ρ) between the mean observed noise annoyance per stimulus in each listening experiment and the estimated noise annoyance by the three PA models described in section 2.4 (Fastl and Zwicker [18], More [12], and Di *et al.* [19]). The 95% confidence intervals for these ρ values are shown between parentheses in Table 2. In this case study, it was found that the roughness R and fluctuation strength FS metrics did not vary significantly within the sound stimuli considered and, therefore, modified versions of the PA models that do not consider these two metrics (i.e. equivalent to setting $C_2 = 0$ in Eq. (1)) were also evaluated and their performance is shown in Table 2. All values in Table 2 consider a logarithmic scale for the PA metric. Table 2 reveals that the PA model by Di *et al.* modified not to account for R and FS presented the highest correlation coefficient values with $\rho = 0.996$ for Experiment 1 and an average ρ value of 0.987 considering both experiments. The modified model of Fastl and Zwicker is a close second with an average ρ value of 0.985 between both experiments. However, due to the considerable overlaps of the 95% confidence intervals in Table 2, it cannot be concluded yet that these models are the best performing. On the other hand, all PA models perform better in estimating the annoyance observed in the two listening experiments (with ρ values larger than 0.969 in all cases) compared to conventional sound metrics (e.g. $\rho \approx 0.877$ for $L_{\mathrm{A,eq,T}}$, with 95% confidence interval from 0.830 to 0.896). It should be noted that these correlation coefficients refer to the mean annoyance ratings averaged between the number of participants and that, in case the non–averaged responses were considered, lower ρ values would be obtained (around 0.91 instead of 0.99 on average). Additional statistical analyses on Experiment 1 can be found in [3].

Figures 4a and 4b compare the observed mean noise annoyance in the listening experiments with the noise annoyance estimated using the modified PA model by Di *et al.* The agreement between modeled and experimental data is higher for Experiment 1 (Fig. 4a) than for Experiment 2 (Fig. 4b). The participants of Experiment 2 reported significantly lower noise annoyance values for the stimuli at an observer distance of 400 m, see Fig. 4c. The ρ value between the observed mean annoyance values in both experiments is very high ($\rho = 0.996$), close to the perfect fit ($\rho = 1$) denoted by the black dotted line in Fig. 4c. The standard errors of the mean observed in both experiments are very similar and relatively low (approximately 0.38 on average). Higher deviations are observed for the sound stimuli cases at an observer distance of 400 m.



(a) Experiment 1: *WT I*
(b) Experiment 1: *WT II*
(c) Experiment 2: *WT I*
(d) Experiment 2: *WT II*

Figure 3. Mean observed noise annoyance in the listening experiments as a function of the wind turbine type, observer distance, noise reduction measure, and listening experiment (1 in top row [3] and 2 in bottom row).



(a) Experiment 1
(b) Experiment 2
(c) Comparison between the two listening experiments

Figure 4. Scatter plots of the mean observed noise annoyance in (a) listening Experiment 1 and (b) Experiment 2 versus the modified psychoacoustic annoyance model by Di *et al.* (PA_{mod}, on a logarithmic scale). (c) Comparison of the mean observed annoyances in both listening experiments. The black dots show the mean values per stimulus, the error bars are the standard error of the mean of the observations, and the red dashed lines show the linear regressions.

The equations of the regression lines to the experimental data of both listening experiments are shown in the legends of Fig. 4. It should be noted that these relationships are not universally true, but would rather change for different noise sources and/or experimental conditions. Nevertheless, once the relationship between PA and the observed annoyance has been established for a certain data set as in the current study, PA can potentially be used to estimate annoyance reactions evoked, e.g. by additional noise reduction measures or observer locations.

Table 2. Correlation coefficients (ρ) between the mean observed noise annoyance in each listening experiment and the different psychoacoustic annoyance (PA) models (on a logarithmic scale). Values between parentheses denote the 95% confidence intervals.

PA model	Experiment 1	Experiment 2
Fastl and Zwicker [18]	0.983 (0.957 – 0.993)	0.981 (0.959 – 0.991)
Fastl and Zwicker (modified)	0.988 (0.969 – 0.995)	0.982 (0.962 – 0.992)
More [12]	0.987 (0.968 – 0.995)	0.969 (0.936 – 0.986)
More (modified)	0.989 (0.971 – 0.996)	0.971 (0.940 – 0.986)
Di *et al.* [19]	0.993 (0.983 – 0.997)	0.977 (0.952 – 0.989)
Di *et al.* (modified)	0.996 (0.989 – 0.998)	0.977 (0.952 – 0.989)

4 CONCLUSIONS AND OUTLOOK

This study proposed an innovative holistic approach to estimate the annoyance caused by wind turbine noise and to evaluate the performance of rotor blade trailing–edge add–ons to reduce it. This approach consists of auralizing plausible acoustical sceneries of wind turbine noise using a parametric wind turbine synthesis tool based on field measurements. The expected modifications caused by noise reduction measures in the wind turbine noise emission can be synthetically auralized and then propagated to different observer locations. The obtained synthetic sound signals can then be reproduced in listening experiments and/or analyzed with psychoacoustic sound quality metrics to estimate short–term noise effects, such as annoyance.

