Chapter 3

Review of evaluation criteria for infrasound and low frequency noise in the general environment

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Abstract
It has been suggested that infrasound (IS) and low frequency noise (LFN) may be responsible for adverse health effects in people living in the vicinity of wind farms. Many studies have indicated that the basic noise measure – an A-weighted sound pressure level (SPL) – is a less suitable descriptor for assessing the effects of IS and/or LFN. Thus, this paper reviews existing or proposed methods for evaluating infrasound and LFN in residential areas with regard with their impact on human health and wellbeing.

Keywords: infrasound, low frequency noise, environmental exposure, effects on humans, measuring methods, exposure limits

1. Introduction

Infrasound (IS) is defined as sound or noise whose spectrum lies mainly in the range from 1 to 20 Hz [1]. In turn, low frequency noise (LFN) – although its international definition has not yet been definitely formulated – is usually referred to as broadband noise with a dominant content frequencies from 10 to 250 Hz, but sometimes the LFN range is limited to 20–200 Hz or 20–500 Hz [2].

Both, IS and LFN comprise a common, everyday-life environmental exposure, produced by natural (sea waves, wind turbulence) as well as by man-made sources (industrial installations, domestic appliances, transportation) sources. Their prevalence in premises is mainly due to ventilation, heating and or air-conditioning systems as well as from outdoor sources of noise and poor attenuation of low frequency components by the walls, floors and ceilings. Moreover, propagation models and field studies have indicated that IS and LFS can propagate with less attenuation with distance than higher frequencies because of their lower sound absorption during passage through the air and on reflection from the ground. Moreover, especially LFN, may be amplified as a result of the phenomenon of resonance of rooms and structural elements of buildings [2, 3].

It has been suggested that IS and LFN may be responsible for adverse health effects in people living in the vicinity of wind farms. Thus, the aim of this paper was to review the evaluation criteria for infrasound and low frequency noise in residential areas in relation to their impacts on humans.

2. Perception of infrasound and its effects on humans

It has been commonly assumed that infrasound is inaudible. However, already in the 1930s this was known not to be true [4]. The perception of infrasound is based on hearing and vibrations. The threshold of auditory perception rises rapidly as the frequency falls, from approximately 65 dB at 32 Hz to 95 dB at 16 Hz, 100 dB at 3 Hz, and 140 dB at 1 Hz [2, 5].

The sound-induced vibrations will be perceivable only at relatively high sound pressure levels, 20 to 40 dB above the hearing threshold. The sensory mechanism is the same as in detecting mechanically induced vibrations [5-8]. Moreover, when infrasound becomes audible, it can be annoying. The annoyance associated with exposure to audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones within the frequency range from 4 to 31.5 Hz. These curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is observed for equal loudness curves, so the annoyance of infrasound is closely related to the loudness sensation [9].

The adverse effects of aural pain, speech interference and temporary threshold shift (TTS), normally appear at levels 30 to 40 dB above the hearing threshold. The threshold for aural pain is approximately 140 dB at 40 Hz and 160 Hz at 3 Hz. A tympanic membrane injury may be the result of exposure to extremely high sound pressure levels [6, 10]. In turn, TTS effects from audiometric frequencies above 125 Hz have been observed after infrasound exposures at 140 dB. As expected, the most significant effects can be observed at frequencies above 1 kHz. The TTS, often of less than 10 dB, have been found to disappear rapidly after exposure [3, 6, 11].

Infrasound as well as low frequency sound (10–75 Hz) may excite resonant vibrations in some parts of the human body e.g. abdomen, chest and throat. Such vibrations in the thorax/abdominal region normally appear at levels above 100–105 dB (40–60 Hz). The vibrotactile sensations in the abdomen and chest region due to infrasonic frequencies (4–20 Hz) appear at much higher levels, close to 130 dB [6, 12].

An American space research project has indicated that the maximum permissible short-term exposure to infrasound should be in the region of 140–150 dB. Beyond this the chest walls of the subjects would vibrate, with a sensation of gagging and blurring of vision. Moreover, the chest wall vibrations may interfere with the respiratory activity [5, 6].

Possible vestibular disturbances (described as the loss of the sense of balance, disorientation and nausea) have been investigated in several studies. The validity of these effects is controversial [6, 10, 12]. In view of some later research, infrasound at the levels normally experienced by man should not have any significant effect on the vestibular function [13].

A close correlation exists between the exposure to infrasound, its perception and the physiological disorders. Therefore, the acoustic pressure levels must always be high enough to allow perception, in order to induce physiological effects. This theory has been experimentally verified in laboratory studies. Reduction of wakefulness identified through changes in EEG, blood pressure, heart activity, respiration, and hormonal production, was found to occur only when the infrasound levels exceeded the hearing threshold. Under the same conditions the deaf subjects presented an absence of weariness [5, 6].

