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Subjective assessment of wind turbine noise annoyance – tests in laboratory conditions

Dariusz PLEBAN, Grzegorz SZCZEPAŃSKI, Łukasz KAPICA, Adrian ALIKOWSKI, Krzysztof ŁADA, Anna WŁUDARCZYK

Central Institute for Labour Protection – National Research Institute, ul. Czerniakowska 16, 00-701 Warszawa, Poland

Corresponding author: Dariusz PLEBAN, email: daple@ciop.pl

Abstract The constant growth of energy demand, as well as the accompanying increase in environmental pollution resulting from the prevailing use of fossil fuels, has led to a rising use of energy from renewable sources. The use of wind turbines to generate electricity has many obvious advantages, such as lack of fuel costs during operation and lack of harmful pollutants, including carbon dioxide. Despite advantages, the use of wind turbines constantly raises questions concerning the impact of wind farms on humans. This impact includes many factors related to the operation of wind farms, and in particular noise emitted by these farms. The wind turbine noise impact on humans has been studied by the Central Institute for Labour Protection – National Research Institute. A test bench to conduct noise annoyance tests of different types of wind turbine noise in laboratory conditions have been developed. During exposures to 6 different virtual acoustic environments, representing different wind turbine noise, 40 participants assessed wind turbine noise annoyance. The paper describes the results of the studies concerning the assessment of wind turbine noise annoyance.

Keywords: wind turbine, noise, assessment, annoyance, laboratory test.

1. Introduction

The increase in energy demand was caused by scientific and technical revolution which coincided with the population increase by a factor of 3.2 in the years 1850–1970. The total energy consumption increased as much as 12 times during this period. This increase was even bigger in the industrial sector, with the energy consumption growing more than 20 times [1]. In the beginning of the 1970s, this trend slightly weakened, but is still exponential. This also applies to the national energy market. In Poland there is a systematic increase in demand for electricity, among other things, and according to forecasts prepared by various institutions, by 2040 it can reach the level of 230 TWh per year [2].

The constant growth of energy demand, as well as the accompanying increase in environmental pollution resulting from the prevailing use of fossil fuels, has led to a rising use of energy from renewable sources, including wind energy.

The use of wind turbines to generate electricity has many obvious advantages, such as lack of fuel costs during operation and lack of harmful pollutants, including CO_2 [3, 4]. Despite advantages, the use of wind energy (wind turbines) constantly raises questions and concerns. The questions concerning the impact of wind farms on humans still remain valid. This impact includes many factors related to the operation of wind farms, and in particular noise emitted by these farms. Issues related to the impact of wind turbine on humans are topics of numerous studies and scientific publications, which, however, in a vast majority relate to the effects of this noise in persons residing in the vicinity of wind farms (e.g. [5–9]). The impact of wind turbines noise on humans has also been studied by the Central Institute for Labour Protection – National Research Institute (CIOP-PIB), but unlike other studies CIOP-PIB focused on the impact of this noise as an annoyance factor affecting the employees' capacity to perform their basic tasks [10–12]. The aim of this paper is to provide an analysis of the results of a survey on subjective assessment of wind turbine noise annoyance during activities requiring focused attention.

2. Test method

In order to determine the wind turbine noise annoyance during activities requiring focused attention, a survey was developed, which constituted a research tool. When preparing the survey, the guidelines and principles set out in ISO/TS 15666:2003 [13] were observed.

The tests were carried out using a specifically developed laboratory facility for testing the wind turbine noise annoyance [14, 15]. The facility has been assembled in the acoustic test chamber of CIOP-PIB and is based on a multi-channel sound reproducing system using the DANTE network (where digital acoustic signals are transmitted over an Ethernet network). The facility (see Fig. 1) includes, among others:

- sixteen Avantone MixCube active studio nearfield monitors with a bandwidth ranging from 90 Hz to 17 kHz,
- two LS600 subwoofers with a bandwidth ranging from 30 Hz to 200 Hz,
- a special laboratory source of infrasounds with a bandwidth ranging from 8 Hz to 70 Hz.

Figure 1. Laboratory facility for testing wind turbine noise annoyance.

