VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2022.3.15
Vibrations in Physical Systems, 2022, 33(3), 2022315

Experimental Verification of the Usefulness of Selected Infrasound and Low-frequency Noise (ILFN) Indicators in Assessing the Noise Annoyance of Wind Turbines

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Abstract This paper presents an overview of the indices used in evaluating ILFN noise, based on C and G weighting curves and L_C-L_A difference parameter, as well as curves compared to the loudness threshold curve. The research section includes measurement results of wind turbine (WT) noise along with proposed indicators for evaluating this noise in the infrasound and low-frequency bands at distances of 250 m, 500 m and 1000 m from the turbine. The results obtained indicate low noise levels in the infrasound band, lower than the threshold curves from a dozen or so dB in the upper part of this band to nearly 60 dB in the lower part. The L_C-L_A indicator has been shown to be of poor utility for evaluating low-frequency noise, with the L_G indicator reasonably useful for evaluating infrasound noise.

Keywords: Wind Turbine Noise, Infrasound, Low-frequency noise indicators, Hearing threshold level.

1. Introduction

Increasing energy problems, and on the other hand: works on a bill to amend the current law in Poland known as the "10H law" [1], which is expected to abolish strict provisions drastically limiting the construction of wind farms, is causing a renewed interest in onshore wind energy. Nevertheless, the development of wind power, which belongs to the so-called Renewable Energy Sources (RES) is accompanied by concerns about its negative effect on the environment. In particular, many disagreements and divergent opinions can be found about the harmful effects of infrasound and low-frequency noise (ILFN). It is believed that low-frequency noise can be more annoying than higher-frequency noise of the same volume, although the reason for this perception is unknown. It is also unclear why some people complain about low-frequency noise, even though it cannot be measured because it is masked. It is possible that extra-auditory perception of low-frequency noise, or the presence of other (secondary) factors, has an additional effect on its global perception [2]. The problem is not made any easier by the lack of legal regulations not only in Poland, but also in many other countries, for assessing the noise nuisance of wind turbines. This can be confirmed based on WHO documents [3] in which wind turbines are classified as annoying noise sources, but with no strong recommendations for assessing their nuisance, and the conditionally recommended assessment criterion is the L_{den} level, which should not be higher than 45 dB, with no recommendation for night time. However, this does not mean that the nuisance of wind turbine noise is not recognized, only that there is a lack of convincing research results, confirming the validity of the evaluation criterion. The annoyance of wind turbine noise is also shown by the results of surveys [4].

While indicators recommended by the WHO [3] for other noise sources, namely L_{den}, L_n or L_{Aeq} levels, possibly adjusted for tonal content, impulsivity [5], or amplitude modulation, can be used to assess the nuisance of turbine noise in the audible band [6-7] there are no such universal indicators for infrasound or low-frequency noise. The L_G level [8] used to assess workplace noise is related to the perception of sound, less so to its nuisance [9], while other proposals for indicators are based on the L_C-L_A difference, or the hearing threshold curve, possibly extended to the infrasound band [10]. In addition to the lack of universally accepted indicators, there is a problem with the assignment of limit values to such indicators.

Currently, there are no legal regulations for assessing infrasound and low-frequency noise from WT in Poland, at all stages of such assessment, from indicators and assessment criteria to measurement methodologies and forecasting, inspired work to fill these gaps.

Selected ILFN indicators proposed by various researchers will be shown and discussed within the framework of this paper, along with examples of their use, based on actual measurement data and an analysis of the usability of these indicators in assessing the annoyance of WT noise.

2. Indicators for infrasound and low-frequency noise

The infrasound band is quite clearly defined and covers the frequency range from 1 to 20 Hz according to ISO 7196 [8] or frequencies below 16 Hz according to IEC [11]. Low-frequency noise, on the other hand, has no clearly accepted definition. Various upper limit values for this noise are reported in the literature. Most commonly, low-frequency noise is defined, as defined by G. Leventhall [2], as noise in the frequency band from 10 to 200 Hz, while according to ACGIH's Threshold Limits Values [12], infrasound and low-frequency noise is noise in the range from 1 to 80 Hz, and according to other researchers: up to 100 Hz or 250 Hz, or even up to 500 Hz [13].

