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IEA Wind TCP Task 39

Wind Turbine Tonalities – 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 tonal 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.

Disclaimer

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What is structure-borne sound?

Every piece of machinery with moving parts emits, to some degree, sound, some loud, noisy and disturbing, some less prominent and almost inaudible. When the machine starts to vibrate, e.g. due to internal friction or unbalanced rotating parts, these vibrations are transmitted through the housing surface into the air. A sound is emitted.

Wind turbines, being some of the largest machinery ever built, are no exception. The components of the drive train, like gear boxes or generators, cause excitations of quite significant amplitude. Moreover, the expansive, thin walled surfaces of the rotor blades, the nacelle cover or the tower can easily resonate, increasing sound emittance almost like a large-scale loudspeaker. Characteristic for this so-called vibroacoustic, or structure-borne sound is its tonal appearance, meaning that it is dominated by only a few, sharp, and often annoying frequencies in the audible spectrum.

Because the human hearing is particularly sensitive to tonal noise, the international certification regulations for wind turbines set strict limits for tonal exposure. It is therefore the task of the turbine designer - and the wind farm operator - to minimize the vibroacoustic footprint of a wind turbine for residents.

Wind turbine noise generation

The audible sound profile surrounding wind turbines has several different sourcing mechanisms, as shown in *Figure 1*, and consequently has very different auditory characteristics. Most recognizable in immediate proximity of the turbine is a broadband, alternating 'swish' sound. This sound is caused by an interaction of the wind and flow characteristics at the blade with its surface. Because of a wide range of involved flow structures the noise generated by this interaction is broadband in nature, with a frequency ranging from about 20 Hz well into the kHz.

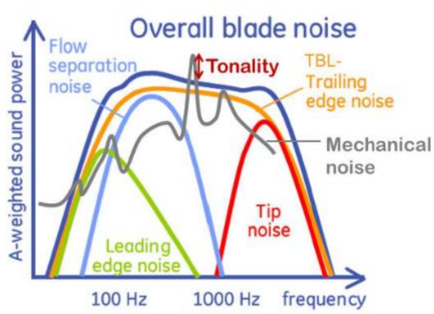

Figure 1: Contribution of different noise sources to the overall wind turbine noise spectrum including a tonal component (Note that the respective quantitative contributions may differ from turbine to turbine, and this graph should only be considered as a qualitative examplei [Source: vanHoellebeke].

The broadband nature of airfoil noise is important for the audibility of tonal noise sources as it effectively masks other noise sources of the turbine, see *Figure 1*. Tonal noise components only become audible to the human ear if the sharp frequency peak stands out significantly above the masking spectrum. The masking spectrum itself is composed of the airfoil noise on the one hand, and everything that contributes to 'background' noise on the other. In many locations, infrastructure such as traffic and industry, provide a significant contribution to the local sound emissions. More importantly the wind itself is a major noise source to the human ear, due to turbulent structures carried within the moving air. In the case of strong and gusty wind, the wind noise will be the predominant and only audible sound surrounding a wind turbine. Tonality as such will, therefore, only be an issue if the blade noise of a wind turbine is low (which is every intention of a turbine manufacturer), and the wind speed is relatively low and constant in time. Under these conditions, the machine borne tonalities are no longer hidden behind the masking noise, and can become audible or in some cases even annoying.

Tonal noise generation on wind turbines

Noise audible to the human ear is the final element in a chain of physical processes. One divides machine noise generation in *excitation, transmission, radiation, propagation* and *immission. Excitations* within the drive train are the primary source for machine noise, but other mechanical devices can also be the source of a tonal acoustic footprint:

- Gearbox induced vibrations
  Wind turbines make use of gear boxes to adjust the rotational frequency of the electrical generator with the demanded grid frequency. Gear boxes of modern-day wind turbines consist of multiple planetary and spur-gear stages. As the contact between the teeth of gear wheels is unsteady (varying between zero and full contact), the transmitted forces between two gear wheels are subject to undulations. These time-varying contact forces are the primary reason for gear box vibrations. The frequency of a harmonic gear pair excitation is proportional to the rotational speed of the wind turbine rotor: if the speed increases, so does the frequency of the tone. The actual pattern of excited gear box frequencies is a function of gear teeth number in the individual gear box stages. The resulting excitation profile usually is a rather complex, fan-type pattern, as shown in *Figure 2*. It consists of the principal and higher harmonic orders associated to multiple gear pair contacts within a multi-stage gear box configuration.

