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WIND TURBINE'S NOISE ANNOYANCE RATINGS RELATED TO THE DISTANCE AND DIRECTIVITY OF A WIND TURBINE

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ABSTRACT

Wind turbine (WT) noise is commonly reported as very annoying. There is an agreement that this is mainly because of the non-stationary nature of the signal which is modulated by the blades' movements. However, measurements and recordings of such noise is very difficult due to the fact that in majority of cases a single wind turbine is only a part of the greater complex (consisted of dozens of them). In this paper we describe a laboratory experiment, in which people were asked to rate annoyance of WT noise in the function of the distance from a WT. Noise generated by the wind turbine was recorded from both sides, downwind and in line with the rotor plane. Results suggest that annoyance ratings decrease with the increasing distance from a WT and the noise recorded from the side (in line with the rotor plane) is marginally more annoying than that recorded downwind. Moreover, road traffic (RT) used as the reference noise, was the least annoying source.

Keywords: *wind turbine noise, wind farm, noise annoyance, road traffic noise.*

1. INTRODUCTION

Large size of WTs and periodicity of blades' movements lead to emission of very specific type of noise. It was shown that this noise is generally rated higher on annoyance scale than other noise sources [1]–[3]. This phenomenon led scientists to investigate different aspects of WTs, including low frequency components, amplitude modulation, timbre/character of generated sounds, visual aspects and attitude towards this type of constructions [1].

One of factors clearly influencing annoyance of WT noise is the distance from the turbine. According to Michaud [4] reduced distance to wind farm was related to the higher noise annoyance ratings. On the other hand such a relation was not found in [5]. Nevertheless, such research is commonly conducted in situ and the distance between turbines and dwellings is the result of the reality (how far houses are built) and cannot be strictly planned or changed. Thus we wanted to strictly control distance values and places in which we recorded WT noise. It was possible thanks to the company running one of the farms in Poland – we could turn off all other turbines and record only one turbine in different distances. Then recordings were used in the laboratory experiment.

2. METHOD

2.1 Recordings

WT noise was recorded in Poland. The wind farm consists of 20 turbines. We recorded one of them, Vestas V90 2.0MW. Diameter of the rotor is 90m and the hub is 105m above the ground. Recordings were done in spring in the stable weather conditions: wind speed at hub was between 7.5 and 9 m/s with a constant direction, temperature was 9 Celsius degrees. All weather data was obtained from wind farm's system as well as from two wind measuring stations installed by us in the field (with the height of 4 and 10m). We decided to record the turbine in two directions: downwind (DW) and in line with the rotor plane (RP). It was planned to record noise in the distances of 150m, 250m, 500m, 750m and 1000m using ambisonic microphones. However, we had only three of them (RODE NTSF1, Sennheiser Ambeo and Soundfield ST450) so we changed location of microphones during the whole recording session. Thus, recordings were made between 3 and 8 PM (each lasting around 45 minutes) and there was

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no situation when all distances were recorded at the same time. However, as the weather conditions were stable and WT performance was also constant, we decided to use these recordings, with a careful analysis before conducting an experiment. At each measuring point there was also a sound meter (SVAN 945) to keep all acoustical information about sound level values and spectral characteristics. Geographical plan of the measuring procedure is presented in Fig. 1.

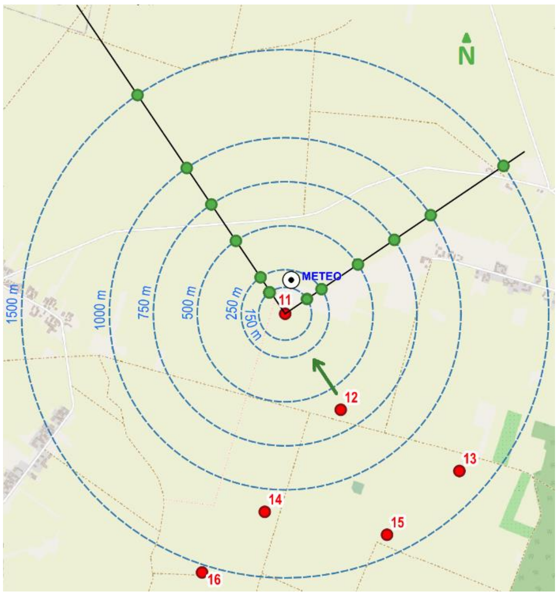

Figure 1. Schematic plan of a measuring session. Each green dot represents location of a sound meter. A location where meteorological station was placed is marked with 'METEO' text. Red dots represent all WTs and green arrow points the wind direction.