Auditory perception of infrasound involves not only the classical hearing of these sounds, but also the sensation of vibrations and the hearing of higher-frequency sounds belonging to the low-frequency band and originating from the same source. This is the case with wind turbines, where audible sounds at higher frequencies "inform" the receiver of possible accompanying infrasound. It is also worth mentioning the high sensitivity of hearing to a change in sound pressure in the infrasound band – a small change in pressure causes large changes in loudness.

Because of that, using C-weighting (L_C) and A-weighting (L_A) or L_C-L_A difference value is a common approach in parameterizing low-frequency sounds. In some cases, taking the difference between L_C-L_A greater than 15 dB, has been the basis for a 6 dB correction to compensate for the annoyance of such noise [14]. Nevertheless, at low noise levels, e.g. with typical background noise in open spaces, even larger values of this difference can be recorded at levels within the infrasound range well below the hearing threshold curve.

On the other hand, the use of absolute L_C levels gave incorrect results for elevated levels in the higher frequency range [15]. In Australia, in the state of New South Wales, L_{Ceq} = 65 dB during the day and 60 dB at night have been adopted as the basis for low-frequency wind turbine noise assessment, and a 5 dB correction is added in case of a difference of L_C-L_A>15 dB [16]. On the other hand, in Canada (state of Alberta), L_C-L_A≥20 dB and, in addition, the presence of a tonal component in the 20 to 250 Hz band was adopted as a condition for the occurrence of low-frequency noise [17]. A difference of L_C-L_A≥20 dB is a distinguishing marker for the presence of low-frequency noise according to DIN 45680:1997 [18], and a threshold curve defined in 1/3 octave bands within the range from 8 Hz to 100 Hz is the basis for the evaluation.

Criteria for assessing low-frequency noise in Europe are mainly based on curves in the 1/3 octave bands between 10 and 160 Hz. Threshold values according to DEFDRA [19] are given in Table 1. Infrasound thresholds estimated by H. Moller and C. S. Pedersen are also included in Table 1 [10], in addition to hearing threshold curve values according to ISO 226:2003 [20]. The curve proposed by H. Moller and C. S. Pedersen's study is the result of analyses of numerous papers devoted to the search for a hearing threshold curve in the band below 20 Hz, obtained by 2nd order regression analysis. As can be easily seen, the curves according to ISO226 and the one proposed by H. Moller and C. S. Pedersen [10], in the common band (20 Hz) differ by 5.3 dB, but coincide with the results submitted by T. Watanabe and H. Moller [21] and M. Lydolf and H. Moller [22].

In some countries, the G-weighting curve has been used to assess the nuisance of low-frequency noise indoors (Denmark, Japan, Australia, among others). The limit value has been set at 85 dB(G), while in Japan it is 92 dB(G).

The threshold curves proposed in Table 1 and the L_A-L_C- and L_G-weighted level values were adopted for further analysis and evaluation of wind turbine noise in the infrasound and low-frequency bands.

Table 1. 1/3 octave threshold levels for infrasound and low frequencies, dB.

f[1/3], Hz	1,6	2	2,5	3,2	4	5	6,3	8	10	13	16	20	25	32	40	50	63	80	100	125	160
M&P	124	122	119	117	114	110	106	102	98	93	88	84									
DIN 45680								103	95	87	79	71	63	56	48	41	34	28	24		
DEFRA									92	87	83	74	64	56	49	43	42	40	38	36	34
ISO 226												78	68	60	52	45	38	32	27	22	18
A-weighting									70	63	57	51	45	39	35	30	27	22	19	16	13

3. Experimental tests

3.1. Measurement apparatus and methodology

The device under test was a Vestas V90 wind turbine that is part of the wind farm, Łódź Voivodeship, Poland. The farm was commissioned in 2014 and is composed of 10 Vestas V90 WT, each with a capacity of 2 MW, a pole height of 105 m and a rotor diameter of 90 m. For testing, a WT was selected with placement allowing measurements to be made at locations furthest from other noise sources that might interfere with them (proximity to buildings or a road with significant traffic). It was also possible to take the other wind turbines out of service for the duration of the measurement session. Measurements of acoustic pressure from the leeward side were carried out at points distant from the WT by 250 m, 500 m, 1000 m and 1500 m (see Fig. 1).