The physiological effects observed in experimental studies often seem to indicate a general slowdown of physiological and psychological functions. The reduction in wakefulness and related physiological responses are probably to be regarded as secondary reactions to a primary effect on the central nervous system (CNS). The effects of moderate infrasound exposure are thought to be based on the correlation between the hearing perception and the resulting CNS stimulation [14]. The participation of the reticular activating system and the hypothalamus is considered to be of great importance [5]. However, the changes in the physiological reactions are not only ascribed to sound at levels above the hearing threshold**.** The response of the CNS (including RAS, hypothalamus, limbic system, and cortical region) are probably also highly influenced by the quality of sound. Thus, some frequencies and characteristics are probably more effective than others in producing weariness [15].

To sum up, it is assumed that infrasound that cannot be heard is not annoying, and it is believed that it has no other adverse or health effects. It is also assumed that infrasound only slightly above the hearing threshold may be annoying.

3. Effects of LFN on humans

There is a large number of studies on health impacts due to occupational and environmental exposure to noise. However, there are still few studies focusing exclusively on health impacts and discomfort due to LFN. One of the main reasons for this is the low sensitivity of the human auditory system to low frequencies.

Since LFN includes both infrasonic and low audible frequencies, numerous effects attributed to IS are also reported to be induced by LFN, e.g., pressure sensation in the middle ear, resonant vibrations in some parts of the human body (mainly chest and stomach), speech interference, temporary loss of hearing acuity, and vestibular disturbance (although the latter effect is disputable in case of IS) [2, 3, 6, 10, 11, 16-18].

However, annoyance is the major and the most frequent effect of the LFN exposure on human subjects, especially at their homes, and it is often accompanied by secondary effects, such as headache, concentration difficulties palpitations and sleep problems [19]. Furthermore, some studies suggest an association between LFN and various physiological and psychological reactions such as annoyance, hearing threshold shift, concentration problems, lower sleep quality, mood effects [19-22] and also controversial conditions such as the so-called vibro-acoustic disease [23]. Additionally, adverse health effects from occupational exposure have been observed on memory, annoyance and performance [24-26]. Evidence on vascular and respiratory effects is inconclusive [27].

However, evidence, especially in relation to chronic medical conditions, is limited. Epidemiological research on LFN and health effects is scarce. LFN in the everyday environment constitutes an issue that requires more research attention [28, 29].

4. Measuring methods

The draft proposal of international standard [30] suggested the use of two weighting characteristics (named G1 and G2) in order to describe infrasound in the frequency region below 20 Hz (Figure 1). These curves were asymptotically weighted in straight lines with different slope. Between 1 and 20 Hz the lines had the slope of 12 dB per octave and 6 dB per octave for G1 and G2 curves, respectively. At frequencies above 20 Hz, both curves had cut-offs with the rates of 24 dB per octave. Below 1 Hz the slopes were 12 dB per octave and 18 dB per octave for G1 and G2 characteristics, respectively.

As human tolerance to infrasound is defined by threshold of hearing perception, the frequency-weighting characteristics G1 have the same slope between 1 and 20 Hz (close to 12 dB per octave) as the hearing threshold curves, equal loudness curves and equal annoyance curves. The G2 curve did not have a scientific basic; it was simply a result of a compromise between the G1 curve and linear curve. The G1 weighting network gave values that corresponded much better with the subjective annoyance rating than G2-weighting filter [9].

Thus, in the final version of ISO 7196:1995 [31] only the G1 curve was left and after slight modifications it was renamed as the G-weighting characteristics. Furthermore, the average hearing threshold for infrasound corresponds to tones each having a G-weighted SPL of approx. L_{pG} = 96 dB.

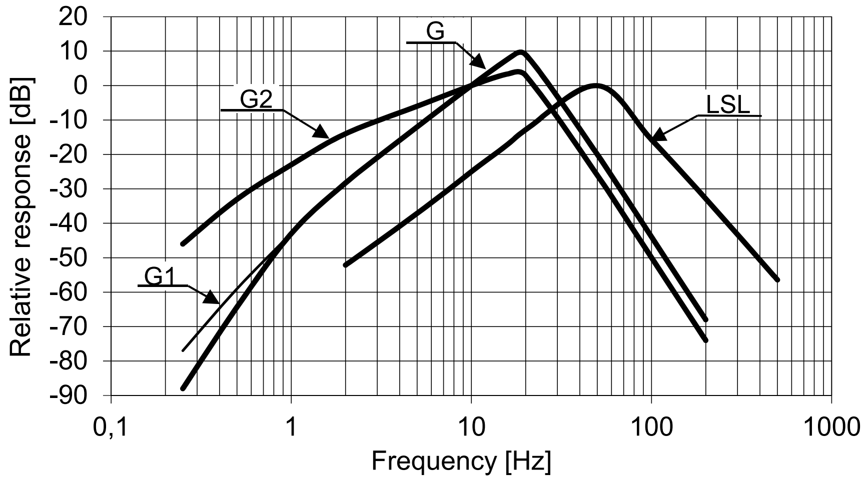

Figure 1. Nominal G1-, G2-, G- and LSL-weighting characteristics [30, 32]