During the test, the following seven acoustic environments were reproduced at the test facility:

- six different virtual acoustic environments representing noise of two different types of wind turbines (Vestas V80-2.0 MW and GE 2.5 xl) with the A-weighted sound pressure levels of 30 dB(A), 40 dB(A) and 50 dB(A),
- silent conditions (i.e. with the A-weighted sound pressure level of 20 dB(A)).

During exposure to each of these acoustic environments, the participants of the study performed activities requiring focused attention – i.e. used a laptop to carry out tests from the Vienna Test System – ALS work performance test and COG Kognitron observation and concentration test [16], and then assessed (using a specifically developed survey) the annoyance of the reproduced wind turbine noise. The sequence of the silent conditions and acoustic environment reproduction conditions representing the wind turbine noise was based on the Latin square method.

The test method was positively assessed by the Committee on Ethics of Research with Human Participation at the Institute of Sciences on Human Nutrition of the Warsaw University of Life Sciences (resolution No 27/2021 of 19.07.2021).

3. Tested sample

A total of 40 persons aged 22 to 60 took part in the survey on the subjective assessment of wind turbine noise annoyance during activities requiring focused attention. There were 20 women and 20 men in this group. Before commencing the tests, each person was acquainted with the course of the test and received an appropriate training. It was assumed that 30 persons (15 women and 15 men) participated in the study on the evaluation of noise annoyance from Vestas V80-2.0 MW wind turbine, and the remaining 10 persons (5 women and 5 men) participated in the study on the evaluation of noise annoyance from the GE 2.5 xl wind turbine.

4. Results

After performing the ALS work performance test and the COG Kognitron observation and concentration test, the participants assessed the annoyance of each of the reproduced wind turbine noise levels by responding to the question "*How burdensome was the wind turbine noise?*" In providing the answer, both a five-level scale describing annoyance was used (which included the following responses: *not at all*, *slightly*, *moderately*, *very*, *extremely*) and a numerical scale from 0 to 10, where lower values mean no annoyance or low annoyance noise and higher values correspond with very burdensome noise.

The wind turbine noise with the A-weighted sound pressure level of 30 dB(A) was assessed as follows (see Fig. 2): most people (45% of the tested persons) stated that the noise was slightly burdensome, for 35% of the tested persons the noise was not burdensome at all, and every fifth person (20% of the tested persons) considered the noise moderately burdensome. None of the participants assessed the wind turbine noise with the A-weighted sound pressure level of 30 dB(A) as very or extremely burdensome. The result of noise assessment using a numerical scale from 0 to 10 is as follows (see Fig. 2): a vast majority of the tested persons assessed the annoyance of this noise as small. In total, 77.5% of the tested persons evaluated it in the range from 0 to 3, including: 15% of the tested persons indicated 0, 40% of the tested persons indicated 1, 10% of the tested persons indicated 2 and 12.5% of the tested persons indicated 3. The remaining participants (i.e. 22.5% of the tested persons) assessed noise annoyance as average (i.e. level from 4 to 6), with 10% of the tested persons evaluating the noise at 4 and at 6, and 2.5% of the tested persons evaluating it at 5. None of the tested persons assessed the noise as highly burdensome (levels 7 to 10).