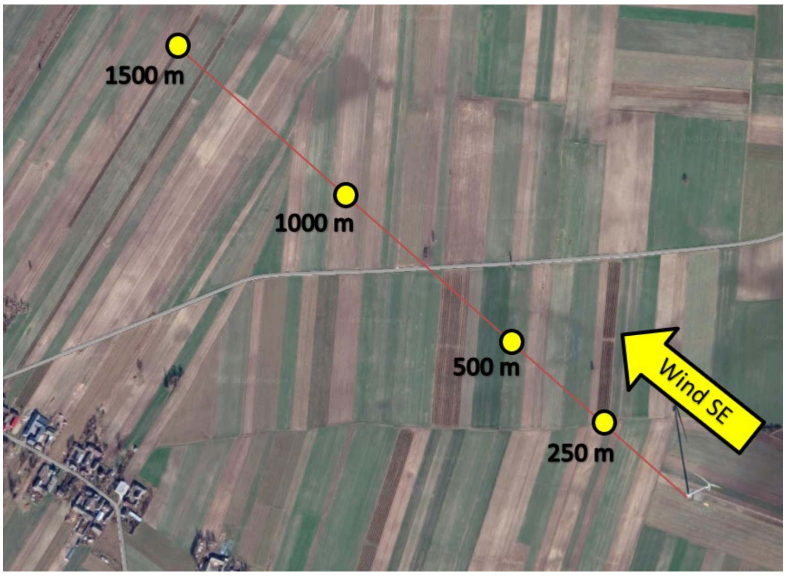

Figure 1. Distribution of measurement points in relation to the wind turbine

Simultaneous recording of sound pressure signals at each point was carried out using SVAN 958/958A four-channel sound meters. ½" G.R.A.S. 40AE microphones were used for the measurement. At each point, sound pressure measurements were taken in three ways: on the measurement board with a single wind shield according to ISO 61400-11 [23], on a 1.5 m-high tripod and on a 4 m-high tripod, both with a typical (90 mm) windscreen. Simultaneous measurement on the board and at heights of 1.5 m and 4 m makes it possible to find a relationship in reference to the measurement on the board (better protected from wind interference) [24-25].

The measurements were made on March 17, 2022, with an average wind speed of 4.2 m/s (gusts up to 5.1 m/s) measured at a height of 10 m during WT operation (WT ON). Whereas the background noise (WT OFF) was measured at an average wind speed of 3.9 m/s (gusts up to 4.7 m/s)

3.2. Experiment results

Measurements were made at distances of 250 m, 500 m, 1000 m and 1500 m from the turbine, but for the evaluation within the study, the focus was on distances of 250 m and 1000 m. At a distance of 250 m, the distinctive features of the noise spectrum from the WT and the highest signal-to-noise ratio are best distinguishable. On the other hand, at a distance of 1000 m, there are often already intensive residential buildings, moreover the distinctive features of turbine noise are already weakly distinguishable and the signal-to-noise ratio is definitely worse. On the other hand, there are poorly distinguishable noise characteristics of the turbine, and definitely worse signal-to-noise ratio.

A summary of the sound pressure level spectrum at all measurement points for the microphone placed on the board is shown in Fig. 2.

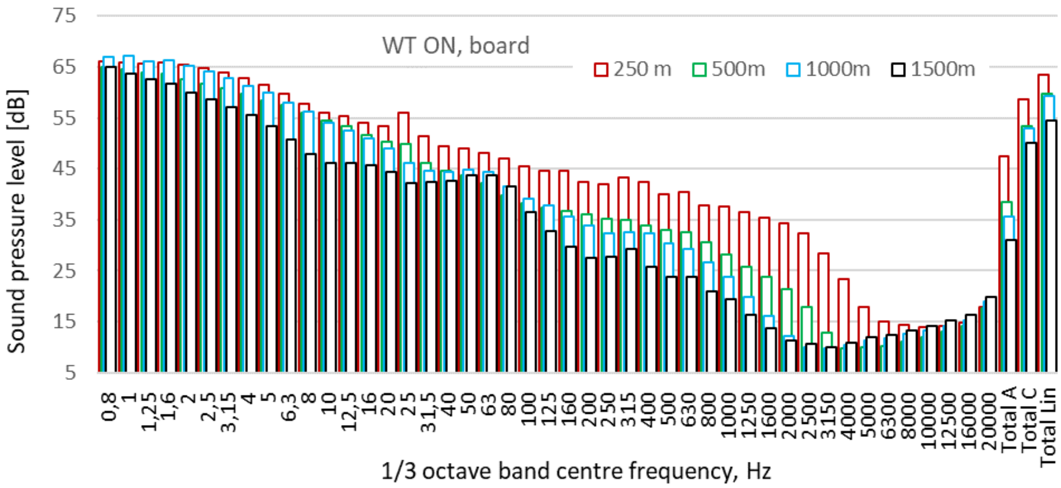

Figure 2. Results of the WT noise spectrum measurements. Measurement on the board at distances of 250 m, 500 m, 1000 m and 1500 m from the turbine.