2.2 Stimuli

All recordings were carefully manually analyzed regarding possible wind-induced noise and other sound sources (dogs barking, RT etc.). Despite of usage of wind-shields (sometimes doubled), many wind blows were recorded – recordings from AMBEO had to be excluded because of that. Clean parts were quite rare, however we succeeded in selection of short (5 minutes) fragments with satisfactory quality of sound. Then, recordings were analyzed regarding their amplitude modulation depth and AM frequency. It was done using the algorithm proposed by Amplitude Modulation Working Group [6]. Results of this analysis are shown in Table 1.

Table 1. Details of eight WT noise recordings.

Location	Distance [m]	Sound Level [dBA]	AM Depth [%]	AM Freq [Hz]
Downwind	150	49.1	20.57	0.4
Downwind	250	49.7	22.38	0.8
Downwind	500	42.8	31.61	0.7
Downwind	750	38.2	29.21	0.7
Downwind	1000	36.3	28.39	0.4
In Plane	150	49.8	25.01	0.7
In Plane	250	42.3	27.56	0.7
In Plane	500	38.4	26.72	0.8

As could be expected, when the distance from a WT increases, sound level values decrease – with one exception for downwind distances 150m and 250m, probably due to terrain shape (small hill) and different surfaces. All these recordings were used in the laboratory experiment. DW recordings were conducted using a RODE microphone while RP - with Soundfield ST450.

To compare annoyance ratings evoked by WT noise with a more common noise, we also used stimuli of RT noise, applied in one of our previous experiments [7]. It was the same 5-minutes recording of RT in the four-lane street (recorded from 30m to the middle of the lanes), but presented at sound levels equal to levels of each WT stimulus (attenuation from propagation or distance was not applied).

2.3 Procedure

The main experiment was preceded by the teaching procedure which we describe in the other FA23 paper ("Noise Annoyance Studied In Different Situations: A Comparison Of Results Obtained In ~~In~~ Situ And Laboratory Conditions"). This procedure familiarize participants with the concept of noise annoyance and noises generated by WTs.

After that, the main experiment was conducted. It contains 16 stimuli, 8 of them are WT noise (presented in Table 1). The other 8 stimuli are the RT noise, presented at the same levels as WT sounds. It means that each WT stimulus has its 'pair' of RT noise. Respondents were asked to relax and read a book during the experiment and after each stimulus rate its annoyance using 0-10 numerical ICBEN scale [8] in its Polish version [9]. Stimuli were presented using a 2+1 loudspeaker configuration, with two Yamaha HS5 and one subwoofer (Yamaha DXS15). They were played from a computer using Reaper as a DAW and RME Babyface PRO audio interface.

The experiment is not finished, we collected data from 34 participants so far (60 are planned).

3. RESULTS

As the recordings were done from both sides only in three distances, results can be presented in different ways: 5 distances but only for RT and DW WT or 3 distances but for both DW and RP 'WT conditions' and RT. The former is presented in Fig. 2, the latter – in Fig. 3.

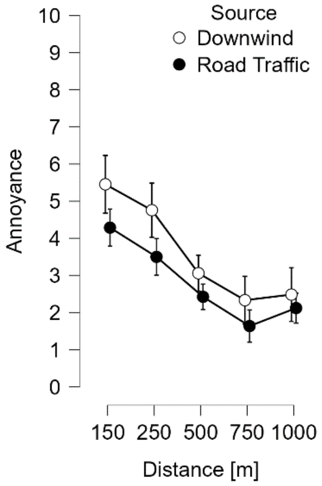

Figure 2. Mean annoyance ratings for WT DW and RT noise recorded in 5 different distances.