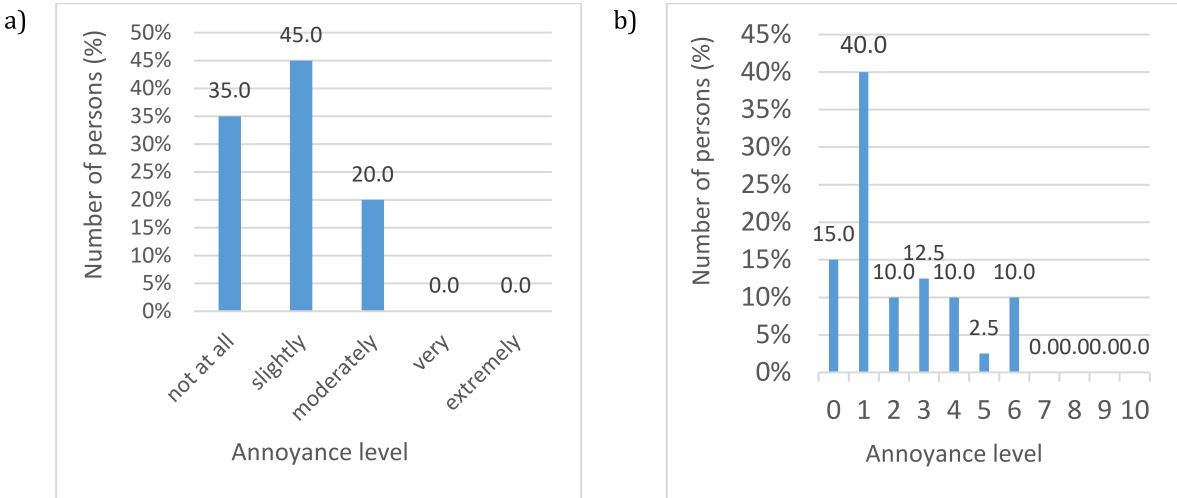

Figure 2. Results of subjective assessment of wind turbine noise annoyance with the A-weighted sound pressure level of 30 dB(A): a) in the descriptive form, b) in the numerical scale.

In the case of the wind turbine noise with the A-weighted sound pressure level of 40 dB(A), the test participants evaluated its annoyance as follows (see Fig. 3): more than half of the tested persons (i.e. 52.5%) stated that the noise was slightly burdensome, 20% of the tested persons assessed the noise as not burdensome at all and the same percentage assessed it as moderately burdensome, and the remaining participants (7.5%) assessed the noise as very burdensome. The result of the evaluation of this noise using a numerical scale from 0 to 10 is as follows (see Fig. 3): the vast majority of the participants (77.5% of the tested persons) assessed the annoyance of this noise as small, as the selected levels from 0 to 3 indicate. In this group, 5% of the tested persons evaluated it at 0, 27.5% of the tested persons specified level 1, 20% of the tested persons specified 2, while level 3 was provided by 25% of the tested persons. The remaining participants of the study provided assessments indicating average noise annoyance (10% of the tested persons specified 4, level 5 was specified by 2.5% of the tested persons and 6 by 2.5% of the participants) or high noise annoyance (level 7 was provided by 5% of the tested persons and 8 by 2.5% of the participants).

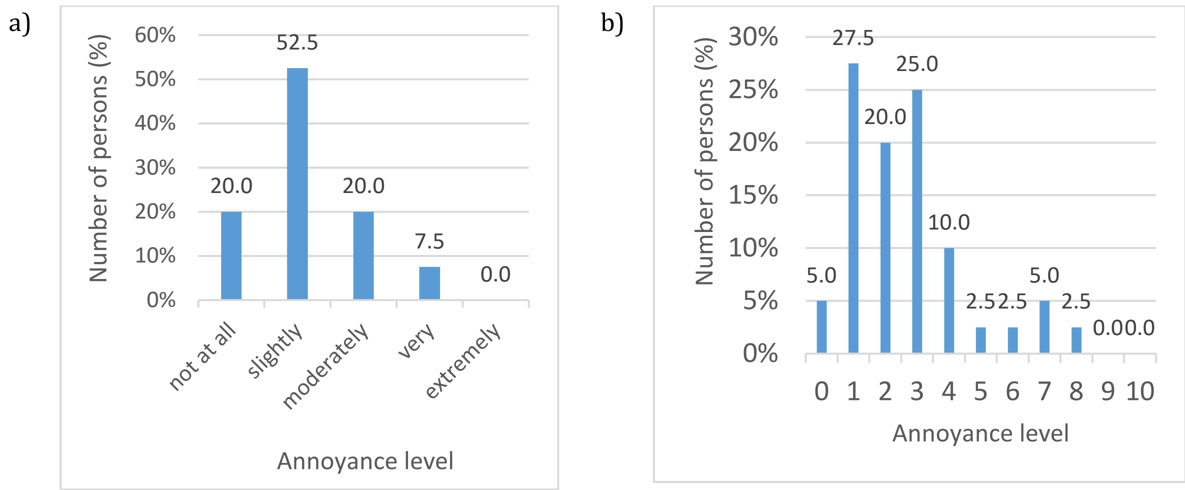

Figure 3. Results of subjective assessment of wind turbine noise annoyance with the A-weighted sound pressure level of 40 dB(A): a) in the descriptive form, b) in the numerical scale.

