Project: A healthy society - towards the optimal management of wind turbine noise

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D3.3. The proposal of infrasounds' indices used for rating their impact on people

Projekt: **Healthy society - towards optimal management of wind turbines' noise**

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PSEW

D3.3. The proposal of infrasounds' indices used for rating their impact on people

Executive summary

The extra-auditory perception of low-frequency noise or the presence of other (secondary) factors can have an additional impact on its global perception. The problem, however, is the lack of legal regulations in Poland and many other countries regarding the assessment of the noise annoyance of wind turbines. This does not mean, however, that the noise annoyance of wind turbines is not recognized, only that there is a lack of convincing research results. As the part of this task, a review of currently used indicators of infrasound and low-frequency noise was carried out, as well as an experimental verification of the usefulness of selected low-frequency indices.
The measurement results obtained confirm the results reported by many other researchers, namely that wind turbine noise in the infrasound range is well below the hearing threshold curve.
With regard to LFN, it was finally decided that limit values would only be set for infrasound. The higher frequency range of LFN (from 20 Hz to 250 Hz) is covered by A-weighted measurements. For infrasound, the G-weighted equivalent continuous SPL ($L_{Geq,T}$) has been chosen as the basis for assessing environmental exposure. Short-term ($L_{Geq,D}$ and $L_{Geq,N}$) and long-term ($L_{DWN(G)}$ and $L_{N(G)}$) indices have also been proposed. In order to avoid annoyance and other possible harmful effects due to exposure to infrasound regardless of land use, 90 dB was chosen as an acceptable value for $L_{Geq,D}$and LDWN(G), and 85 dB for LGeq,N and LN(G)as an acceptable value for the $L_{Geq,D}$ and $L_{DWN(G)}$levels while 85 dB was adopted for the $L_{Geq,N}$ and $L_{N(G)}$ levels.

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Tadeusz Wszołek Maciej Kłaczyński Paweł Małecki Dominik Mleczko Paweł Pawlik Bartłomiej Stępień	31.X.2023	It can be made available on the project website: https://hetman-wind.ios.edu.pl

1. Introduction

Increasing energy problems, and on the other hand: works on a bill to amend the current law known as the "10H law" (Act, 2016), 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 about the harmful effects of infrasound and low-frequency noise (ILFN) can be found. 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 (Lavethall, 2009). 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 (Environmental NOISE Guidelines for the European Region, WHO, 2018), 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 (Pawlaczyk-Łuszczyńska et al., 2018)

While indicators recommended by the WHO for other noise sources, namely L_{den}, $L_n$or L_{Aeq}levels, possibly adjusted for tonal content, impulsivity (ISO 1996-2, 2017), or amplitude modulation, can be used to assess the annoyance of turbine noise in the audible band (AMWG 2016, Pamuła 2016), there are no such universal indicators for infrasound or low-frequency noise. 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 document 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. The vast majority of research and work related to noise generation (including infrasound) involves HAWT (Horizontal Axis) wind turbine analysis. However, there are studies of vertical-axis Wind Turbine - VAWT constructions (Pierzga et al., 2013). The results obtained in the area of infrasound do not indicate significant differences between the noise generated by HAWT and VAWT. Therefore, the usefulness of the noise indicators was verified on the basis of tests carried out in the HAWT environment.

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 (ISO 7196, 2002) or frequencies below 16 Hz according to IEC (IEC, 1994). 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, by G. Leventhall (Leventhall, 2004), as noise in the frequency band from 10 to 200 Hz, while according to ACGIH's Threshold Limits Values (2010), 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 (Pawlas K. et al., 2013).According to Polish standard PN-B-02151-2:2018-2, the noise is considered as LFN (≤ 250 Hz) if the difference between the (equivalent or maximum) C- and A-weighted SPLs exceeds 20 dB or if the noise spectrum