As can be seen from Fig.2, both DW WT and RT are rated quite the same – with a small shift toward higher ratings for WT. Moreover, the larger the distance is, the smaller annoyance is evoked, but this tendency flattens from 750m. Ratings given for 1000m are almost the same, even marginally higher than for 750m.

To better understand these differences we ran two-way Bayesian ANOVA using JASP software. Results of this analysis are presented in Table 2. In Bayesian approach we are interested in values of BF_{10}. It describes how much more probable is an alternative hypothesis (that the factor has influence on dependent variable) over the zero one (that there is no influence). As Jeffreys suggested [10], the strength of evidence for BF between 5 and 10 is 'substantial' while all values above 100 are 'decisive'.

We can see in Table 2 that the most influential factor is Distance while Source has only small influence on annoyance ratings. However, the best model is that one which takes into account both these factors.

Table 2. Results of Bayesian ANOVA test ran for annoyance ratings of RT and WT noises recorded from 5 different distances.

Models	P(M|data)	BF_{10}	error %
Null model	1.314×10^{-25}	1.000	
Distance + Source	0.948	$7.210\times10^{+24}$	1.343
Distance + Source + Distance ✻ Source	0.052	$3.973\times10^{+23}$	2.369
Distance	2.200×10^{-4}	$1.674\times10^{+21}$	0.002
Source	8.123×10^{-25}	6.181	0.004

For the case when all three 'source conditions' are presented (but for three distances) results are shown in Fig. 3 and Table 3.

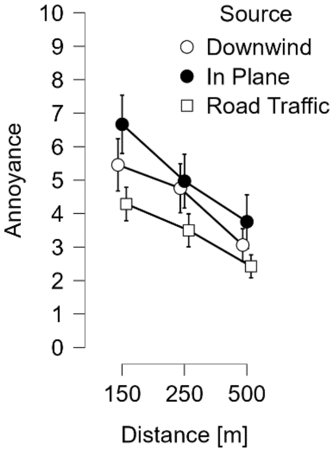

Figure 3. Mean annoyance ratings for RT and WT (both DW and RP) noise recorded in 3 different distances.

Fig. 3 suggests that noise annoyance of DW WT is marginally higher than of RP WT. These differences are not large, so again two-way Bayesian ANOVA was conducted to find out what are the Bayes Factor (BF) values.

As can be seen from Table 3, the best model takes into account both Source and Distance factors. However, Source was also analyzed using post-hoc analyses. Results take into account a correction for multiple comparisons (posterior odds, PO). This time we can observe that there are no differences in noise annoyance ratings between DW and RP (PO = 0.69, lower than 1). Differences are between RT and both WT sources (RT with DW, PO = 179.9; RT with RP, PO = $6.85x10^6$).

Table 3. Results of Bayesian ANOVA test ran for annoyance ratings of RT and WT (both downwind and in plane) noises recorded from 3 different distances.

Models	**P(M|data)**	**BF$_{10}$**	**error %**
Null model	2.021×10^{-22}	1.000	
Source + Distance	0.930	$4.603\times10^{+21}$	2.905
Source + Distance + Source ✻ Distance	0.070	$3.439\times10^{+20}$	1.515
Distance	1.255×10^{-9}	$6.207\times10^{+12}$	0.010
Source	2.631×10^{-15}	$1.302\times10^{+7}$	0.020

4. DISCUSSION AND CONCLUSION

In this research we have shown that for WT noise RP stimuli were rated slightly higher than DW. It can be related to the fluctuating distance from the tip of a blade (and thus, Doppler effect), but further research is needed. It was also shown – in contrary to [5] – that noise annoyance decreases with the increasing distance from sources. However, this function flattens around 750m from the source – which is equal to ~36dBA. This is probably very close to the background noise, so it should not be surprising. There are also differences in annoyance ratings between WT and RT, but they are not large. It is in contrary to other papers in which WT was rated much higher than RT [2] but in line with findings in [1]. The crucial factor can be the teaching procedure; participants got used to annoyance concept and sound of WTs.

5. ACKNOWLEDGMENTS

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