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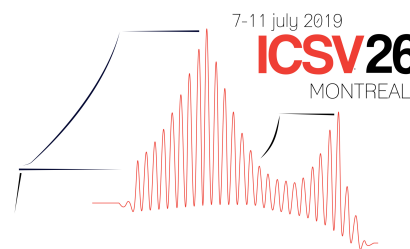
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ASSESSMENT OF THE SOUND QUALITY OF WIND TURBINE NOISE REDUCTION MEASURES

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Noise emissions from wind turbines are one of the main issues that the wind energy industry must deal with nowadays. Strict noise regulations often prevent wind turbines to operate at maximum power conditions, causing large losses of power production and, hence, of revenue. Several noise reduction measures have been proposed so far, but the use of trailing-edge serrations and permeable inserts seem to be the two most promising approaches, showing broadband noise reductions of several decibels. This paper considers the noise reductions (with respect to the baseline blade) observed in previous wind-tunnel measurements featuring these two measures, and scales and synthetically applies them to an experimental recording of a full-scale Vestas V90-2.0 MW wind turbine in operational conditions. The calculated results are then auralized for the observer location used for noise certification in the IEC 61400-11 standard. State-of-the-art sound quality metrics (loudness, tonality, sharpness, roughness and fluctuating strength) are then applied to these simulated sound signals to better understand the achieved reduction in noise annoyance experienced by humans. Reductions in the maximum A-weighted sound pressure level ($L_{p,A,max}$) of about 2.4 and 1.2 dBA are observed for the serrations and permeable inserts, respectively. In general, trailing-edge serrations seem to reduce the calculated annoyance experienced (17% lower than the baseline) more efficiently than the permeable inserts (just 2% lower).

Keywords: wind turbine noise, sound quality metrics, trailing edge serrations, permeable inserts.

1. Introduction

Wind turbine noise is an important cause of annoyance for the population living next to wind farms [1]. The increasing demand for wind energy only aggravates this issue even more, thus, noise regulations for wind turbines become stricter with time. This situation prevents wind turbines to operate at maximum power conditions (and to even stop operating at night in some occasions), with the consequent loss of power and, hence, of revenue. It is estimated that a decrease of 1 dB in the sound pressure level (L_p) is expected to allow an increase in power production by 2 to 4 % [2]. Considering that the average expected

lifetime of a typical modern wind turbine is approximately 20 years, these restrictions can cause losses of millions of euros **per** wind turbine [3].

The main noise source of modern wind turbines within their typical operating envelope is the turbulent boundary layer trailing edge (TBL–TE) noise [4, 5] of the rotor blades, especially at the tips, due to their higher velocity. This type of noise is caused when the unsteady pressure surface fluctuations convected within the boundary layer arrive at the trailing edge, where they experience a sudden change in acoustic impedance and they scatter as broadband noise [4, 3]. Several noise reduction measures have been proposed for alleviating this acoustic impedance mismatch, from which trailing–edge serrations [6, 7, 8, 9] and permeable inserts [10, 11] are the most promising approaches, showing noise reductions ($\Delta L_p = L_{p,baseline} - L_{p,add-on}$) in certain one–third–octave frequency bands of about 10 dB with respect to the straight, solid trailing–edge baseline case.

The aim of this research is to assess the potential improvement in the perceived annoyance produced by wind turbine noise provided by these two noise reduction measures. In order to do so, the wind–tunnel experimental results by Arce León et al. [6, 7, 8] for trailing edge serrations and by Rubio Carpio et al. [10, 11] for permeable inserts are employed. The ΔL_p of both measures are then scaled and synthetically applied to an experimental recording of a full–scale wind turbine and auralized for an observer location on the ground [12, 13].

To evaluate the change in psychoacoustic annoyance of the auralized wind turbine noise, rather than simply just the change in L_p , more sophisticated sound quality metrics (SQM) [14, 15] were employed. A detailed explanation of these metrics is beyond the scope of this paper, thus a brief description of them is included in section 2.