For evaluating noise containing not only infrasonic but also the audible frequencies, especially in living environments, another type of frequency weighting curve named LSL (abbreviation for low-frequency sound level) was proposed in Japan. It had a dominant frequency of 50 Hz and +12 dB per octave and -18 dB per octave slopes in the lower and upper frequency range, respectively (Figure 1) [32].

Since the threshold of hearing perception defines human tolerance of infrasound it is sometimes thought that any pertinent hygienic evaluation of infrasound should consequently be based on the frequency analysis [15].

As regards LFN, many studies have indicated that A-weighted sound pressure level (SPL) is less suitable descriptor for assessing effects of LFN [18, 19, 33]. Therefore, the usage of the C-weighting has been proposed instead by WHO [34].

5. Review of exposure limits for infrasound

The first proposals of criteria for infrasound exposure were presented at Colloquium on Infrasound, in Paris, in 1973 [3]. During that conference two groups of researchers, one led by Stan (Figure 2) and the other led by Pimonow (Table 1), presented the results of their research. These studies suggested that exposure to infrasound at sound pressure levels (SPL) above 180 dB posed a risk of death, and that a 2-minute exposure at levels in the 150–172 dB range is tolerated by healthy individuals, while many hours of exposure to levels of 120–140 dB might induce fatigue and health disorders [3].

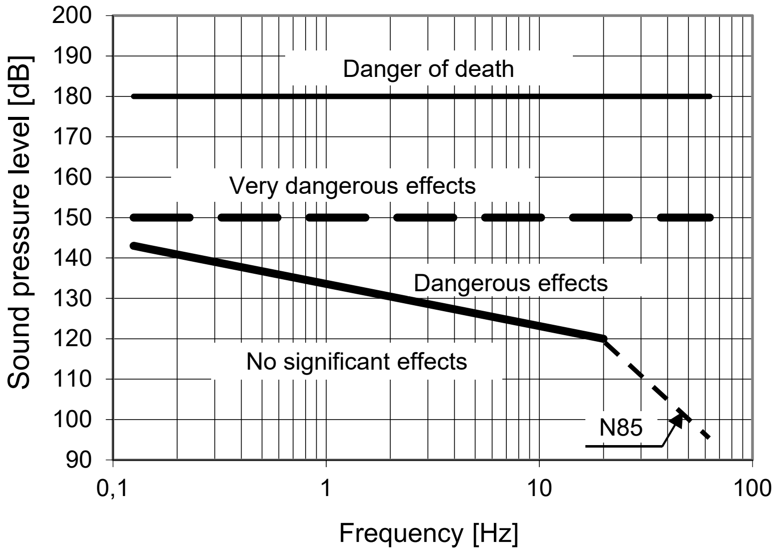

Figure 2. Limiting levels for effects of infrasound proposed by M. Stan [3]

Table 1. Zones of infrasound health effects specified by L. Pimonow [35]

Zone	Sound pressure level, L_p [dB]	Consequences
I	$L_p \geq 185$ dB	fatal danger (the variable pressure of such levels can induce pulmonary alveolar rupture)
II	$172 \geq L_p > 140$	2-minute exposure is tolerable for the healthy human
III	$140 \geq L_p > 120$	exposure is able to induce mild physical disturbances and fatigue in case of many hour exposures
IV	$120 \geq L_p$	no health harmful effects if time of exposure is less than several minutes; reactions of the long-time exposure are the subject for future studies

Somewhat later, the first criteria for assessing infrasound exposure began to be set. In the USA, in 1977 the Committee on Hearing, Bioacoustics and Biomechanics (CHABA) proposed limit values for urban exposure (uncontrolled population) (Table 2) [6].