measured in the 1/3-octave bands from 12.5 to 250 Hz has at least one component 5 dB above the reference curve A10.
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 (Kjellberg et al., 1997). 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 (Broner, 2011). 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 (Davy at al., 2018). 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 (Berger et al., 2015). 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, 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 LFN in dwellings are in use some European countries(Moorhouse et al, 2011). Evaluation of exposure to LFNis usually based on the frequency analysis 1/3-octave bands in the various frequency ranges from 8 to 250 Hz. In most cases, the measured levels are compared with corresponding reference curves. Only in Denmark and Germany are the results of the spectral analysis subjected to further calculations (Pawlaczyk-Luszczynska and Dudarewicz, 2022). For example, in Denmark, a low-frequency A-weighted sound pressure level ($L_{pA,LF}$) is determined on the basis of the results of measured the 1/3-octave bands SPL from 1 to 160 Hz. In addition, a penalty of 5 dB is taken into account for impulsive noise. Recommended limit values for apartments during daytime (7:00-18:00) are 25 dB, and during nighttime (18:00-7:00) - 20 dB. In offices, classrooms, etc., the $L_{pA,LF}$ level should not exceed 30 dB, and in other rooms - 35 dB (Jakobsen, 2001). In turn, in Germany, if the noise is not tonal the A-weighted SPL in the 10-80 Hz frequency range is calculated based only on bands exceeding the hearing threshold. While for tonal noise, the level of the 1/3-octave bandwith a tone is compared with the hearing threshold modified by penalty, depending on the frequency and time of day.

Threshold values according to DEFRA (Moorhouse, et al., 2011) are given in Table 1. Infrasound thresholds estimated by H. Moller and C. S. Pedersen are also included in Table 1 (Moller&Pedersen, 2004), in addition to hearing threshold curve values according to ISO 226:2003. 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, in the common band (20 Hz) differ by 5.3 dB, but coincide with the results submitted by T. Watanabe and H. Moller (Watanabe&Moller, 1990) and M. Lydolf and H. Moller (Lydolf&Moller, 1997).

In some countries, the G-weighting curve has been used to assess the annoyance of infrasound indoors (Denmark, Japan, Australia, among others). The limit value has been set at 85 dB(G), while in Japan it is 92 dB(G). Denmark, on the other hand, is perhaps the only country so far to have regulations specifying acceptable levels of low frequency noise indoors caused by wind turbines. This is a low-frequency sound level A of 20 dBA.(Jakobsen, 2012.).

The threshold curves proposed in Table 1 and the L_A-L_C- and L_G-weighted level values were initially 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

Denmark, on the other hand, is perhaps the only country, so far, which has regulations specifying acceptable levels of low frequency noise indoors caused by wind turbines. This is a low-frequency A-weighted SPL equal to 20 dB.It is worth noting that earlier Poulsen (2003) and Subedi I wsp. (2005) compared various criteria used for evaluating LFN in dwellings and found that the low frequency A-weighted SPL gave the best correlation with annoyance rating. However, the aforesaid parameter cannot be measured directly. This is calculated based on the results of the frequency analysis in the 1/3-octave bands from 10 to 160 Hz using the following formula:

$$L_{p,ALF} = 10 \times \log \sum_{f=10Hz}^{160Hz} 10^{0,1 \times (L_{fieq} + K_{Af})}$$

Where:

L_{fieq} is the measured sound pressure level in 1/3-octave frequency bands from 10 to 160 Hz, K_{Af} is the value of the A-weighted correction from 10 to 160 Hz

3. Experimental verification of the usefulness of selected LF indices

3.1. Measurement apparatus and methodology

The device of the test was a Vestas V90 wind turbine that is part of the Głuchów 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 the 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).