2. Sound quality metrics (SQM)

The most common SQM [14] in decreasing order of influence to the experienced annoyance are:

- **Loudness** (N) is the subjective perception of the magnitude of a sound and corresponds to the overall sound intensity [14, 15]. The calculation of loudness has been standardized within the ISO norm 532–1 [16] using Zwicker’s method. The unit of this metric is the sone.
- **Tonality** (K) measures the perceived strength of the unmasked tonal energy within a complex sound [14, 15, 17]. In this work Aures’ method [17] was employed. The unit of this metric is the tonality unit (t.u.).
- **Sharpness** (S) describes the high–frequency content of a sound [14, 15]. In this paper von Bismark’s [18] method was used. The unit of this metric is the acum.
- **Roughness** (R) refers to the rapid amplitude fluctuations of some sounds in the frequency range between 50 Hz and 90 Hz [14, 15]. The method by Daniel and Weber [19] was used and the unit of this metric is the asper.
- **Fluctuation strength** (F) assesses slow fluctuations in loudness, having its maximum value for fluctuations of approximately 4 Hz. The method by Fastl and Zwicker [20] was employed. The unit of this metric is the vacil.

For this paper, rather than considering the maximum values, the values of these SQM that are exceeded 5% of the time are considered, since this is commonly done in psychoacoustic studies [14, 15]. Thus, a subscript “5” is added to the SQM henceforth.

Lastly, a combined metric called Psychoacoustic Annoyance (PA) [14, 15], which is typically used to simultaneously account for all the five aforementioned SQM in a weighted manner, was also considered.