As shown in Figure 2, the spectra of the recorded signals at distances of 500 and 1000 meters are very similar, and the most noticeable difference (the drop in sound level from the turbine) occurs in the bands from about 160 Hz to 3150 Hz. In the infrasound band (up to 20 Hz), noticeable changes occur only for distances of 1500 m.

A comparison of noise spectra recorded at the board and heights of 1.5 m and 4 m and the background noise at a height of 1.5 m, at points 250 m and 1000 m away, are shown in Fig. 3 and Fig. 4, respectively.

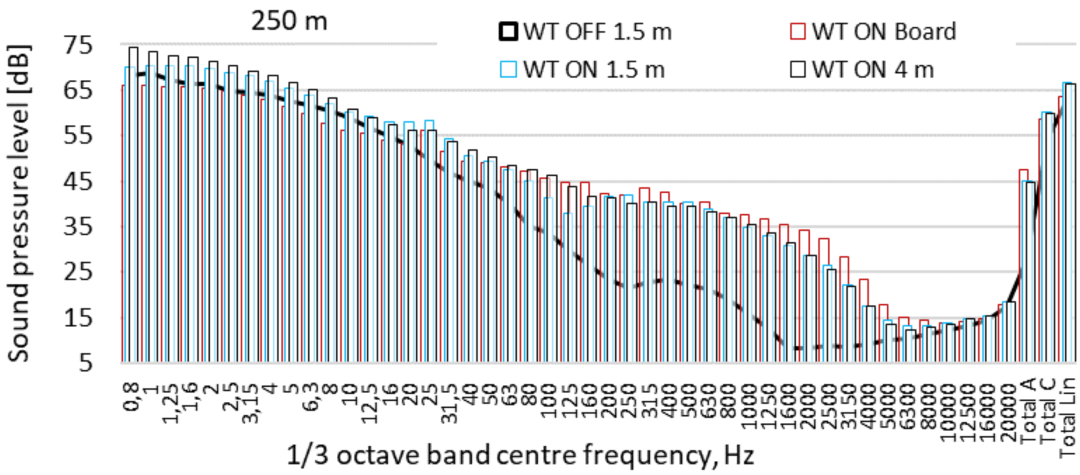

Figure 3. Results of the WT noise spectrum measurements (WT ON – board, 1.5 m and 4 m) and the background noise (WT OFF – 1.5 m) at a distance of 250 m from the WT.

The results shown in Fig. 3 and Fig. 4 indicate high interference from wind in the infrasound and low frequency ranges for signals recorded at heights of 1.5 m and 4 m. WT features are well visible at a distance of 250 m (Fig. 3) and definitely less pronounced at a distance of 1000 m (Fig. 4), although still clearly noticeable in the mid-frequency bands - 80 Hz to about 2 kHz

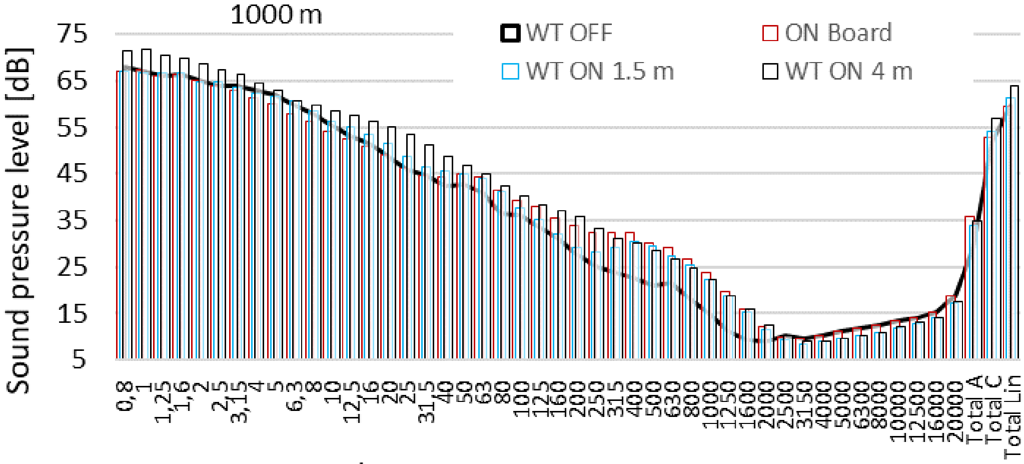

Figure 4. Results of the WT noise spectrum measurements (WT ON – board, 1.5 m and 4 m) and the background noise (WT OFF – 1.5 m) at a distance of 1000 m from the WT.

