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Low Frequency Noise from Wind Turbines – Fact Sheet

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IEA Wind TCP - Task 39
Quiet Wind Turbine Technology

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Forewords

This document summarizes a number of facts concerning low-frequency noise emissions from wind turbines, and related issues such as human perception and regulations. It is addressed to non-specialists in the field of acoustics and wind turbine noise in general. Attempts have been made to define most of the technical concepts introduced in this document. A number of references to various scientific articles, reviews and reports are provided. However, in some cases their contents are very technical and may be more difficult to grasp for the layman. This document has been drafted with contribution from scientists and engineers working in scientific fields related to wind turbine sound issues.

Low Frequency Noise from Wind Turbines – Fact Sheet

What is Low Frequency Noise (LFN)? General considerations

The human perception of sound arises from the ability of the auditory system in the ear, and subsequently the brain, to detect acoustic waves travelling in the air. However, it must be emphasized that the audibility of different frequencies (or pitches), i.e. the intensity at which they are subjectively perceived relative to their actual physical intensity or energy content, varies with frequency. Whereas an ideal microphone with a constant sensitivity at all frequencies can measure the actual acoustic energy content or noise level of all these frequencies, the human ear has indeed a specific frequency response. It is most sensitive to sound waves in a frequency interval ranging *approximately* from 1 kHz to 5 kHz[1]. Below and above this frequency range, the ear sensitivity progressively decreases. In other words, for an equal amount of physical acoustic energy or actual noise level, the loudness of the noise will appear to a listener increasingly quieter as the frequency of the emitted noise decreases below 1 kHz, or increases above 5 kHz. In other words, in order to be perceived equally loud by the human ear, a noise source emitting at a frequency outside the above frequency interval therefore needs to have more physical energy content than a noise source emitting at a frequency within this interval.

Generally speaking, LFN refers to the low frequency end of the audible sound spectrum. Conventionally, sound at frequencies below 20 Hz is referred to as infrasound (IS). LFN is usually referring more specifically to sound waves above 20 Hz and below 200 Hz. Below 20 Hz, acoustic waves may be perceived provided that the noise level, i.e. their energy content, is high enough. As an example, the average[2] human audibility threshold for a sound at 8 Hz is around 100 dB [Watanabe & Madsen, 1990; Møller & Pedersen, 2004], compared to 20 dB at 200 Hz (i.e. a sound with 100 million times less energy), and 0 dB at 2000 Hz (i.e. 10,000 million times less energy), as displayed in Figure 1.

[1] Some sources mention a peak sensitivity ranging from 2 to 4 kHz. For reference, normal voice speech typically ranges from 100 Hz to 1000 Hz. A male with a deep bass voice can reach below 70 Hz, while a female soprano above 1200 Hz (a female high-pitched scream to 3000 Hz). A tuba brass instrument can play notes down to around 50 Hz and a cathedral pipe organ down to 8 Hz, while a piccolo flute can play up to 5 kHz and higher pitches can be obtained with cymbals or triangles.
[2] Note that the measure of audibility varies from one person to the other, including factors such as age, and that it can be measured using several methods for which the results may also differ.

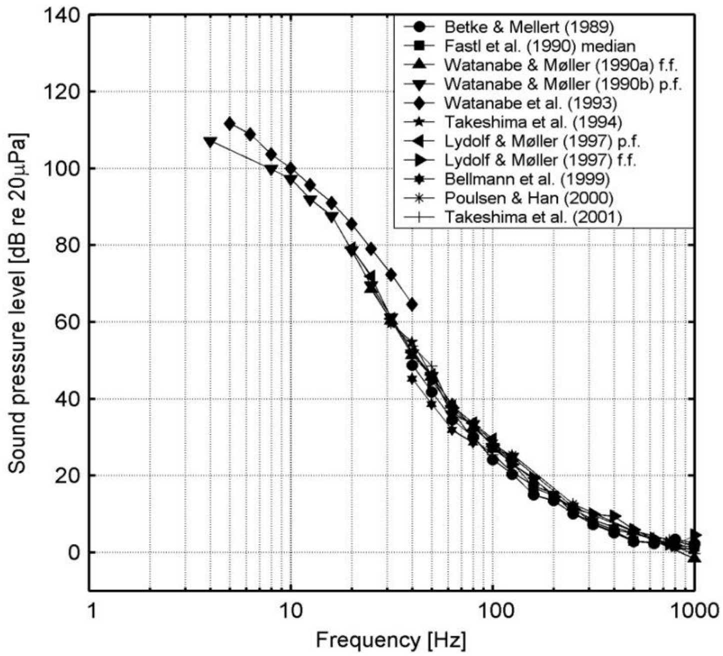

Figure 1 - Low-frequency hearing threshold measured between 1989 and 2001 [Source: Pedersen PhD thesis, 2008]

It is also important to note that sound levels decrease as the distance from their source increases, a phenomenon called `geometric spreading' which applies similarly to all frequencies. In addition, acoustic waves are dissipated when travelling through the air due to `air absorption'. This dissipation is increasingly efficient at higher frequencies. Therefore, LFN propagates from the source more easily compared to high-frequency noise.