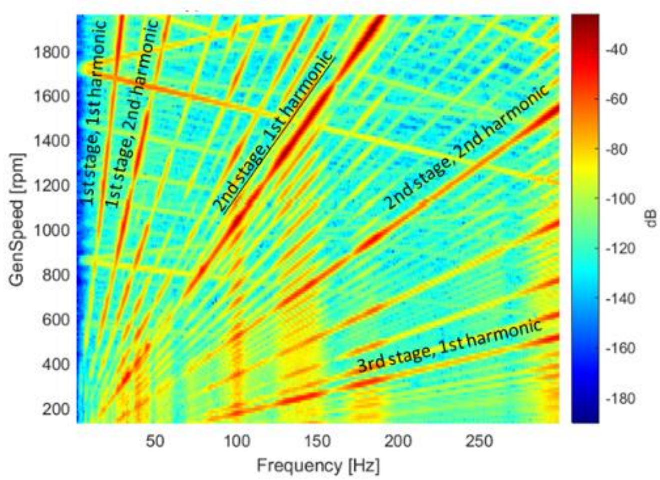

Figure 2: Typical response pattern of a geared wind turbine.

- Generator induced vibration
  The wind turbine generator is equally a source for structural vibrations, and for gearless wind turbines it is the most significant one. The passing of rotor poles and stator windings result in periodic variations of the electromagnetic forces in the airgap, commonly known as the cogging torque. Like in gear boxes, the generator internal excitation is characterized by the principal and higher harmonics, and comparably this leads to a fan type excitation pattern. Generator induced vibrations are particularly relevant for the design of tonality-free direct drive wind turbines, as the corresponding forcing magnitude as well as the resonating generator structures are large.
- Power electronics
  Power electronics components serve to match the generated electrical frequency and voltage levels to the grid demands. The electrical switching frequency in those devices, rectifiers, and transformers in particular, can translate into narrow-banded vibrations and direct tonal noise. Power electronics in modern day wind turbines are usually installed directly within the nacelle to reduce cable losses. Noise and vibrations must be shielded adequately to avoid a tonal character of the noise spectrum.
- Cooling fans
  Some wind turbine types operating in hot climatic conditions require an external, fan-driven cooling system to exchange excess heat. The noise of those fans can be tonal in character and is strongly correlated to the fan rotational speed, not necessarily the turbine rotational speed. Fan related tones can thus become increasingly apparent at low wind speeds or close to turbine standstill when the aerodynamic masking noise is low. The primary measures to reduce fan induced tonality are noise shielding and redirecting.
- Aerodynamic tonal noise
  As described by [Dawson2014] and others, aerodynamic effects on wind turbines can produce tonal type sounds. The underlying effect is so-called laminar-boundary-layer-vortex-shedding, a local flow phenomenon at the rotor blades unrelated to vibroacoustic emissions. The appearance of aerodynamic tonality points to inadequate blade performance, potentially due to degradation or icing. These effects can be easily avoided or mitigated if occurring.

Vibrations created within the drive train are transferred within the entire turbine structure, passing between individual components via bearings and fixations, see *Figure 3*. Along this **transfer path**, most oscillations will be absorbed by structural damping or lead to internal noise emissions. In both cases they are no longer relevant for external noise emission. Tower and blades, along with the nacelle housing, are the primary radiation surfaces of wind turbines. Being thin walled, large structures, the surfaces of these components can easily resonate with a wide range of excitation frequencies. If resonance occurs, the structure starts to amplify the vibrations of certain frequencies. A potential resonance within the frequency window of a critical excitation, thus, must be avoided to keep tonality levels low.