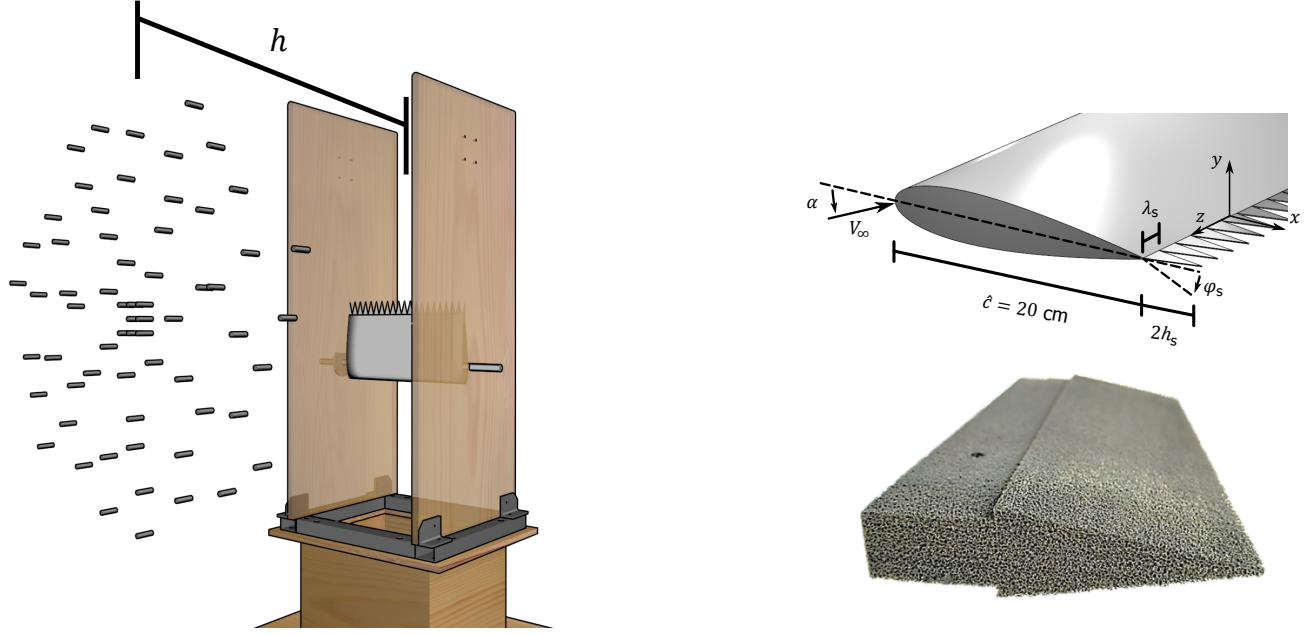


Figure 1: Experimental setup for the wind tunnel experiments. Left: Illustration of the microphone array and the airfoil in the test section, adapted from [7]. Top right: Schematic view of the trailing edge serrations, adapted from [7]. Bottom right: Photograph of the metal permeable foam trailing-edge insert, extracted from [3].

3. Experimental setups

3.1 Wind-tunnel experiments

A NACA 0018 airfoil manufactured in aluminum was tested in the anechoic vertical wind tunnel at Delft University of Technology [3]. The airfoil had a span (b) of 40 cm and a chord ($\hat{c}$) of 20 cm and was installed between two vertical side plates, see Fig. 1 left. The flow velocity considered for this paper is 40 m/s.

In the first test campaign, saw-tooth serrations were retrofitted to the trailing edge of the straight solid edge baseline. Several serration geometries and conditions were tested [6, 7, 8], but the largest noise reductions were obtained for an angle of attack of $\alpha = 0^\circ$, a flap angle of $\phi_s = 0^\circ$ and a serration length of $2h_s = 4$ cm (i.e. 20% of the airfoil chord $\hat{c}$) and a serration width of $\lambda_s = 2$ cm, see Fig. 1 top right. Hence, the ΔL_p values considered in this paper correspond to these conditions.

The second experimental campaign featured permeable inserts of different metal foams at the trailing edge of a NACA 0018 airfoil of the same dimensions, see Fig. 1 bottom right. From the many permeable inserts studied [10, 11], the one providing the largest ΔL_p values was made of a foam of NiCrAl alloy with a porous cell diameter of $800 \mu\text{m}$ and a flow permeability of $27 \times 10^{-10} \text{ m}^2$, at an angle of attack of $\alpha = 0^\circ$, and was, therefore, considered for this work.

The far-field noise emissions of the airfoil were measured employing a 64-microphone array located parallel to the airfoil at a distance h that was 1.26 m in the first campaign and 1.48 m in the second, see Fig. 1 left. The noise emitted by the trailing edge was isolated by integrating over a region of interest around the trailing edge following the approach explained in [21, 22, 23].

For further details of these experimental setups, the reader is referred to references [6, 7, 8, 10, 11].