Since noise levels decrease with the distance from the source. At a certain distance these levels will be masked by, and eventually become negligible compared to other natural (wind-induced noise in the vegetation, birds, etc) and/or anthropogenic (traffic noise, industrial activities, etc) noise sources. Probably, the most critical issue concerning LFN is a proper assessment of the distance at which this masking occurs.

How wind turbines create LFN?

In the context of WTN, it is usual to segregate the two main sources of noise: aerodynamic noise and mechanical noise. As these designations indicate, the former is related to aerodynamic features of the flow around the wind turbine blades as they rotate. In the latter case, noise is generated by the rotating and vibrating machinery of the drive-train, such as the generator and gearbox, produces sound waves during the operation of a wind turbine. Fans from cooling devices also emit noise, even during periods of stand-still. Accordingly, these two mechanisms are reviewed separately below.

Aerodynamic noise

As far as aerodynamic noise is concerned, a first contribution to LFN stems from the interaction of the atmospheric turbulence with the blade surfaces as they rotate. As the blades move through the air at relatively high speed (in particular in the tip region), atmospheric inhomogeneities inherent to the turbulent wind flowfield generate pressure fluctuations on the blade surfaces. These fluctuations subsequently radiate as sound waves away from the turbine. The contribution of atmospheric turbulence to noise emissions is largest in the low frequency range due to the blade velocity and the size of the inhomogeneities involved. In addition, most of the sound energy is generated toward the tip of blades because the radial velocity is highest there. This type of noise is called broadband, in the sense that sound is emitted over a large range of continuous frequencies corresponding to the various sizes of the turbulent vortices contained in the atmospheric wind. It is estimated that the turbulent inflow impinging on the rotor blades generates broadband sound in the low frequencies with a maximum at 10 Hz [VanDenBerg2005].

Other aerodynamic phenomena create LFN by the same basic physical principle described above, but through different mechanisms. Flow disturbances and inhomogeneities can be created by the wind turbine itself (e.g. the turbine tower does alter the incoming wind flowfield) and these can interact with the blades. In the case of an upwind rotor concept (see Fig. 2 (left)), the tower slows down the flowfield upstream of itself, which influence can be felt by the blades as they pass by the tower at each rotation. More significantly, in the case of a downwind rotor concept (see Fig. 2 (right)), the flowfield disturbances are even stronger in the form of a downstream tower wake. When the blades pass through these disturbances, blade surface pressure fluctuations arise and sound waves are generated (similarly to the effect of the atmospheric turbulence above). In this latter case, the noise emission is `impulsive' in the sense that the noise wave emissions occur at each passage of a blade near the tower. Note that wind turbines with a downwind rotor configuration have been discarded from utility-scale commercial use since the 80's [Hubbard90], partly because it became clear that this configuration was an important source of LFN. In the same way that the tower flow disturbances create pressure fluctuations on the blade, radiating as noise, the passing blades reciprocally generate pressure fluctuations on the tower surface (mostly in the case of a cylindrical steel tower) which also radiate as noise. Recent studies have shown that this mechanism may contribute substantially to infrasound emissions [Klein2018, Zajamsek2019]. This type of blade-tower interaction may occur for upwind rotor concepts when the wake of the blade(s) hit the rotor as illustrated in Fig. 2 (left), but can also be the result of the impact on the tower of the air displacement caused by the passing blade which occurs both for upwind and downwind rotor concepts. It is not clear yet which of these two phenomena dominate.