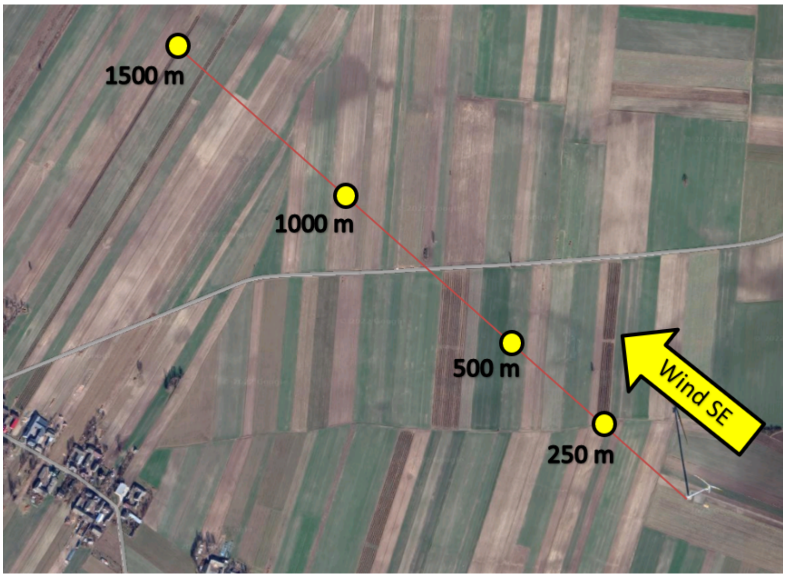

Figure 1. Distribution of measurement points in relation to the wind turbine

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, 2013, 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) (Kłaczyński & Wszołek, 2014) (Wszołek et al., 2020).

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 acoustic background (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.

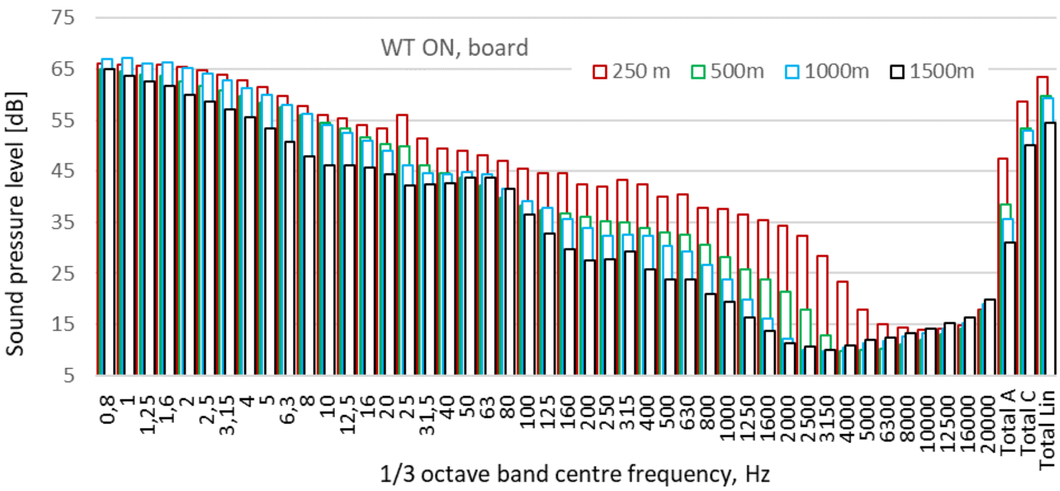

Figure 2. Results of the WT noise spectrum measurements. Measurement on the board at distances of 250 m, 500 m, 1000 m and 1500 m from the turbine.

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.