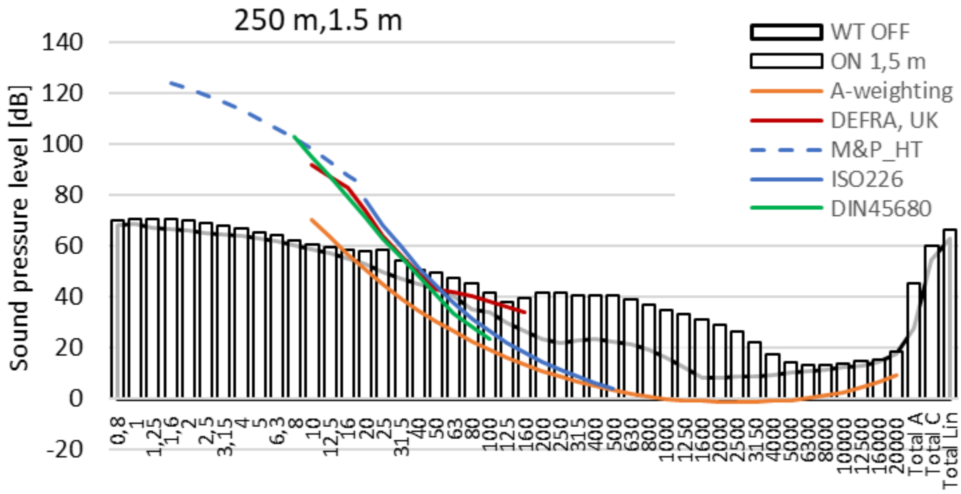

Figure 5. Results of the WT noise spectrum measurements and background noise with the threshold curves plotted as in Table 1 and the inverted A-curve for the 0 dB level. Measurements at height of 1.5 m and a distance of 250 m from the WT.

The results shown in Fig. 5 and Fig. 6, at distances of 250 and 1000 m from the WT, respectively, indicate that the recorded infrasound values are at about 70 dB at a distance of 250 m from the turbine, and slightly above 65 dB at a distance of 1000 m. At a distance of 1000 m, the L_G level from the turbine almost coincides with the background noise level, as does the L_C level, with the L_A level quite noticeably lower. In practice, this means there is no audible infrasound or low frequencies from WT operation, although WT is audible in the higher frequency range. At both distances, sound levels in the infrasound band range from approximately 25 dB to 57 dB below the threshold curve proposed by H. Moller and C. S. Pedersen [10]. Similarly, concerning the other threshold curves – DEFRA [19] and DIN 45680 [18]– the results in the infrasound band are well below these curves, starting at 13 dB for DIN 45680, and 16 dB with respect to DEFRA [19] in the 20 Hz band, while the difference is already over 30 dB in the 10 Hz band.