Table 2. Limit values of the environmental exposure to infrasound according to CHABA [6]

Frequency f [Hz]	Permissible SPL [dB]			Notes
	Time of exposure T_e [min]			
	$T_e \leq 1$	$1 < T_e \leq 100$	$T_e > 100$	
$0{,}1 \leq f \leq 5$	120	$120–10 \lg T_e$	100	The threshold of annoyance related to the occurrence of vibrations in the building structures or the feeling of pressure in the middle ear
$5 < f \leq 20$	$120–30 \log(f/5)$	$120–30 \log(f/5)$ $-10 \lg T_e$	$100–30 \log(f/5)$	

6. Limit values of environmental exposure to infrasound

In Denmark a set of guidelines for measurement and assessment of environmental LFN, infrasound, noise and vibration was published in 1997 as Information from the Danish Environmental Protection Agency no. 9/1997 [36]. Given that the environmentally acceptable infrasound level must be below the hearing threshold (HT), thus the recommended limit value for infrasound inside dwellings during the day, evening and night and inside classrooms and offices is 85 dBG (Table 3). For occupied rooms in commercial enterprises the limit is 90 dBG. The noise is measured over a 10-minute period and a 5 dB penalty is added for impulsive noise e.g. single blows from a press or drop forge hammer [36].

Table 3. Recommended limits for infrasound, LFN and noise indoors according to the Danish Environmental Protection Agency no. 9/1997 [36]

Type of space	Infrasound* L_{Geq}	LFN $L_{p\,ALF}$	Noise $L_{p\,Aeq}$
Dwelling (evening & night)	85 dBG	20 dBA	30/ 25 dBA
Dwelling (day)	85 dBG	25 dBA	30 dBA
Classroom, office etc.	85 dBG	30 dBA	40 dBA
Other rooms in enterprises	90 dBG	35 dBA	50 dBA

*If the noise is impulsive, e.g. from single blows with a press or a forging hammer, the recommended limits are reduced by 5 dB

In Queensland (Australia), a low frequency noise guidelines have been developed by the Environmental Protection Agency [37]. These guidelines are applicable to infrasound and LFN emitted from industrial premises, commercial premises and mining operations (not blasting), and is intended for planning purposes as well as for the evaluation of existing problems. Similar to the Danish recommendations, the limit value of the G-weighted sound pressure level inside dwellings, classrooms and offices is 85 dBG.

In June 2004, the Ministry of the Environment of Japan published "Handbook to Deal with Low Frequency Noise, which suggest "reference values to deal with complaints about low level LFN from stationary sound sources like factory plant and facilities such as shops, which generate LFN continuously. This handbook is not applicable to fluctuating or impulsive LFN emitted by such sources as roads, airplanes, railways, and blasts. Regarding infrasound and analyzing the prevalence of complaints of mental and physical discomfort, if the measured G-weighted SPL is ≥ 92 dB, it is very likely that there is an effect of infrasound [38].

7. Criteria for assessing exposure to LFN indoors

Over the years many different methods have been suggested for the assessment of LFN in the general environment (dwellings) indoors. Exposure criteria are in use or are proposed in Sweden, the Netherlands, Denmark, Germany, Poland, Finland, the United Kingdom, Austria, Australia and Japan.

For example, the Swedish method is based on the frequency analysis in 1/3-octave bands from 31.5 to 200 Hz [20]. The measured (equivalent-continuous) SPLs are compared with criterion curve specified by the National Board of Health and Welfare (Table 4).

Table 4. Limit values of exposure to LFN indoors according to the Swedish National Board of Health and Welfare [20, 39]

f [Hz]	31.5	40	50	63	80	100	125	160	200
$L_{f\,eq}$ [dB]	56	49	43	41.5	40	38	36	34	32

In the Netherlands, several proposals of criteria for assessing LFN have been prepared, including a criterion based on the frequency analysis in the 1/3-octave bands from 20 to 100 Hz and the median hearing thresholds of the 10% best-hearing individuals from an unselected age group of 50-60 years taken as reference values (Table 5). These levels are typically 4-5 dB lower than the average threshold for otologically normal young adults (18-25 years) as given in [40]. Thus, this method determines if LFN is audible or not, rather that it is annoying [41, 42].

Table 5. Limit values of exposure to LFN indoors according to the Dutch audibility criterion [41]

f [Hz]	20	25	31.5	40	50	63	80	100
$L_{f\,eq}$ [dB]	74	64	55	46	39	33	27	22

The Finnish guidelines of the Ministry of Social Affairs define the permissible values of the 1-hour equivalent-continuous SPLs in the 1/3-octave bands from 20 to 200 Hz at night (Table 6) [44].

Table 6. Limit values of exposure to LFN indoors according to the Finnish guidelines [43]

f [Hz]	20	25	31.5	40	50	63	80	100	125	160	200
$L_{Aeq,\,1h}$ [dB]	74	64	56	49	44	42	40	38	36	34	32

In Denmark, according to the guidelines of Environmental Protection Agency [36], the exposure to LFN is evaluated based on the low frequency A-weighted sound pressure level ($L_{pA,\,LF}$), which is determined from the results of the frequency analysis using the following formula (1):

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

where:

L_f 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.