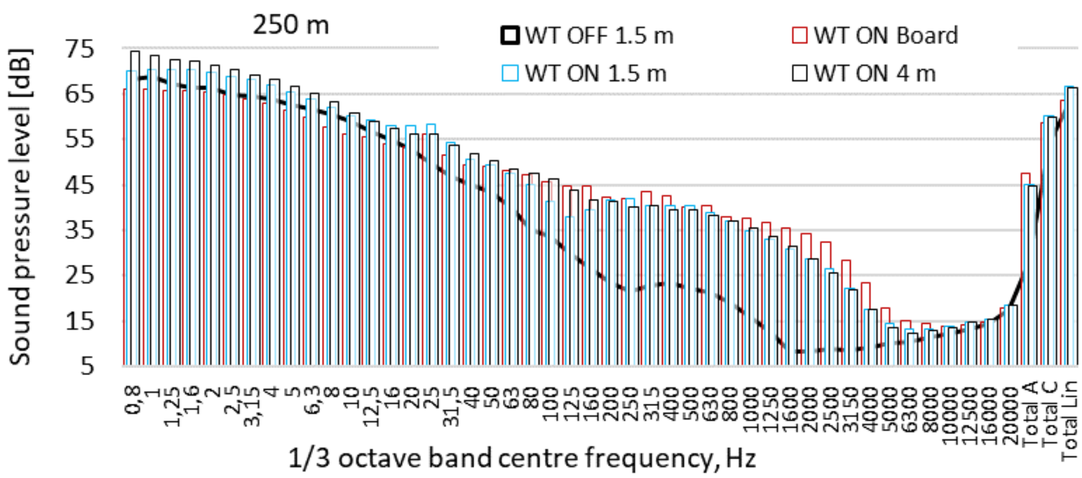

Figure 3. Results of the WT noise spectrum measurements (WT ON – board, 1.5 m and 4 m) and the acoustic background (WT OFF – 1.5 m) at a distance of 250 m from the WT.

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

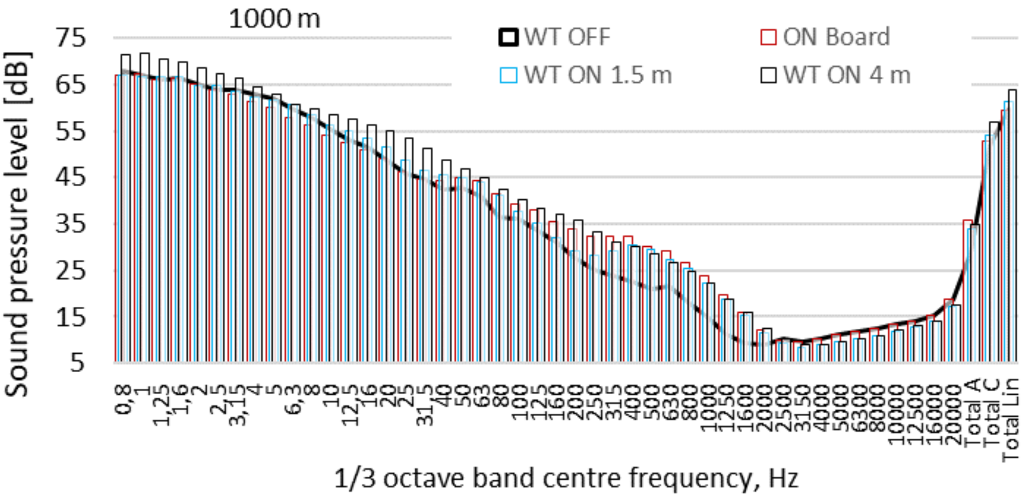

Figure 4. Results of the WT noise spectrum measurements (WT ON – board, 1.5 m and 4 m) and the acoustic background (WT OFF – 1.5 m) at a distance of 1000 m from the WT.