The importance of the sound characteristics of wind turbine noise for the perceived annoyance was highlighted, such as the tonality or the spectral content. The characterization of sound by psychoacoustic metrics can help to quickly estimate the short–term annoyance caused in different scenarios and for different observer locations. This is especially useful if the findings are previously validated by listening experiments.

Future work should also investigate the effect of different amplitude modulations in the wind turbine sound signals, especially when considering different rotational velocities because this parameter is also expected to influence the perceived annoyance.

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REFERENCES

[1] Pieren R, Bertsch L, Lauper D, Schäffer B. Improving future low–noise aircraft technologies using experimental perception–based evaluation of synthetic flyovers. Science of the Total Environment. 2019 July;692:68-81.

[2] Persson Waye K, Agge A. Experimental quantification of annoyance to unpleasant and pleasant wind turbine sounds. In: 29th International Congress and Exposition of Noise Control Engineering; 2000. .

[3] Merino-Martinez R, Pieren R, Schäffer B. Holistic approach to wind turbine noise: From blade trailing–edge modifications to annoyance estimation. Renewable and Sustainable Energy Reviews. 2021 May;148(111285):1-14.

[4] Arce León C, Merino-Martinez R, Ragni D, Avallone F, Snellen M. Boundary layer characterization and acoustic measurements of flow–aligned trailing edge serrations. Experiments in Fluids. 2016 October;57(182):1 22.

[5] Arce León C, Merino-Martinez R, Ragni D, Avallone F, Scarano F, Pröbsting S, Snellen M, Simons DG, Madsen J. Effect of trailing edge serration–flow misalignment on airfoil noise emission. Journal of Sound and Vibration. 2017 May;405:19 33.

[6] Avallone F, van der Velden WCP, Ragni D. Benefits of curved serrations on broadband trailing–edge noise reduction. Journal of Sound and Vibration. 2017 April;400:167 177.

[7] Rubio Carpio A, Avallone F, Ragni D, Snellen M, van der Zwaag S. 3D–printed Perforated Trailing Edges for Broadband Noise Abatement. In: 25th AIAA/CEAS Aeroacoustics Conference; 2019. AIAA paper 2019–2458.

[8] Rubio Carpio A, Merino-Martinez R, Avallone F, Ragni D, Snellen M, van der Zwaag S. Broadband Trailing Edge Noise Reduction Using Permeable Metal Foams. In: 46th International Congress and Exposition of Noise Control Engineering; 2017. .

[9] Rubio Carpio A, Merino-Martinez R, Avallone F, Ragni D, Snellen M, van der Zwaag S. Experimental characterization of the turbulent boundary layer over a porous trailing edge for noise abatement. Journal of Sound and Vibration. 2019 March;443:537-58.

[10] Pieren R, Heutschi K, Müller M, Manyoky M, Eggenschwiler K. Auralization of Wind Turbine Noise: Emission Synthesis. Acta Acoustica United with Acoustica. 2014 October;100:25-33.

[11] Merino-Martinez R, Vieira A, Snellen M, Simons DG. Sound quality metrics applied to aircraft components under operational conditions using a microphone array. In: 25th AIAA/CEAS Aeroacoustics Conference; 2019. AIAA paper 2019–2513.

[12] More SR. Aircraft Noise Characteristics and Metrics. Purdue University; 2010. Report No. PARTNER–COE–2011–004.

[13] Greco GF, Bertsch L, Ring TP, Langer SC. Sound quality assessment of a medium–range aircraft with enhanced fan–noise shielding design. CEAS Aeronautical Journal. 2021;12:481-93.

[14] ISO norm 532–1 – Acoustics – Method for calculating loudness – Zwicker method. International Organization for Standardization; 2017. 1.

[15] Aures W. Procedure for calculating the sensory euphony of arbitrary sound signal. In German: Berechnungsverfahren für den sensorischen Wohlklang beliebiger Schallsignale. Acustica. 1985;59(2):130-41.

[16] von Bismark G. Sharpness as an attribute of the timbre of steady sounds. Acta Acustica united with Acustica. 1974;30(3):159-72.

[17] Daniel P, Webber R. Psychoacoustical Roughness: Implementation of an Optimized Model. Accustica – acta acustica. 1997;83:113-23.

[18] Fastl H, Zwicker E. Psychoacoustics – Facts and models. Third ed. Springer Series in Information Sciences; 2007. ISBN: 987–3–540–68888–4.

[19] Di GQ, Chen XW, Song K, Zhou B, Pei CM. Improvement of Zwicker's psychoacoustic annoyance model aiming at tonal noises. Applied Acoustics. 2016;105:164-70.