In addition, a 5 dB penalty for impulsive noise is taken into consideration. The recommended limit values (of the $L_{pA,LF}$ levels averaged over 10 min) in dwellings are 20 dB during the night/evening and 25 dB during the day. On the other hand, the $L_{pA,LF}$ level in classrooms, offices etc. should not exceed 30 dB, while in other rooms it should be lower than 35 dB [36].

In Germany, according to the recommendation of DIN 45680:1997 [44], a difference between the (equivalent or maximum) C- and A-weighted SPLs ≥ 20 dB indicates the occurrence of LFN. The assessment is based on a frequency analysis in the 1/3-octave frequency bands between 10 and 80 Hz. However, in exceptional cases the 1/3-octave bands of 8 Hz and/or 100 Hz are also considered. The assessment takes into account the tonal character of the noise. The noise is considered tonal if in any 1/3-octave frequency band the sound pressure level is at least 5 dB greater than the levels in the two adjacent bands.

If the noise is tonal, the sound pressure level of the 1/3-octave band with tone is compared with the hearing threshold modified by penalty, depending on the frequency and a time of the day (Table 7).

Table 7. Criterion curve specified in DIN 45680:1997 [44]

f [Hz]	8	10	12.5	16	20	25	31,5	40	50	63	80	100
L_{HS} [dB]	103 +5/0	95 +5/0	87 +5/0	79 +5/0	71 +5/0	63 +5/0	55.5 +5/0	48 +5/0	40.5 +5/0	33.5 +5/0	28 +10/5	23.5 +10/5

*Penalty for tonal noise in the day/night period

On the other hand, in case of non-tonal noise, the A-weighted SPL in the 10–80 Hz frequency range is calculated based only on bands exceeding the hearing threshold levels LHs (close to those of ISO 226:2003 [40]. The maximum acceptable level for the A-weighted equivalent SPL (1080 Hz) is 35 dB during daytime and 25 dB during the night. In turn, the limit for the A-weighted maximum SPL is 45 dB during daytime and 35 dB during the night. night period, respectively [44].

In 1995-1998, the Polish criteria for the assessment of LFN in residential buildings in were developed the Building Research Institute. The frequency analysis in the 1/3-octave bands from 10 to 250 Hz was adopted as the basis for the evaluation of exposure to LFN from equipment installed inside and outside the building. The A10 characteristic has been accepted as the reference curve. (The reference curve has been derived from $L_{f\,A10} = 10 - K_{Af}$, where L_{fA10} is sound pressure level in the f-th 1/3-octave band, K_{Af} is the value of the A-weighting characteristics in the f-th 1/3-octave band; f is from 10 to 250 Hz) [45].

According to the Instruction No 358 of the Building Research Institute [46], LFN is annoying if the sound pressure levels exceed the A10 curve and simultaneously exceed the background noise level by more than 10 dB for tonal noise and by 6 dB for broadband noise.

In 2018, after some updates, the aforesaid method for evaluating exposure to LFN indoors has been published as Polish standard PN-B-02151-2:2018-2 [47]. According to this standard, the noise is considered as LFN 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.

In Great Britain, for a number of years, the so-called low frequency noise rating curves (LFNR curves), which were a modification of noise rating curves (audible) (NR curves), were used to assess LFN in residential premises. However, in 2005 new proposals of the criteria for the assessment of LFN disturbances were prepared by the Department for Environment, Food and Rural Affairs (DEFRA). These were based on measurement of equivalent-continuous sound pressure level ($L_{feq,T}$) and statistical levels L_{10} and L_{90} in 1/3-octave bands between 10 Hz and 160 Hz. The proposed reference values – based on the (Table 8) can be increased by 5 dB if the noise occurs only during daytime or if noise is steady [48]. A noise is considered steady if either L_{10}-L_{90} < 5 dB or the rate of change of SPL (measured with the time constant Fast) is less than 10 dB/s.

Table 8. Limit values for exposure to LFN indoors according to the DEFRA recommendations [48]

f [Hz]	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
$L_{f\,eq}$ [dB]	92	87	83	74	64	56	49	43	42	40	38	36	34

In the Australian state of Queensland, according to the Guidelines of the Environmental Protection Agency, the initial assessment of LFN is to check that the total sound pressure level in the living areas does not exceed 50 dB ($L_{LINeq} \leq 50$ dB) [36].

If $L_{LINeq} - L_{Aeq} > 15$ dB then further frequency analysis in the 1/3-octave bands between 20 and 200 Hz is required. In the next step, these results should be compared with the reference curve, i.e., with the median hearing threshold level for the best 10% of the older population (55-60 years old) (Table 9) to determine the degree of LFN audibility. It should be also check for the existence of an amplitude-modulating component, where the noise level changes cyclically at a particular 1/3-octave band frequency. The added perception of loudness caused by this attribute can be accounted for by subtracting a 5 dB penalty from the L_{HS} value [36].