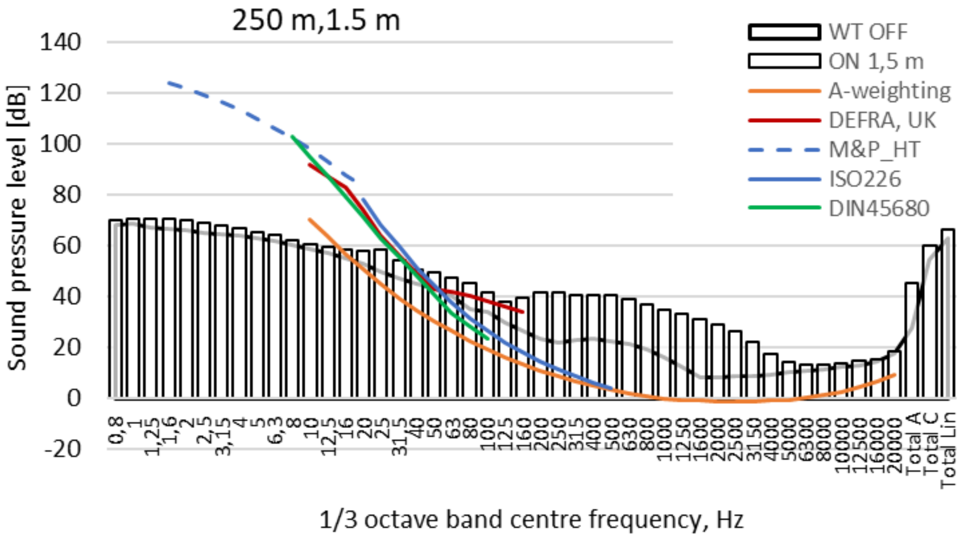

Figure 5. Results of the WT noise spectrum measurements and background noise with the threshold curves plotted as in Table 1 and the inverted A-curve for the 0 dB level. Measurements at height of 1.5 m and a distance of 250 m from the WT.

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 sound 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 (Moller & Pedersen, 2004). Similarly, concerning the other threshold curves – DEFRA and DIN 45680 – 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 in the 20 Hz band, while the difference is already over 30 dB in the 10 Hz band.

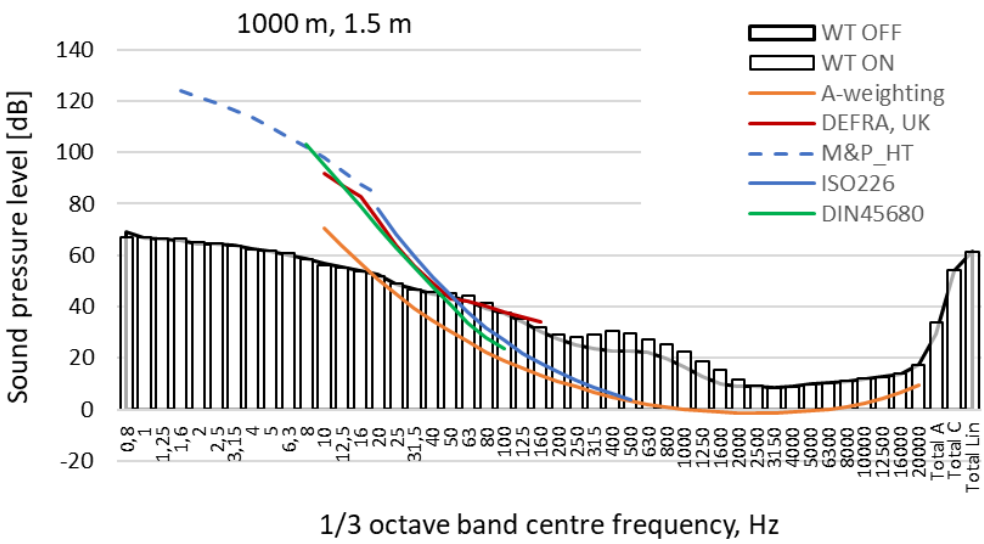

Figure 6. Results of the WT noise spectrum measurements and background noise with the threshold curves plotted as in Table 1 and the inverted A-curve for the 0 dB level. Measurements at height of 1.5 m and a distance of 1000 m from the WT.

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 acoustic background 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 (ambient 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. Proposals of exposure limits for infrasound

It has been commonly assumed that infrasound is inaudible. However, already in the 1930s this was known that if the level is sufficiently highhumans can perceive infrasound. At levels somewhathigher the hearing threshold it is possible to feel vibrations in various parts of the body (Møller H, Pedersen; 2004). Slightly above the threshold of auditory perception, infrasound becomes annoying. Its annoyance increases significantly with increasing sound pressure levels (Møller H., 1978). Furthermore¸according to results of previous investigations, a person's tolerance to infrasound is determined by the threshold of auditory perception. Infrasound that cannot be heard (or sensed) is not annoying and does not cause other adverse health effects (Landstrom and Palmear, 1993, Landstrom, 1995). Findings of recent experimental studies largely confirm previous observations. There is no evidence that infrasound at sound pressure levels well below their hearing threshold can affect human health and well-being (van Kamp and van den Berg, 2018; 2021). Similar conclusions might be formulated from the laboratory study performed within this workpackage.