The annoyance of the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) was assessed as much higher. More than half of the tested persons (55% of the them) assessed the noise as slightly burdensome (20% of the tested persons) and moderately burdensome (35% of the tested persons), almost every third person (30% of the tested persons) assessed the noise as very burdensome, and only 15% of the tested persons assessed the noise as not burdensome at all (see Fig. 4). The results of the evaluation of this noise using numerical scale from 0 to 10 were as follows (see Fig. 4): less than half of the tested persons (40%) assessed the annoyance of this noise as small, indicating number 0 to 3. In this group of tested persons, score of 0 was given by 7.5% of the tested persons, score of 1 was also given by 7.5% of the tested persons, score of 2 was given by 15% of the tested persons and score of 3 was given by 10% of the tested persons. The scores corresponding with average noise annoyance (i.e. scores from 4 to 6) were given by a total of 32.5% of the tested persons, with 15% of the tested persons scoring it 4, 10% of the tested persons scoring it 5 and 7.5% of the participants scoring it 6. For this noise, the largest percentage of tested persons assessed the noise annoyance as high – this was in total 27.5% of tested persons. In this group, 10% of the tested persons gave score of 7 and 8, 5% of the tested persons gave score of 9 and 2.5% of the tested persons gave score of 10.

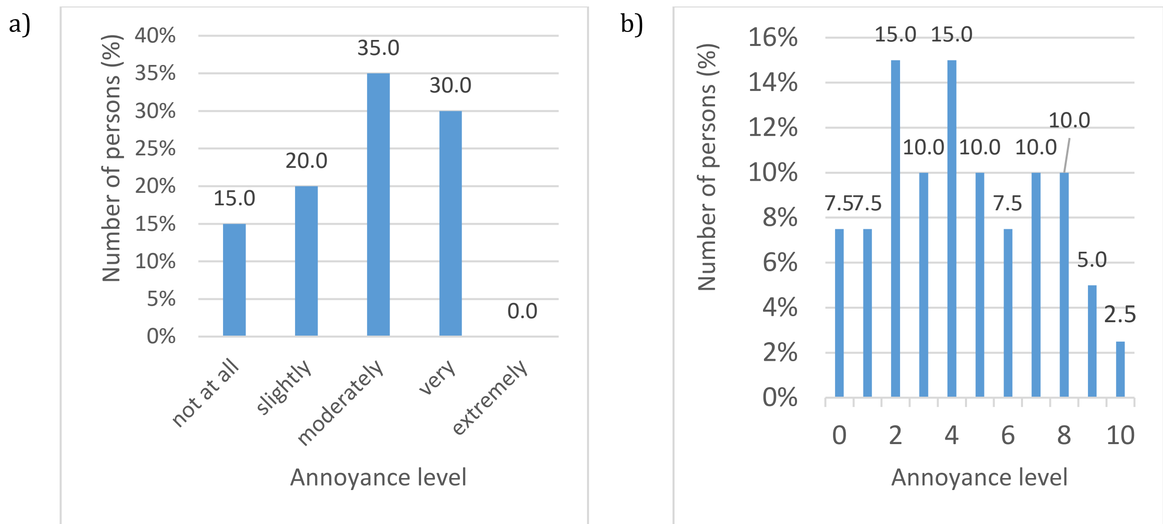

Figure 4. Results of subjective assessment of wind turbine noise annoyance with the A-weighted sound pressure level of 50 dB(A): a) in the descriptive form, b) in the numerical scale.

5. Statistical analysis

In the first stage of statistical analyses of the test results obtained, a statistical description was made with an assessment of the normality of distributions. In the next step, an analysis of the variance for the dependent tests was used to assess the differences in the survey results obtained under various acoustic conditions. In order to assess the sphericity of the variance, the Mauchley Test was performed. In order to reduce the risk of rejection of the zero hypothesis (no differences between the averages), when it is true, in the event of a significant result of the Mauchley test (indicating the lack of sphericity of the variances obtained), the Huynha-Feldt correction was applied in the ANOVA test. An eta squared partial measure was used to evaluate the size of the effect. The following interpretations of this measure were used: < 0.05 – small effect; 0.06–0.13 – average effect; > 0.14 – large effect. For relevant results of the ANOVA test, multiple pair comparisons with Bonferronis correction were used. For all statistical tests applied, the validity level $p < 0.05$ was assumed. However, due to the complexity of the cognitive load issue (many factors may affect the variability of the results of a dependent variable), the validity level $p < 0.10$ was considered as a statistical trend [16, 17]. The analysis was performed using IBM SPSS Statistics package (version 22). The results of this analysis are presented in Tab. 1.