For tonal noise, the level in the frequency band/s with the tone/s is compared to the hearing threshold level (L_{HS}) in the corresponding bands (Table 9). It is then found how much the tonal value is above the threshold level. The levels in the other frequency bands are not taken into account. The limit values for exceedance of the threshold table values by the equivalent level of the tone/s are as given in Table 10.

Table 9. Criterion curve for LFN indoors according to guideline of the Environmental Protection Agency in Queensland [36]

f [Hz]	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
L_{HS} [dB]	96	92	88	84	75	62	55	46	39	33	27	22	18	14	10

Table 10. Limit values for exceedance for annoyance due to tonal noise [36]

Period	**1/3-octave frequency band**			
	8 Hz to 63 Hz	80 Hz	100 Hz	> 100 Hz and < 200 Hz
Day	5	10	15	17
Evening/night	0	5	10	12

On the other hand, for the non-tonal noise, the low frequency A-weighted SPL ($L_{pA,LF}$) is determined based on results of frequency analysis using the equation (1). The noise is considered acceptable if the corresponding limit value given in the Table 11 is not exceeded.

Table 11. Limit values for non-tonal low frequency noise ($L_{pA,LF}$) [36]

Type of space	**$L_{pA,LF}$ (dBA)***
Dwelling, evening and night (18:00 – 7:00)	20
Dwelling, day (7:00 – 18:00)	25
Classroom, office, etc.	30
Rooms with commercial enterprises	35

*If the LFN is impulsive in nature (e.g., forge, disco music), the limit values are reduced by 5 dB

As mentioned earlier, the Ministry of the Environment of Japan published "Handbook to Deal with Low Frequency Noise", which suggest reference values to deal with complaints about low level LFN from stationary sound sources like factory plant and facilities such as shops, which generate LFN continuously. This handbook is not applicable to fluctuating or impulsive LFN emitted by such sources as roads, airplanes, railways, and blasts [38].

As regards LFN, the reference values have been established for complaints of mental and physical discomfort and because of rattling (vibration). These have been defined in the 1/3-octave bands 10–80 Hz (Table 12) and 5–50 Hz (Table 13), respectively.

Table 12. Reference values for complaints of mental and physical discomfort [38]

f [Hz]	10	12.5	16	20	25	31.5	40	50	63	80
L_f [dB]	92	88	83	76	70	64	57	52	47	41

Table 13. Reference values for complaints of rattling windows and doors [38]

f [Hz]	5	6.3	8	10	12,5	16	20	25	31.5	40	50
L_f [dB]	70	71	72	73	75	77	80	83	87	93	99

If the 1/3-octave band SPL is higher or equal to the reference values for mental and physical discomfort (Table 12), at any frequency band, it is highly likely that the frequency band is the cause of the complaint. Additionally, if the measured G-weighted SPL is 92 dB or higher, it is highly likely that there is an effect from infrasound. If the measured value is less than the reference value at every frequency, noise, ground vibration, and other factors are needed to be surveyed [38].

On the other hand, when 1⁄3-octave band SPL exceed the reference value for rattling of doors or windows (Table 13) in any frequency band, it is highly possible that this frequency band is the cause of the complaint. If the 1⁄3-octave band SPL are less than the reference value for complaints of rattling, however, rattling will occur rarely. In this case, it is necessary to look for another cause, for example ground vibration or noise, for the complaints [38].

So far, Denmark is one of the few countries where it has been established indoor acceptable LFN levels for wind turbine noise. According to Danish Turbine Noise Ordinance no. 1284 of 15 December 2011 [49], the basis for the assessment of LFN in dwellings (residential buildings) is the low-frequency A-weighted SPL ($L_{pA,LF}$) determined by the computational method. The calculated $L_{pA,LF}$ level at wind speeds of 6 and 8 m/s must not exceed 20 dBA.

8. Criteria for assessing exposure to LFN outdoors

In 1992, a draft version of standard was prepared in Poland which specified the limit values for environmental exposure to continuous and intermittent LFN outdoors. The assessment was based on measurements of sound pressure levels in 1/1-octave bands between 4 and 63 Hz (Table 14) [50].

Table 14. Permissible sound pressure levels in 1/1-octave bands from 4 to 63 Hz for LFN in the general environment outdoors [50]

1/1-octave frequency band [Hz]	Permissible sound pressure level [dB]	
	Continuous noise	Intermittent noise
4	102	102
8	90	90
16	78	78
31.5	65	60
63	51	56

In the United States, in 2005, Hessler [51] proposed criteria for low frequency industrial noise in residential areas, based on his experience in investigating and solving low frequency noise problems, mainly from open cycle combustion turbine installations. Although most LFN criteria are expressed in terms of 1/3-octave band spectra near the ISO 226:2003 [41] definition for the threshold of audible noise, these limit values were expressed as the C-weighted overall levels (Table 15). Their author believes that the recommended C-weighted limits are applicable to most common steady low-frequency noise sources in addition to combustion turbines due to the combined tonal and broadband character of the sound.