Although there is currently no hard evidence that inaudible infrasound has an impact on human health and well-being, it has been proposed limits for infrasound while higher frequency range of LFN (from 20 Hz to 250 Hz) is covered by A-weighted measurements and the appropriate limits.

Based on assumption that the infrasound that cannot be heard (or sensed) is not annoying and does not cause other adverse health effects, it was assumed that ideally acceptable infrasound levels should be below the hearing threshold (Landstrom and Palmear, 1993; Landstrom 1995). Furthermore, taking into account the recommendation of the international standard ISO 7196:1995, it was decided that the G-weighted equivalent-continuous SPL will be the basis for evaluating environmental exposure to infrasound outdoors. Formal requirement for accreditedtesting laboratories to ensure measurement consistency, also pointed to the reasonableness of this assumption. (It is worth noting the Central Office of Measures calibrates sound level meters or analyzers in the infrasound frequency range for compliance with the requirements of PN-ISO 7196:2002 but there is a problem with calibration of the 1/3-octave bands filters below 20 Hz).

The frequency range from 20 Hz (or 16 Hz) to 20 kHz (or 16 kHz)is traditionally accepted as the range of human hearing. Although, the hearing thresholds within this interval have been standardized (ISO 226, ISO 389-7, ISO 28961), those below 20 Hz havenot yet been determined, but such attempts have been made by Vercammen (1989), Møller and Pedersen (2004), and Kurakata and Mizunami (2008), among others.

According to the literature data , the average hearing threshold for infrasound - the so-called G96 curve - has a slope close to that of the G-weighting characteristics (i.e. about 12 dB/octave) and corresponds to tones with G-weighted SPLs (L_G) of about 96 dB (Jakobsen, 2001; Moller and Pedersen, 2004;Vercammen, 2007). For the 10 Hz reference tone, the average hearing threshold is approximately 96 dB, while for the 2 and 16 Hz tones it is 124 and 88 dB, respectively.

The G96 curve is represented by a straight line with 96 dB at 10 Hz and a slope of 12 dB/octave below 20 Hz (Fig. 7) This curve can also be obtained from the formula:

L_{fi}= 96 – K_{Gfi}, [dB]

where L_{fi} is the sound pressure level in the 1/3-octave band with center frequency f_i in dB; K_{Gfi} is the attenuation (correction) of the G-weighting characteristics in the 1/3-octave band with center frequency f_i, in dB.

Taking into account the variability of hearing thresholds noted in the analyzed experiments (standard deviation equal on average to about 5dB), the G86 curve was assumed to be the threshold for hearing infrasound which is exceeded by 90-95% of the population. (This line is shifted 10 dB downward in parallel with the G96 curve and takes a value of 86 dB at 10 Hz).

The aforesaid G96 and G86 curves, along with statistical distributionof infrasound hearing threshold determined by Kurkata and MIzunamiare shown in Figure 7(Watanabe and Møller, 1990;Møller and Pedersen, 2004; Kurakata and Mizunami 2008). As can be seen from Figure7, 10% of young people would perceive a 10 Hz tone at SPL of 90 dB. Furthermore, an analysis of hearing thresholds in young people (around 20 years old) and older people (over 60 years old) showed that the difference in their medians (in the 10-200 Hz range), regardless of frequency, is about 10 dB. This means that in the low-frequency range, older people retain good hearing acuity, in contrast to the often significantly impaired sensitivity in the higher frequency range.