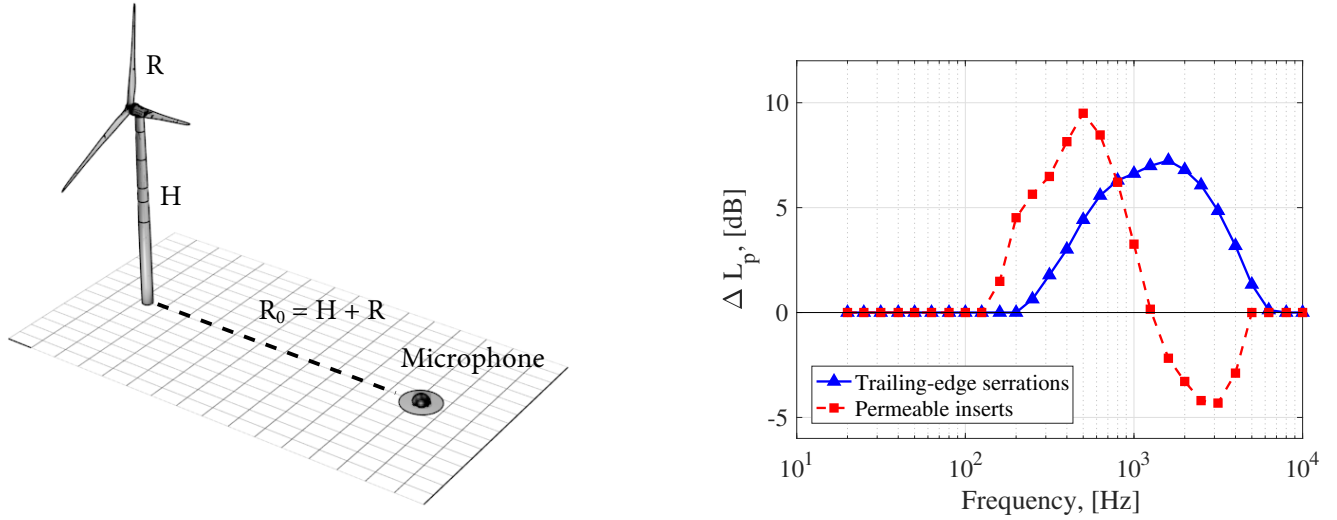


Figure 2: Left: Relative location of the microphone for the wind turbine field test. Adapted from [5]. Right: ΔL_p values for the trailing-edge serrations and the permeable inserts scaled for the V90–2.0 MW wind turbine. Positive ΔL_p values represent noise reductions and vice versa.

3.2 Wind turbine field test

The field experiment corresponds to a Vestas V90–2.0 MW [24] wind turbine located at Mont Crosin in Switzerland on September 7, 2011 at 12 h operating at nominal power with strong wind conditions [12]. The hub height of the turbine was $H = 95$ m, the rotor radius was $R = 45$ m, and the rotational speed 15 rpm. A single omnidirectional microphone B&K 4006 was employed for recording, which was placed on a hard plate of 0.6 m diameter on the ground at a horizontal distance of $R_0 = H + R = 140$ m from the tower in the downwind direction, following the IEC 61400–11 standard for noise certification of wind turbines, see Fig. 2 left. The weather conditions were obtained by a nearby weather station operated by MeteoSwiss. The measured sound pressure signal had a duration of 20 s and is available in [25].

4. Results

The ΔL_p values obtained in the wind-tunnel experiments for both noise reduction measures were scaled to consider the geometry, wind speed and the (expected) displacement thickness of the boundary layer δ^* at the trailing edge corresponding to the full-scale wind turbine blade. For estimating δ^* at the trailing edge, the values obtained in the wind-tunnel experiments [6, 11] were scaled using the relation $\delta^*/x \propto Re_x^{-0.2}$, where x is the streamwise distance from the leading edge and Re_x is the Reynolds number based on x [26].

It was assumed that the same ΔL_p values measured at the wind-tunnel tests are obtained at the same Strouhal numbers based on δ^* ($St = f V_\infty / \delta^*$) for the full-scale wind turbine. Here f represents the sound frequency in Hz and V_∞ is the flow velocity in m/s. This assumption is a common approximation [27, 1, 7] but it represents one limitation of the current research as explained later in section 5.1. Figure 2 right shows the scaled ΔL_p values considered corresponding to the V90–2.0 MW wind turbine. For the frequencies where no experimental data was available, a value of $\Delta L_p = 0$ was selected. The negative values for the case of the permeable inserts denote a noise increase, which is attributed to their higher surface roughness [11]. These ΔL_p values were used to modify the input parameters of the sound synthesis to auralize the full-scale wind turbine at the observer location denoted by the microphone in

Table 1: Predicted sound quality metrics for the baseline wind turbine and those equipped with trailing-edge serrations and permeable inserts at the observer position.