Table 15. Maximum allowable dBC levels at residential areas to minimize resident complaints from low-frequency industrial sources [51]

	For normal suburban/urban residential areas, daytime residual level, L_{90} > 40 dBA	For very quiet suburban or rural residential areas, daytime residual level, L_{90} < 40 dBA
For intermittent daytime only or seasonal source operation	70	65
Extensive or 24/7 source operation	65	60

Ideally, the LFN criteria should be set for indoors where the LFN complaints normally occur. However, for the purpose of planning, it is much easier to establish outdoor limit values. Table 16 presents exposure criteria which were proposed by Broner (2010) [52] based on a review of many case histories and the literature data.

Table 16. Criteria for assessment of LFN outdoors proposed by Broner [52]

	Sensitive receiver	Range criteria	Leq (dBC)
Residential	Night time or plant operation 24/7	Desirable Maximum	60 65
	Daytime or intermittent (1–2 hours)	Desirable Maximum	65 70
Commercial/office	Night time or plant operation 24/7	Desirable Maximum	70 75
Industrial	Daytime or intermittent (1–2 hours)	Desirable Maximum	75 80

It is worth noting that if the measured dBC level is fluctuating (at least ± 5 dBC), thus the above criteria should be reduced by 5 dBC. What's more, when measuring the noise, all energy down to 10 Hz should be considered and a minimum sampling duration of 3–5 minutes should be used so as not to average out the LFN fluctuations which are characteristic of many LFN problems. This is further to ensure that the low frequency sound level is sampled accurately.

According to the aforesaid Australian researcher [52], the noise levels to be recorded are the maximum and minimum C-weighted SPL's using the Fast time weighting, the L_{C10} and L_{C90} levels for the purpose of providing an indication of the level fluctuation of the LFN. The same metrics are to be recorded using the A-weighting instead of the C-weighting.

In Australian State of New South Wales, it is recommended to measure the C-weighted sound pressure levels at intermediate locations to identify any anomalies such as mechanical problem or a need for any further investigations. As the LFN limit values were adopted sound pressure levels (65/60 dBC) which were proposed by Broner (2010) [52]. In addition, a 5 dB penalty is applied to the measured noise level for the periods and meteorological conditions under which the LFN has been identified. Moreover, it has been assumed that the difference dB(C) – dB(A) > 15 dB indicates the presence of LFN [53].

The recommendations of the state of South Australia follow the suggestions made by the New South Wales Industrial Noise Policy, but do not provide any specific limit or required actions [53].

In Canadian province of Alberta, it is assumed that the LFN problem occurs when the time-weighted difference between C- and A-weighted sound pressure levels for the measured period of day or night time is ≥ 20 dB, and a clear tonal component is present within the frequency below 250 Hz [53]. When a LFN has been identified, measurements of C- and A-weighted SPLs are to be made simultaneously. The following two criteria indicate the presence of a low frequency noise measured at a dwelling. Satisfying only one criterion does not result in a finding that low frequency noise is present. Firstly, the isolated (e.g. non-facility noise, such as wind noise, has been removed) time-weighted average dBC – dBA value for the measured daytime or night-time period is equal to or greater than 20 dB. Secondly, a clear tonal component exists between 20 to 250 Hz, i.e., for the 1/3-octave bands from 20 to 250 Hz: (i) the linear sound pressure level of one band must be at least 10 dB or more above one of the adjacent bands within two one-third octave bandwidths, and (ii) there must be at least a 5 dB drop in level within two bandwidths on the opposite side of the frequency band exhibiting the high sound level.

If a LFN condition as defined above exists, 5 dB must be added to the measured comprehensive sound level. If this value exceeds the permissible sound level, the licensee must identify the source of the low frequency noise and implement noise attenuation measure to address the issue in a timely way. Once LFN control measures have been implemented, a follow-up comprehensive sound level and complaint investigation must be conducted to confirm that the low frequency noise condition has successfully been addressed. Since wind generates high levels of low frequency sound that can mask the assessment of low frequency noise. Measurements of LFN should only be taken when atmospheric conditions are favorable for accurate measurement [53].

In Japan, reference values for outdoor LFN measurements are specified in the handbook cited earlier. These values provide guidelines for how to handle complaints about rattling windows and doors, given for 1/3-octave bands from 5 Hz to 50 Hz [38].