Table 7. Mean hearing threshold of infrasound determined for otologically healthy young adults[1] aged 18-25 years along with G96 and G86 curves

Frequency [Hz].	Hearing threshold [dB] according to Watanabe and Moller (1990)	Hearing threshold [dB] according to Moller and Pedersen (2004)	G96 curve [dB] according to Vercammen (2007)	G86 curve [dB] according to Vercammen (1989)
1			139	129
1,25		133,5*	133,5	123,5
1,6		128,6*	128,6	118,6
2		124,3*	124,3	114,3
2,5		120,1*	120,1	110,1
3,15		116 */117 (110-124)**.	116	106

[1]An otologically healthy person, i.e., one who shows no signs or manifestations of ear disease or wax buildup in the ear canals, who has not previously been subjected to excessive noise exposure, who has not taken potentially ototoxic drugs, or who has a family history of hearing loss (ISO 226:2023(en) Acoustics - Normal equal-loudness-level contours 2023)

4	107	112*/ 114 (107-120)**	112	102
5	-	108*/ 110 (103-117)**	108	98
6,3	-	104*/ 106 (99-113)**	104	94
8	100	100*/ 103 (96-106)**	100	90
10	97	96* / 98 (91-105)**	96	86
12,5	92	92*	92	82
16	88	88,3*	88,3	78,3

**Average hearing threshold –data fitted to a linear regression (Møller and Pedersen, 2004).*
***Average hearing threshold (-/+) standard deviation –data fitted to a second-order polynomial regression curve by Nguyen et al., (2023) based on data from Møller and Pedersen (2004).*

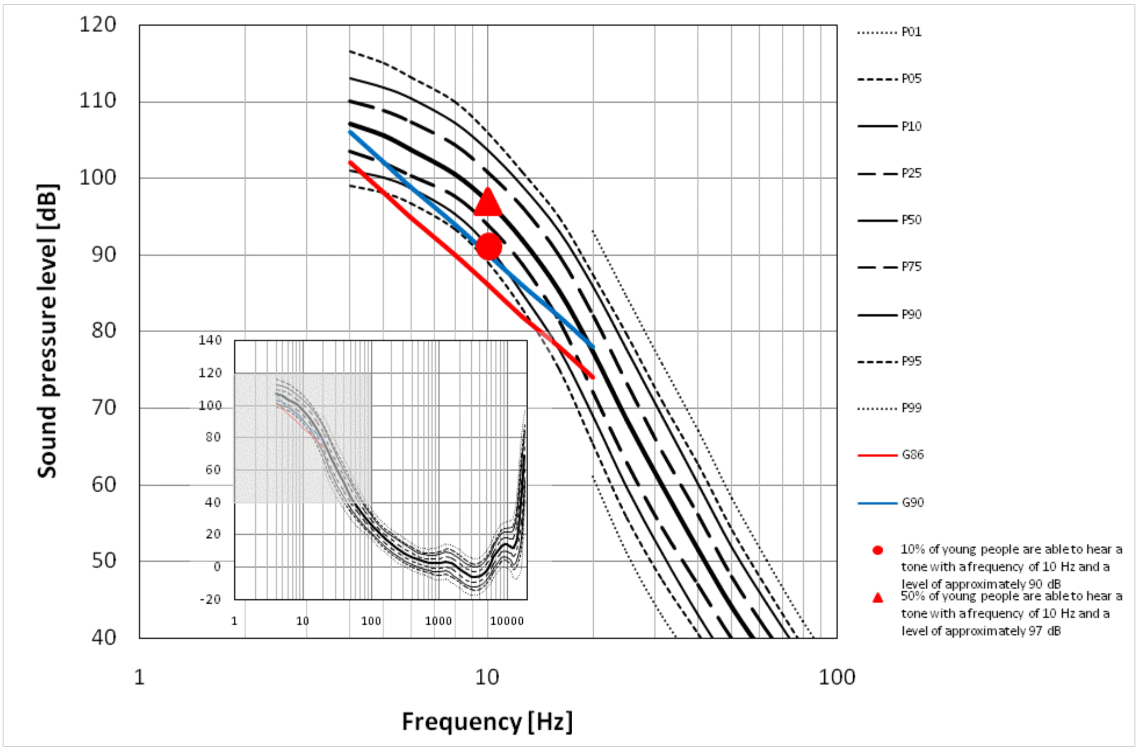

Figure 7. Statistical distribution of infrasound hearing thresholds (from 5th percentile (P05) to 95th percentile (P95)) for young (aged 18-25 years) otologically healthy subjects determined by Kurakata and Mizunami (2008) and curves G96 and G86.