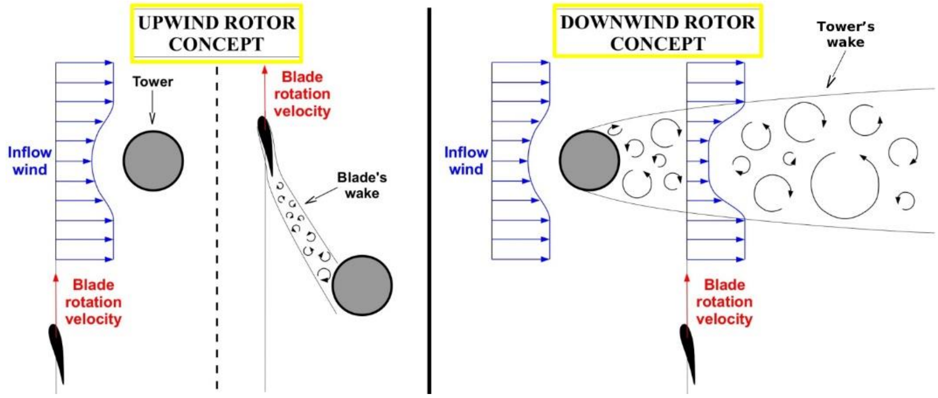

Figure 2 - Sketch of upwind (left) and downwind (right) wind turbine rotor concepts as seen from a cross-section in a plane perpendicular to the tower, and visualizing the airfoil section from one of the blades passing in front of, or behind respectively, the tower.

Mechanical noise

Because some of the structural vibrations originating from the drive train or other components (e.g. cooling system) can generate noise at relatively low frequencies, these mechanical noise sources may fall in the category of LFN. However, they have the peculiar property of being tonal, i.e. noise is emitted only at a specific frequency associated with the rotating speed of the mechanical components and/or the resonance frequencies of the structure. Tonal noise, if loud enough, easily stands out from the broadband noise and is therefore more noticeable, thus potentially more annoying. Note that the wind turbine nacelle may contain equipment or machinery that emit noise without structural vibrations (e.g. humming of electricity converters or cooling fans). Mechanical sound sources can usually be considerably attenuated, e.g. by using proper insulation of the nacelle or dampening devices at critical structural locations.

Propagation

Because LFN can travel further away than high frequency sound waves (see above), some studies have reported that LFN from wind turbines could be measured at quite large distances [Bolin2014, Zajamšek2016], although this may occur in specific weather conditions. Nevertheless, it has also been found that, at normal residential distances, measured LFN from a single turbine, or even from a wind turbine cluster, rarely exceeds the natural ambient background noise or other LFN sources, even in a quiet environment such as the country side [Ratzel2016, JapanMoE2016, JapanMoE2017]. Although very low frequencies, which travel further away, can be measured at slightly higher levels than ambient ones, at these distances these are again far below the hearing threshold.

Another mean of propagating noise away from a vibrating structure, in particular in the LFN and IS range, is by ground-borne noise. In this case, the medium that conveys the acoustic energy is not the air, but the ground itself. This may cause other structures at distances from the noise source to vibrate and/or emit noise on their own because of the energy transmitted to them through this mechanism. This has been investigated mostly in the case of rail and road traffic, but to our best knowledge, this has been very rarely reported for wind turbines [Sjöström2014] and the amount of energy communicated to the ground by this mechanism is far lower than what can be produced by a train on a railway or other heavy industrial machinery. Consequently, the recorded levels are below the threshold of perception [HayesMcKenzie2006, Gastmeier2008, Nguyen2020].

Measuring LFN

It can be challenging to measure LFN, and even more so infrasound, emitted from a wind turbine accurately. Firstly, as the distance from the turbine increases, the noise immission[3] will rapidly become of the same order of magnitude as the ambient noise already present in the environment and the actual turbine noise can easily be drowned in this background noise. To segregate the background noise from wind turbine noise, it is necessary to compare the noise measured when the wind turbine is operating and shutdown periods. However, background noise vary significantly between day and night, but time of the day, atmospheric conditions, and possibly other factors, play significant roles. Therefore, it is recommended to conduct these measurements during extensive time-periods over several weeks or even months [Bluemendeller2020].

Secondly, measuring sound waves presents some specific difficulties at the lower end of the frequency range. Microphones are usually designed and optimized to measure sound in the human audible range say from 10 Hz up to 10 kHz or much higher. Their performances can deteriorate toward lower frequencies depending on the microphone technical specifications. Although so-called IEC 61672 Class 1 microphones should be able to measure with sufficient accuracy, some microphones are specifically designed for LFN measurements. More importantly, setting a microphone in the open-air also creates noise because of the wind interacting with the microphone itself, a phenomenon denoted as wind-induced noise which is predominant at low-frequencies. Foam and/or fur wind shields are used to minimize this effect (see pictures in Fig. 3). These wind shields are effective in the audible range but perform poorly at low frequencies and sometimes it is the wind-induced noise in the wind shield which is being measured, not wind turbine or ambient noise. There are ongoing investigations to improve wind shields for very low frequency measurements or placing them below ground level to avoid wind effects [Zajamšek2014, D'Amico2019, Bluemendeller2020].