9. Discussion and conclusions

Although, over one hundred years ago, the American scientist and businessman Charles F. Brush was the first to use wind energy to produce electricity, a wind turbines are relatively new sources of infrasound and LFN, and their effects on health and well-being are not fully recognized. Wind turbines are specific type of noise source, which has impact on large areas. The noise emitted by wind turbines does not resemble the common industrial noise – it has a different temporal-spectral characteristics [54].

Research on the impact of wind turbine noise (WTN) focuses on noise annoyance, sleep disturbance, quality of life, general health and mental health issues. Sustained research on the impact of wind turbine noise began in 2007 [55]. Recently, more and more attention has been given to of LFN and infrasound. In particular, it has been suggested that IS and LFN may be responsible for adverse health effects in people living in the vicinity of wind farms. Meanwhile, it does not seem to be completely true.

For example, recently a big cross-sectional study was carried out in Finland which aim was to analyze the role of infrasound in health ailments related to wind turbines [56]. The aforesaid study revealed that 70 out of 1.351 respondents (5%) reported symptoms which they attributed to infrasound from a wind farm). The symptomatic respondents lived closer to the wind farm than the asymptomatic respondents. Furthermore, they more often suffered from chronic diseases, complained about the annoyance of wind turbines and believed that wind turbines posed a health risk. What's more, out of all respondents, 10% considered wind turbine infrasound as a high risk to personal health, and 18% as a high risk to health in general [56].

In another Finish study, recordings of the wind turbine noise with the highest levels of infrasound and amplitude modulations were selected for laboratory experiment. It has been shown that people who have reported symptoms related to (infra)sounds showed no increased sensitivity to wind turbine infrasound. Total wind turbine SPL and amplitude modulation resulted in increased annoyance, not infrasound. In turn, the wind turbine IS or wind turbine sound annoyance were not related to either heart rate or heart rate variability, or to skin conductivity (physiological measures of stress) [57].

As regards results of new research concerning the impact of infrasound and LFN in general, most of them have looked at measuring brain activity in response to infrasound, often in comparison with low-frequency or normal sound. The latest research largely confirms the previous results. The perception of infrasound and low frequency sound is generally consistent with what it was known from the literature, and there is no indication that infrasound well below the threshold of hearing may have any effect on humans. This leads to the conclusion that low-frequency sound is part of the total sound of wind turbines and has the same effects normal sound [58, 59].

However, only a few jurisdictions (i.e., Danish, Australian and Japanese), have established IS limits, so far. These criteria are usually not greater than 85–90 dBG and none of them are specific to wind turbines. Furthermore, there are currently also no widely accepted international health based limits for LFN, specifically derived for wind turbines.

For example, LFN outdoor limits have been introduced by some states or provinces in Australia and Canada and by Japan, but they also do not directly apply to wind turbines. A number of them assume that the difference (dB(C) – dB(A)) > 20 dB indicates presence of LFN, and they set the upper limits of L_{Ceq} equal to 65 and 60 dB(C) during the day and night, respectively [53].

In turn, exposure criteria for the assessment of LFN in dwellings are in use or are proposed in some European countries, including Denmark, Germany, Sweden, the Netherlands, Finland, Poland, UK, as well as in Australia, Canada and Japan. However, to the best of the authors' knowledge, Denmark is one of the few countries with regulations that specify indoor acceptable LFN levels which are specific for wind turbine noise. As regards criteria concerning LFN indoors, the majority of them are based on the frequency analysis in 1/3-octave bands in various frequency ranges between 8 and 250 Hz. Basically, measured SPLs are compared with reference values. Only in the Danish and German methods are the results of frequency analysis subjected to further recalculations. On the other hand, low frequencies from 8 Hz or 31.5 Hz were included in guidelines used in German and Swedish criteria, respectively [48]. Also of note is that all criteria curves except Netherlands criteria are lower than the standard hearing threshold levels at frequencies below 31.5 Hz.

It is worth noting that indoor LFN limits provide a basis to address specific complaints from local residents; however, for wind farm development, regular monitoring of outdoor sound levels presents a more practical option.

Given evidence to support that specific wind farm noise acoustic characteristics [60, 54], such as amplitude modulation (AM) and tonality, LFN and infrasound components can contribute to higher perceived annoyance, a specific penalties for these characteristics should be developed. Penalties applied to LFN and infrasound may be more reliable if the real broadband nature of LFN and infrasound is considered [61]. Reasonable approach seems to deal with LFN could be based on allowable limits for 1/3-octave bands as well as an overall allowable limit. Moreover, the percentage of highly annoyed individuals and audibility of LFN and infrasound are highly variable between people and warrants further larger well-controlled studies.

Nevertheless, infrasound and LFN limits for wind farms cannot be recommended in the absence of definite evidence of health effects from IS or LFN. Thus, further studies are needed before firm conclusions can be drawn.

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