As mentioned above the mean hearing threshold for infrasound can be determined by the G96 curve. Thus, similarly to Nquyen et al. (2022), it was assumed that infrasound will be heard if the sound pressure level in at least 1/3-octave octave band from the frequency range 2-16Hz exceeds the average hearing threshold, i.e. the G96 curve. In extreme case, when the above-mentioned condition is met in all 1/3-octave bands from 2 to 16 Hz, the average hearing threshold, i.e. the

G96 curve, corresponds to the G-weighted SPL of approx. 106 dB, while if only in one 1/3-octave band – this corresponds to 96 dB.

Taking the average infrasound hearing threshold as the limit value would mean that 50% of people could hear it. To reduce this percentage, it would be necessary to take into account the variability of hearing thresholds found in previous studies, expressed as an average value of the standard deviation (equal to approx. 5 dB) and adopt the permissible value at lower levels .

Since some people may hear infrasound at lower SPLs, based on Danish and Japanese regulations, the permissible values of short-term indicators, i.e. the G-weighted SPL, were assumed to be 90 and 85 dB, for the reference time T = 16 h and T = 8 h during the day and night, respectively. In turn, the limit values of long-term indicators were 90 and 85 dB, respectively, in the case of the $L_{DWN(G)}$ and $L_{N(G)}$ indicators.

According to the above mentioned assumptions, the L_{pG}levelof 90 dB corresponds to the G90 and G80 curves. Comparing thelatter curves with the distribution of hearing thresholds (Kurakata and Mizunami, 2008), it can be expected that, on average,less than8% of people, especially young people, can hear infrasound at a level of L_G =90 dB and can thereforemay experience high annoyance (HA%). Annoyance at this level (i.e., %HA <=10%)is acceptable from the point of view of setting noise limits for wind turbines based on the expected percentage of people finding the noise highly annoying. (Davy et al. (2018).

On the other hand, the comparison of the G85 and G75 curves with the distribution of hearing thresholds (Kurakata and Mizunami, 2008) shows that infrasound at level LpG= 85 dB is inaudible, so it should not be a source of annoyance and cause adverse health effects.

In conclusion, it has been proposed permissible levels of infrasound in the environment caused by wind turbines expressed as the short-term indicators ($L_{Geq,D}$ and $L_{Geq,N}$) and long-term indicators ($L_{DWN(G)}$ and$L_{N(G)}$). Irrespective of land use, the G-weighted equivalent-continuous SPLwas set at 90 dB for a reference time T=16 h during the day and 85 dB for reference time T=8 h during the night. Similarly, the following values were adopted as acceptable values for long-term indicators, irrespective of land use: 90 dB - for $L_{DWN(G)}$ and 85 dB - for $L_{N(G)}$.

The aforesaid proposals do not exclude the possibility of carrying out a frequency analysis in 1/3 octave bands, particularly in relation to the daily use of the environment, and comparing its results with the G90 and G85 curves during the day and the night, respectively. Furthermore, regardless of the output criterion used (G-weighting characteristics or threshold curve), the result obtained might be adjusted regarding the presence of tonal components and amplitude modulation.

5. Summary

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 (Downey., Parnell, 2017) or H. Moller and C. S. Pedersen (Moller&Pedersen, 2004).

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, 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.

Due to the lowest wind disturbance, on the other hand, the high similarity of the measurement results obtained on the board with double windscreen with the results at a height of 1.5 m, also with the double wind screen, in the frequency range below 50 Hz, the results on the board can be applied directly to assessment of infrasonic noise annoyance, without additional correction

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.

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