Table 1. Results of the statistical analysis of the results of the survey concerning the assessment of wind turbine noise annoyance.

A-weighted sound pressure level of the wind turbine noise, dB(A)	Min	Max	M (arithmetic average)	SD (standard deviation)	Skewness	Kurtosis	Shapiro-Wilk test *p* value
30.0	0	6	2.14	1.86	0.87	-0.28	< 0.001
40.0	0	8	2.63	1.89	1.23	-0.28	< 0.001
50.0	0	10	4.32	2.69	0.21	-0.85	0.223

The result of the Shapiro-Wilk test indicates that the distribution of survey results for wind turbine noise with the A-weighted sound pressure level of 50 dB(A) does not differ statistically from the normal distribution. For wind turbines noise with the A-weighted sound pressure levels of 30 dB(A) and 40 dB(A), the result of the Shapiro-Wilk test proved to be statistically significant. However, skewness and kurtosis did not exceed or exceeded to a minor extent the absolute value 1, which indicates a slight deviation from the normal distribution. Furthermore, the ANOVA statistics are very resistant to deviations from normal [17, 18] and if the kurtosis is greater than 0 then the F result approaches small values and a trend is created not to reject the zero hypothesis even if it is not true. When the kurtosis value is less than 0, the trend in this range is inverse. On the other hand, the skewness of the distribution has a minor impact on the value of statistics F [18, 19]. Taking into account this information and since it is recommended to use parametric tests as more precise than non-parametric tests, whenever possible [20], it was decided to carry out the analysis of the survey results using the ANOVA test.

Figure 5 presents the average level of annoyance declared by the test participants. The annoyance was assessed as the highest in the case of the wind turbine noise with the A-weighted sound pressure level of 50 dB(A), whereas as the lowest in the case of the wind turbine noise with the A-weighted sound pressure level of 30 dB(A). When dividing the tested group by gender, it can be concluded that women assess the noise annoyance of wind turbines slightly lower than men. The difference between these assessments increases with an increase in the A-weighted sound pressure level of wind turbines (see Fig. 5).

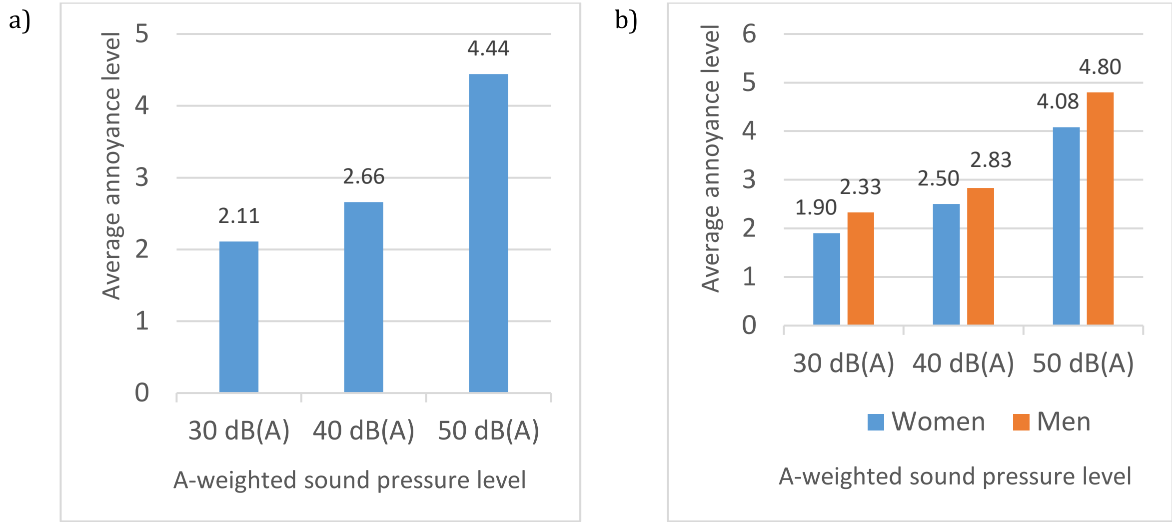

Figure 5. Average annoyance level of wind turbine noise:
a) declared by all test participants, b) depending on the gender.