Metric	Baseline turbine	Trailing-edge serrations	Permeable inserts
$L_{p,A,F,max}$, [dBA]	57.3	54.9	56.1
$L_{p,A,eq}$, [dBA]	55.9	53.2	54.8
EPNL, [EPNdB]	78.3	76.5	78.7
Loudness (N_5), [sone]	17.03	13.99	16.16
Tonality (K_5), [t.u.]	0.24	0.26	0.27
Sharpness (S_5), [acum]	1.32	1.31	1.49
Roughness (R_5), [asper]	0.06	0.06	0.06
Fluctuation strength (F_5), [vacil]	0.30	0.29	0.31
PA, [-]	22.67	18.76	22.24

Fig. 2 left [12].

The SQM calculated for the three cases considered (baseline, trailing-edge serrations and permeable inserts) are included in Table 1, as well as other conventional acoustical metrics (the maximum A-weighted sound pressure level calculated with fast time weighting ($L_{p,A,F,max}$), the equivalent continuous A-weighted sound pressure level ($L_{p,A,eq}$) and the effective perceived noise level (EPNL)) [28]. The relative differences with respect to the baseline values are presented in Fig. 3 as bar plots for the conventional metrics (left plot) and for the SQM (right plot, in percentage values).

For the conventional metrics, reductions in the $L_{p,A,F,max}$ metric of 2.4 and 1.2 dBA are obtained for the serrations and the permeable insert, respectively. The first value is similar to the findings by Oerlemans et al. [1] in field measurements featuring a full-scale wind turbine equipped with trailing-edge serrations which also had a length of 20% the blade chord. Similar reductions in the $L_{p,A,eq}$ metric are obtained: 2.7 dBA and 1.1 dBA, respectively. In case no A-weighting is applied, there is almost no improvement in the $L_{p,max}$ metric because wind turbine sound is typically dominated by low-frequency noise [29], where the two noise reduction measures do not offer much improvement. Lastly, the serrations offer a EPNL reduction of 1.8 EPNdB, whereas the permeable inserts cause an increase of about 0.4 EPNdB, most likely due to the increase in high-frequency noise and tonality generated by these devices, see Fig. 2 right and Fig. 3 right, respectively.

For the SQM, the largest improvements are obtained in terms of loudness (N_5) with reductions of about 18% for the serrations and 5% for the permeable inserts. The tonality metric (K_5) is, however, worsened (8% by the serrations and 12% by the permeable inserts). This is because the ΔL_p values of both measures were applied to the broadband noise only, which causes the existing tonal sounds present (most likely due to the mechanical components in the nacelle [29]) to become more prominent since there is less masking of the tones [17, 23]. The sharpness (S_5) is barely improved (< 1%) by the serrations, but considerably worsened by the permeable inserts (13%) because of the increase in high-frequency noise of this measure. The baseline signal has a relatively low roughness (R_5) and no changes occur for either of the reduction measures, since they do not alter the noise levels between 50 Hz and 90 Hz, see Fig. 2 right. The fluctuation strength (F_5) is slightly improved by the serrations (3%) and slightly worsened by the permeable inserts (3%). This is maybe a coincidence since the change in temporal structure was not included in the simulation process. Lastly, the changes in PA obtained resemble those from the loudness metric, since this is the most influential metric for the experienced annoyance [14]: 17% for the serrations