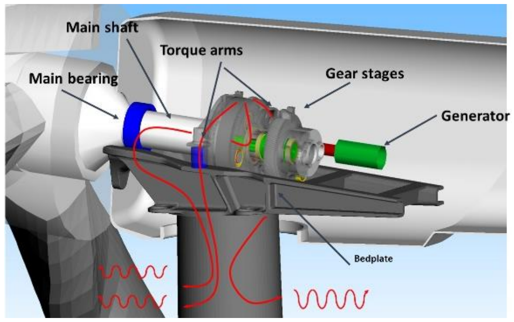

Figure 3: Vibration transfer and radiation within a wind turbine.

Tones emitted via tower or blade surfaces can potentially occur in very low frequency ranges below 20 Hz, due to the large dimensions of the radiating components. The highest tonal frequencies may be observable around 600 Hz, depending on the source. The most common range for drive train borne tones is from 60 Hz to 200 Hz.

Tonal noise assessment and regulations

Tonal noise from wind turbines may be addressed differently in different jurisdictions. However, many regulatory frameworks make use of the well-known IEC 61400-11 standard, in which tonal noise measurement is a part of the regular noise measurement of wind turbines. This part of the standard is shortly summarized below.

A measurement campaign is conducted with one or multiple microphones positioned in a sector downwind of the turbine. The microphone distance corresponds to the tower height plus half the rotor diameter. Narrow-banded spectra of sound pressure levels are obtained for 10s measurement periods. All 10s band spectra are categorized by the corresponding measured mean wind speed. This ensures that a wind turbine is assessed for all wind speeds individually.

Generally, a tone is defined in a spectrum when a local maximum stands out significantly compared to the neighboring bands. In order to identify the potential tones in a spectrum the following method is applied:

- Identify the local maxima in the narrow-banded spectrum.
- Calculate the background noise level as the average energy level of the *critical frequency band*, centered around the local maximum, excluding the identified local maximum and its two neighboring bands. Except for tones between 20 and 70 Hz, the width of the critical frequency band Δf_c increases with increasing tonal frequency f_c, according to the following formula:

$$\Delta fc = 25 + 75 \left(1 + 1.4 \left[\frac{f_c}{1000}\right]^2\right)^{0.69}$$

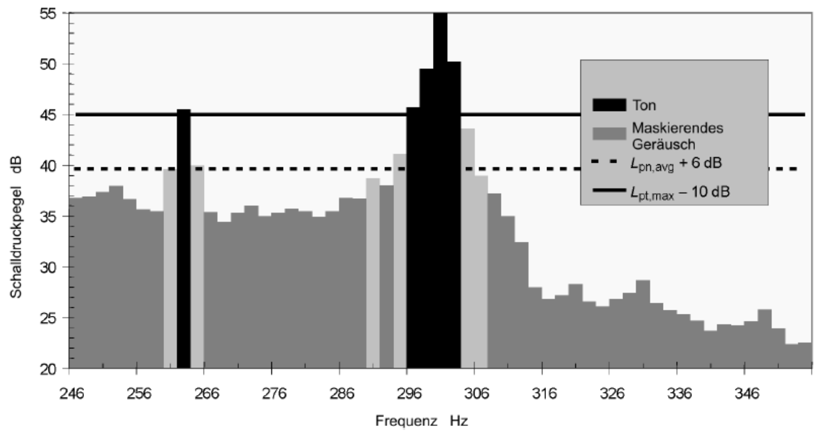

Figure 4: Classification of spectral lines for tone identification. [IEC 61400-11]

- A *potential tone* is identified if the local maximum exceeds the average level of the masking noise within the critical frequency band by at least 6dB.
- The spectral bands are classified into masking bands, neutral bands and tonal bands. The *tonal audibility* is calculated relating the sound pressure levels of the tonal bands to the average levels of the masking bands. After factoring in a frequency dependent perceptibility term (around +2dB for the most common wind turbine tonal frequencies), a *perceivable tone* is declared if the perceived tone level exceeds the masking noise level by 3 dB.