In order to assess the differences between the results for the three variants, an ANOVA test for the dependent tests was performed. The result turned out to be statistically relevant and the size of the effect was large: the value of ANOVA test, F, was $F(1.789; 67.979) = 30.557$; the probability value, p, was $p < 0.001$; the partial eta squared value, η_p^2, was $\eta_p^2 = 0.45$.

The Bonferroni multiple comparisons showed that the average result for the wind turbine noise with the A-weighted sound pressure level of 30 dB(A) differs from the average result for the wind turbine noise with the A-weighted sound pressure level of 40 dB(A) at the statistical trend level ($p < 0.10$), whereas the average result for the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) differs significantly statistically ($p < 0.001$). The difference between the average result for the wind turbine noise with the A-weighted sound pressure level of 40 dB(A) and the average result for the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) also turned out to be statistically significant ($p < 0.001$).

At the next stage of analyses, an analysis of differences in average survey results due to the A-weighted sound pressure level of wind turbine noise was performed, taking into account also the sequence of occurrence of a given noise during laboratory tests (see Fig. 6). As already stated, the sequence of acoustic environments (i.e. reproduced wind turbine noises and quiet conditions) was based on the Latin quadrilateral plan. Therefore, each of the wind turbine noise with the A-weighted sound pressure level of 30 dB(A), 40 dB(A) and 50 dB(A) respectively was reproduced as the first, second, third or fourth.

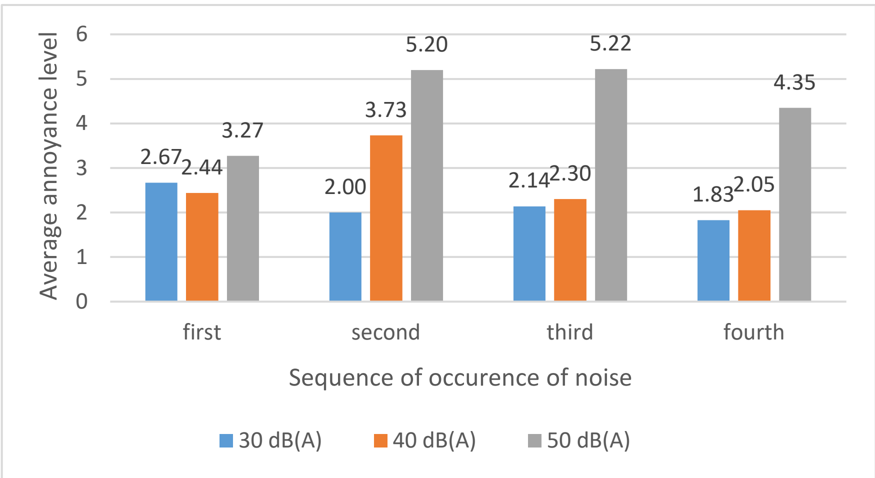

Figure 6. Average annoyance level of wind turbine noises with the A-weighted sound pressure levels of 30 dB(A), 40 dB(A) and 50 dB(A) taking into account the sequence of occurrence of a given noise during laboratory tests.