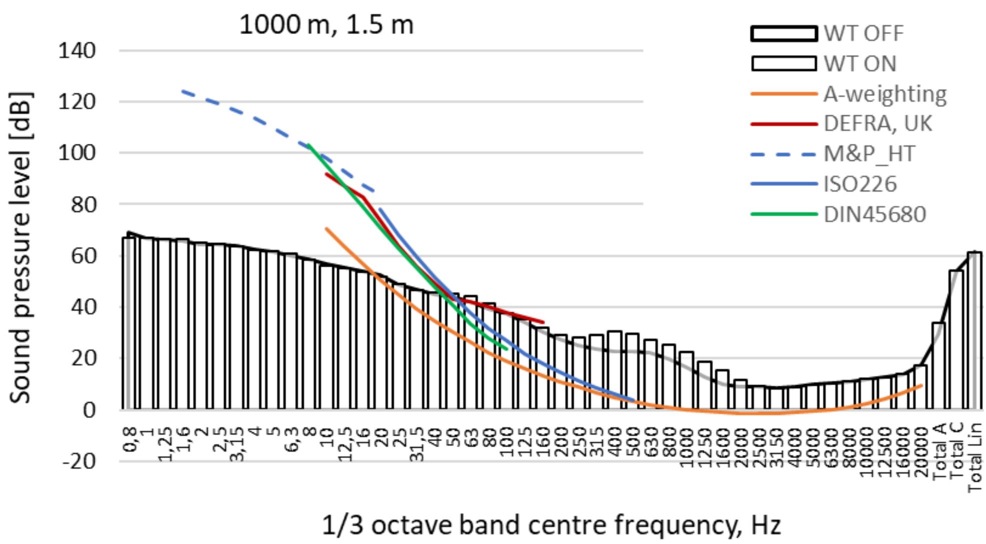

Figure 6. Results of the WT noise spectrum measurements and background noise with the threshold curves plotted as in Table 1 and the inverted A-curve for the 0 dB level. Measurements at height of 1.5 m and a distance of 1000 m from the WT.

Regardless of the location of these results below the threshold curves in the infrasound band, it is worth noting that these levels at a distance of 1000 m are comparable to the background noise level, with the WT noise distinctive features still quite clearly visible, but in the bands from 200 Hz to 1600 Hz (see Fig. 6).

A summary of the results of the A-, C- and G-weighted levels and the L_C-L_A difference at distances of 250 m, 500 m and 1000 m from the operating WT (WT ON) and the background noise with the WT turned off (WT OFF) for measurements on the board and at a height of 1.5 m is included in Table 2.
The values of recorded L_G-weighted levels range from 67.8 dB on the board to 71.8 dB (69.4 dB after taking background noise into account) at the height of 1.5 m at distances of 250 m and 500 m. At a distance of 1000 m, the values are lower by 3-4 dB. In all cases, these values are well below 85 dB(G), which is the accepted limit in some countries.

In summary, one can notice that the final evaluation of the results obtained based on threshold curves and G-weighting quantitatively is similar. This indicates the excellent usability of this indicator in a simplified assessment of infrasound noise annoyance.

Considering the obtained results, the evaluation of the ILFN band using the L_C-L_A difference seems completely useless. Significantly higher values of this difference were obtained for the background noise signal than for the working WT in all cases. Given that the results obtained are for measurements at a relatively low wind speed of about 4 m/s, it can be presumed that the differences will be even higher at higher wind speeds and therefore more significant interference at low frequencies.

Table 2. A summary of the results of measurements of L_A, L_C and L_C-L_A levels on the board and at a height of 1.5 m and with the WT ON and WT OFF (background noise).

Weighting curve	On board						At a height of 1.5 m					
	250 m		500 m		1000 m		250 m		500 m		1000 m	
	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
L_G	67,8	62,5	67,8	62,5	64,1	64,7	71,8	68,1	71,8	68,1	66,5	67,0
L_C	58,7	49,6	53,4	49,6	52,9	51,8	60,1	54,4	56,7	54,4	54,1	53,9
L_A	47,3	27	38,6	27	35,7	29	45	27,8	38,4	27,8	33,9	29,5
L_C-L_A	11,4	22,6	14,8	22,6	17,2	22,8	15,1	26,6	18,3	26,6	20,2	24,4

4. Conclusions

The obtained measurement results confirm the results reported by numerous other researchers, namely that the wind turbine noise in the infrasound range is significantly lower than the hearing threshold curve, modified in the lowest frequency range by DEFRA [19] or H. Moller and C. S. Pedersen [10].

In the frequency range above 20 Hz, as well as for infrasound noise, the use of the L_C-L_A difference shows low indicator utility for assessing this noise, which is confirmed by the results obtained and literature reports.

Relatively good usability was obtained using the G-curve weighted level (L_G) for evaluating infrasound noise results. The evaluation results are close to the evaluation according to threshold curves.

Due to the high sensitivity of individual characteristics to noise change in the infrasound range, it seems reasonable to adopt the threshold curve proposed by H. Moller and C. S. Pedersen [10], as a starting criterion for evaluating infrasound annoyance. Evaluation based on the threshold curves in 1/3-octave bands, compared to assessment based on the G-curve, allows identification of possible tonal components in the noise spectrum.

Regardless of the output criterion used (G-curve weighting or threshold curve), the result obtained can be adjusted regarding the presence of tonal components and amplitude modulation.

Acknowledgments

This research work was founded by the research project No. NOR/POLNOR/Hetman/0073/2019 titled "Healthy society-towards optimal management of wind turbines' noise", and by the Polish Ministry of Science and Higher Education, No. 16.16.130.942

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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