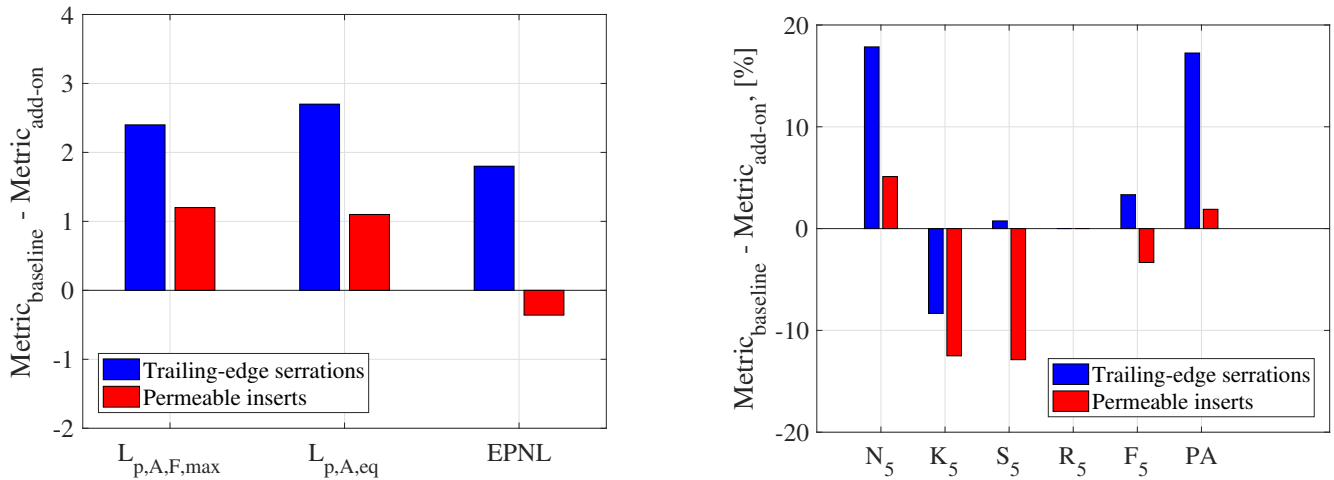


Figure 3: Change in the predicted SQM by both noise reduction measures with respect to the baseline full-scale wind turbine. Left: Absolute differences for the conventional sound metrics. Right: Percentage differences for the rest of SQM. In both graphs, positive values denote improvement in the SQM and vice versa.

and 2% for the permeable inserts.

Thus, in general and for the conditions considered in this paper, trailing-edge serrations seem to be a better approach for reducing the annoyance experienced due to wind turbine noise than permeable inserts, even if the latter provide a maximum ΔL_p value about 2 dB higher than the former, see Fig. 2 right.

5. Conclusions

Trailing-edge serrations and permeable inserts are two of the most promising noise reduction measures for wind turbine noise. In this paper, the noise reductions observed in previous wind-tunnel measurements featuring these two measures were scaled and synthetically applied to a field recording of a full-scale Vestas V90-2.0 MW wind turbine. The results were then auralized for the observer location typically used for noise certification. Sound quality metrics from the field of psychoacoustics were then applied to these simulated sound signals to better understand the reduction in annoyance achieved by these devices, if any. It was found that, despite an increase in the tonality metric (K_5), both measures reduced the $L_{p,A,max}$, the loudness (N_5) and the overall Psychoacoustic Annoyance (PA). Overall, it seems that the trailing-edge serrations are more effective to reduce the PA (17% lower than the baseline) compared to the permeable inserts (just 2% lower).

5.1 Limitations of this research

The research presented in this paper should be considered as preliminary since it has the following limitations:

- The ΔL_p values for the noise reduction measured considered correspond to an experiment with a NACA 0018 symmetric airfoil, whereas typical wind turbines are equipped with more complex and cambered airfoils. This fact, combined with the *basic* scaling performed on the wind-tunnel results to a full-scale turbine, indicate that the actual annoyance reduction that serrations and permeable inserts provide in reality might be different, most likely poorer.
- For simplicity, both noise reduction measures were assumed to cause the same ΔL_p for all the emission directions, rather than considering a more complicated and realistic directivity pattern

[30].

- The ΔL_p values considered for both measures correspond to an angle of attack of $\alpha = 0^\circ$ and no serration flap angle $\phi_s = 0^\circ$, see Fig. 1 top right. Actual operational conditions will likely differ from these, worsening the performance of both noise reduction measures.

This research is ongoing work that intends to perform field measurements on of full-scale wind turbines equipped with these noise reduction devices to assess the results estimated by the method presented in this paper. Different wind turbine types, wind velocities and observer locations will be considered. In addition, a detailed survey on a representative amount of people should also be performed to evaluate the actual annoyance levels of wind turbine noise (with and without add-ons).

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