For each sequence, the highest average result of the annoyance was in the case of the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) (M from 3.27 to 5.22). In order to assess the relevance of differences between average results, an analysis of variance (ANOVA) was carried out for the independent tests in each of the four sequences. Differences in the survey results for the "first" sequence between persons who were tested in different acoustic variants turned out to be not statistically significant ($F(2; 23) = 0.421$; $p = 0.66$; $\eta_p^2 = 0.04$). For the remaining sequences, the results of the ANOVA test were statistically significant and demonstrated large effects. Second sequence of occurrence: $F(2; 28) = 5.622$; $p < 0.01$; $\eta_p^{\ 2} = 0.25$), third sequence: $F(2; 27) = 6.338$; $p < 0.01$; $\eta_p^2 = 0.32$), fourth sequence: $F(2; 26) = 4.303$; $p < 0.05$; $\eta_p^2 = 0.25$). The post hoc analyses of Bonferroni showed that there is a significant difference in the survey results for the "second" sequence of occurrence for the A-weighted sound pressure levels of 30 dB(A) and 50 dB(A) ($p< 0.01$). The differences between the cases of the A-weighted sound pressure levels of 30 dB(A) and 40 dB(A) ($p = 0.22$) and 40 dB(A) and 50 dB(A) ($p = 0.38$) were not statistically significant. For the third sequence, significant differences were observed between the cases of the A-weighted sound pressure levels of 30 dB(A) and 50 dB(A) ($p < 0.01$) and 40 dB(A) and 50 dB(A) ($p < 0.05$), whereas the difference between the cases of the sound pressure levels 30 dB(A) and 40 dB(A) ($p > 0.99$) was not statistically significant. For the fourth sequence, it turned out that the difference in results between the cases of the A-weighted sound pressure levels of 30 dB(A) and 50 dB(A) was statistically significant ($p < 0.05$), the difference between the cases of the sound pressure levels 40 dB(A) and 50 dB(A) was at the level of statistical trend ($p < 0.10$), whereas between the cases of sound pressure levels 30 dB(A) and 40 dB(A) ($p > 0.99$) the difference was not statistically significant.

6. Conclusions

A survey was carried out on a group of 40 persons (under laboratory conditions) concerning the assessment of annoyance of wind turbine noise reproduced under laboratory conditions.

The conducted analyses of the results of the survey concerning the subjective assessment of wind turbine noise annoyance during activities requiring focused attention indicate that the tested persons evaluated the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) as the most burdensome. This noise was assessed by the tested persons to a statistically relevant degree as more burdensome than the wind turbine noise with the A-weighted sound pressure levels of 30 dB(A) and 40 dB(A) respectively, which was confirmed in the analyses of the results – both in the collective analysis and in the analysis taking into account the sequence of the wind turbine noise during laboratory tests. The results of this second analysis showed that, for the second, third and fourth sequence, the average assessments of the wind turbine noise annoyance with the A-weighted sound pressure level of 40 dB(A) were higher than the average evaluations of the wind turbine noise annoyance with the A-weighted sound pressure level of 30 dB(A), but these differences were not always statistically significant. Moreover, this relationship did not occur for the first sequence of wind turbine noises during the tests. In this case, the load resulting from performing cognitive tasks is probably the lowest (lower fatigue than in other cases), and moreover, the tested persons did not yet have reference to other acoustic conditions (which were present only in subsequent measurements). This could have affected the differences in the indicated answers between the first sequence of wind turbine noise and the remaining ones.

The comparison of the average assessments of wind turbine noise annoyance obtained in the survey (using a numerical scale from 0 to 10) shows that the increase of the A-weighted sound pressure level of wind turbine noise leads to an increased average annoyance assessment, from 2.11 for noise with the A-weighted sound pressure level of 30 dB(A), through 2.66 for noise with the A-weighted sound pressure level of 40 dB(A), to 4.44 for noise with the A-weighted sound pressure level of 50 dB(A). Therefore, according to the tested persons, only the wind turbine noise with the A-weighted sound pressure level of 50 dB(A) shall be considered as noise with average annoyance. The wind turbine noise with lower sound pressure levels was assessed as slightly burdensome.

The test results described in this paper and test results of the following studies:

- a survey on the assessment of the wind turbine noise annoyance at workplaces located near wind farms [11],
- laboratory studies, mentioned in this paper, within Vienna Test System (ALS work performance test and COG Kognitron observation and concentration test) [21, 22],
- propagation of wind turbine noise research [12, 23],

were the basis for proposing a limit value for the wind turbine noise level due to the employee's ability to perform his basic tasks. The proposed limit value, i.e the equivalent continuous A-weighted sound pressure level of the wind turbine noise is 50 dB(A) [21, 22].

Moreover, the test results described in this paper and test results described in [11, 12, 21, 22] were the basis for a proposal of the extent of the noise annoyance zone due to the employee's ability to perform his basic tasks [23].

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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