Local regulations may vary, but usually a perceivable tone is accounted for by a noise penalty on the overall turbine noise level when assessing compliance.

Tonal noise perception

The human ear and the cognitive system interpreting sounds is not a neutral receptor. Humans' hearing is adapted to perceive certain frequency ranges better than others, specifically those frequencies related to speeches and whisper. Similarly, humans can focus on particular noise phenomena apparent within a broad background noise, such as impulsiveness, modulation and tones. Perception and annoyance of noise in general are not equivalent to each other, but both correlate to the hearing's sensitivity [Pedersen2004].

Laboratory and field studies have confirmed that a tonal component in a sound spectrum is perceived as more annoying than constant, broadband, or steady noise, even if the overall sound pressure level is maintained constant [Hongisto2018, Landström1994]. Further studies have shown that the working performance of individuals can suffer due to the presence of tonal sounds, even at very low ambient levels [Lee2017]. Psychoacoustic annoyance due to tones is generally correlated to the **frequency** (higher tonal frequencies imply higher annoyance) and the **loudness of the tone**. **Multiple tones** in a spectrum can cause significantly higher annoyance. Frequency impact, loudness as well as multitude of tones are all evaluated and penalized in the guiding international standards. Further research on residential annoyance can help to draft more specific regulations for wind turbines, for example accounting for typical background characteristics and low-frequency tones.

Tonal noise mitigation

Due to the advances made in reducing the aerodynamic blade noise, tonality of wind turbines has become an increasing concern for manufacturers. Because machine borne sound is no longer necessarily hidden behind the curtailed aerodynamic masking noise, wind turbine developers nowadays devote significant resources to identify and mitigate the tonal impact. The challenge for the engineers is the complex combination of variable speed operation, variations in wind conditions, site specific requirements as well as local regulations and residential concerns. This requires an integrated system engineering approach in the concept and design phase of the turbine. High-fidelity numerical models are widely used throughout the engineering pipeline, to capture the essential physics of the acoustic chain:

- **the sources of excitation**
  Possible countermeasures consist of smoothing and mitigation of gear pair forces, minimizing and manipulating electro-magnetic forces in generators, shielding and damping transformers, and others.
- **the mechanisms of vibration transfer**
  Support structure and housing properties need to be adapted, joint and bearing characteristics modified or additional damper elements introduced.
- **noise propagation**
  Numerical tools capture variations in air temperature and density, account for directivity, doppler-effect, etc, helping estimating noise immission levels at residential area.

Subcomponent testing and prototype noise measurements are a crucial step in the product development process in the run-up to certification. The latest wind turbines on the market are now equipped with advanced monitoring systems. Several sensors inside and outside the turbine capture critical vibrations and noise emissions. Concepts for machine learning in combination with virtual sensing are in an infant stage but have the potential to contribute to both tonality-free design and operation of wind turbines in the future.

Summary

Tonality is one specific aspect of wind turbine noise emissions into the environment. The general mechanisms from which it originates are well understood, but it can still be difficult to control. State-of-the-art engineering allows to reduce or damp this type of noise. Nevertheless, in some cases, counter-measure packages are needed to address the problem on site on an individual basis, e.g. when the tonal noise emissions do not comply with the local noise regulations. This is an active field of research, as broadband wind turbine noise emissions have been considerably reduced in the past decade (e.g. with the widespread use of serration), making tonal noise emerging more clearly from the overall wind turbine noise emission.

Acknowledgments

This document was written and reviewed by scientists and engineers working in the field of wind turbine acoustics. In particular, Birger Luhmann has been the main contributor in writing this document.

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