Finally, when considering noise inside dwellings, low-frequencies are influenced by the noise emission levels, but the building itself (e.g. its structure) plays also an important role [Hansen2017]. If possible, outdoor noise measurements in front of the building should be correlated with indoor measurements providing more information [Søndergaard20XX, Thorsson2018, Maijala2020]. Note that also the measurement location inside a building or a room is a significant factor, making it difficult to obtain a unbiased quantitative measure of indoor LFN levels.

[3] In contrast to noise emission which characterizes the sound source, noise immission refers to the sound levels that can be measured or perceived at a listener position at a given distance from the source, possibly inside a dwelling.

Figure 3 – Top left picture: Outer fur wind screen, with inner foam wind screen for extra protection, shielding a microphone from the wind for outdoor noise measurements [Source: FORCE Technology, Denmark] - Bottom picture: Foam outer (left) and inner (middle) wind screens with the inner assembly contains the microphone (right) [Source: Norsonic AS, Norway] – Top right: Microphone (with foam wind screen) placed in a wooden box at the ground level to minimize wind effect [Source : Blumendeller2020]

Perception and impact on humans

Psycho-medical studies have reported that, at high enough levels of LFN, like for any other sound at high levels, humans can be affected in the form of annoyance, stress, irritation, unease, fatigue, headache, possible nausea and disturbed sleep [Hansen2020]. However, it must be remembered that the LFN emissions from a wind turbine, when heard at residential locations at a few hundred meters, are comparable with, or often below, the natural ambient levels. Although LFN can be measured in the immediate vicinity of a wind turbine and sometimes far away as well, there is no evidence that wind turbine noise can cause direct physical effects on people living nearby, considering the low levels involved at distances equal or larger than the typical minimum legal distances between wind turbines and dwellings. Typically, LFN and infrasound from wind turbines falls well below the level of audibility [ONeal2009, Howe2010, Ewans2013, Ratzel2016, Maijala2020]. A resident's attitude to wind turbines is an important factor in their response to them and annoyance certainly plays a role here [VanKamp2018, Leventhall2019, Maijala2020].

Metrics for quantifying LFN and regulations

Noise levels are commonly measured in decibels (dB) although other units do exist. As sound waves are characterized by air pressure fluctuations, a sound pressure level (SPL) in dB provides a measure of the amplitude of these fluctuations. A specific SPL can be associated with each of the measured sound frequencies[4]. For standard noise level assessment over the whole audible frequency range, noise is measured in dB(A), namely A-weighted decibels. A-weighting is a filter of the measured sound levels at all frequencies which is adapted to reflect human hearing in order to create a realistic metric for noise levels. Its effect is to attenuate the contribution of frequencies associated with lower audibility for humans, say below 1000 Hz and above 5000 Hz as discussed in the Introduction. Thus, quantifying LFN and infrasound require different metrics, so that they can be used for legislating. Note that noise regulations concerning LFN from wind turbines are not enforced in all jurisdictions. However, when they are, fixed limits on quantitative metrics of LFN can be applied, or these metrics can be included as an additional penalty to the standard noise limits in regulatory schemes.

The International standard (ISO) for quantifying infrasound is called G-weighting [IEC 61672-1] which, in the same way as for A-weighting, filters out the contributions outside of the frequency range from 10 to 30 Hz (e.g. as used in Denmark). Germany has its own standard by comparing A- and C-weighting. The latter filter being more orientated toward low-frequency sound than the former, it is possible to enhance the contribution of LFN to the overall noise using this metric. In Denmark, two specific metrics are used for noise regulations. Infrasound is evaluated using the G-weighted noise levels. Separately, LFN is evaluated based on A-weighting but restraining the summation to frequencies between 10 to 160 Hz. Furthermore, different limits are applied for day and night, and residential or working areas.

Final words

For further details about low-frequency noise from wind turbine, the reader is referred to the extensive reviews by Leventhall [Leventhall2009] and Howe [Howe2010].

Acknowledgments

This document was written and reviewed by scientists and engineers working in the field of wind turbine acoustics.

[4] Conventionally, the SPLs are summed up over what is called octave bands. The latter define consecutive frequency intervals with center frequencies increasing exponentially. This is a mean to cover a large range of frequencies, from very low to very high, with a relatively small number of discrete center-frequencies.

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