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Aerodynamic Wind Turbine Emissions and Vestibulo-Cochlear Coupling: Impulsive Pressure Signatures and Their Health Relevance

Stephan Kaula, MD

Independent Researcher, Environmental and Sensory Physiology, Germany

dr.kaula@gmail.com

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ABSTRACT

Background: Wind turbine–related airborne emissions are commonly assessed within a classical acoustic framework, extending conventional sound concepts into the infrasonic range. However, increasing empirical observations and physiological reports suggest that this approach insufficiently captures the physical nature and biological relevance of wind turbine exposure.

Objectives: This study aims to provide a physically consistent classification of wind turbine emissions based on their aerodynamic origin and to link these emission forms to plausible physiological interaction pathways. A central objective is to distinguish harmonic acoustic phenomena from non-harmonic, impulse-dominated pressure dynamics and to introduce the concept of wind turbine emission signatures as an integrative descriptor.

Methods and conceptual framework: Wind turbine emissions are analyzed along an aerodynamic–energetic cascade, differentiating four airborne emission forms ranging from flow-bound volume-flow modulation to impulsive, acoustically describable infrasonic pressure signals. The analysis emphasizes time-domain characteristics, energy transfer mechanisms, and the distinction between periodicity and harmonicity. Physiological interaction is examined with particular focus on vestibulo-cochlear coupling and autonomic regulation.

Results: Wind turbine rotor systems generate sequences of discrete aerodynamic events rather than continuous oscillatory sound sources. Periodic repetition of these events produces spectral components that reflect mathematical periodicity, not harmonic sound generation. A substantial fraction of signals commonly measured and reported as wind turbine infrasound consists of impulsive, temporally asymmetric pressure events that retain their non-harmonic character over large distances. These structured pressure impulses form a characteristic wind turbine emission signature. From a physiological perspective, such signals preferentially interact with the vestibulo-cochlear system, which is highly sensitive to low-frequency pressure gradients and fluid displacement, even below auditory perception thresholds.

Conclusions: Framing wind turbine emissions in aerodynamic and vestibular rather than purely acoustic terms resolves several inconsistencies in the existing literature. The concept of wind turbine emission signatures provides a coherent link between emission physics, measurement characteristics, and reported health effects. This framework supports a shift from level-based acoustic metrics toward time- and structure-sensitive assessment approaches in environmental and medical evaluations of wind turbine exposure.

Keywords: wind turbine emissions; wind turbine emission signatures; vestibulo-cochlear coupling; low-frequency pressure fluctuations; impulsive pressure events; non-harmonic infrasound; autonomic regulation; sleep disturbance; sensory physiology; environmental exposure; aerodynamic forcing; time-domain signal structure.

1. Introduction

Wind turbine–related emissions are commonly discussed under the umbrella term *infrasound*, defined acoustically as pressure fluctuations below approximately 20 Hz. Historically, low-frequency phenomena below the threshold of conscious perception or not readily classifiable as sound occupied a largely neglected domain, as long as they did not manifest as distinct audible or otherwise clearly identifiable signals. Consequently, little effort was made to differentiate between fundamentally different low-frequency processes.

When potential health effects associated with wind turbine operation entered scientific and regulatory debate, these heterogeneous phenomena were therefore largely assigned to an established acoustic framework by default. Within this framework, infrasound was interpreted strictly in acoustic terms, despite the fact that low-frequency, repetitive phenomena may arise from diverse physical mechanisms, including flow-induced dynamics, pressure transients, periodically modulated airflow, mechanical vibrations, and structure- or ground-coupled processes. This conceptual narrowing is reinforced by measurement practices and risks conflating distinct physical phenomena through an exclusive reliance on level-based acoustic metrics.

The present work addresses this conceptual limitation by reframing wind turbine emissions from an aerodynamic and time-domain perspective. Rather than treating low-frequency phenomena as variants of acoustic infrasound, it distinguishes harmonic sound from non-harmonic, impulse-dominated and mechanically coupled processes and introduces the concept of *wind turbine emission signatures* as an integrative descriptor of their characteristic temporal structure.

2. Conceptual Framework and Methods

From Harmonic Sound Generation to Aerodynamic Forcing: This work presents a physics-based, conceptual analysis integrating aerodynamic emission theory with established principles of sensory and vestibulo-cochlear physiology. The aim is to provide a physically consistent classification of wind turbine–related airborne emissions and to link their characteristic temporal structures to plausible physiological interaction pathways.

The analysis is based on established aerodynamic principles, time-domain signal characteristics, and published high-resolution measurement studies. No new exposure measurements or experimental data are presented.

2.1 HARMONIC SOUND FROM VIBRATING SURFACES

In classical acoustics, sound is generated by vibrating surfaces that couple their mechanical motion to the surrounding air. Typical examples include loudspeaker membranes or oscillating machine components. Due to the inertia and compressibility of air, the resulting pressure signal is generally smooth, continuous, and largely harmonic. In this context, it is appropriate to describe sound as a propagating wave characterized by a fundamental frequency and its possible overtones.

This reference model implicitly underlies many definitions of infrasound, which interpret low-frequency pressure fluctuations as a direct extension of audible sound into lower frequency ranges.

2.2 AERODYNAMIC EMISSIONS OF WIND TURBINES

Wind turbine rotor systems fundamentally differ from classical acoustic sources. Their rotor blades do not constitute vibrating surfaces in the acoustic sense, capable of sustaining oscillatory radiation, nor do they act as extended radiating membranes; instead, they periodically displace air volumes and generate pressure gradients within the surrounding flow field.

Each blade passage produces a temporally limited, directed aerodynamic event shaped by local flow dynamics, shear forces, and wake interactions.

The primary physical process is therefore not a continuous oscillation but a sequence of discrete aerodynamic events that repeat periodically due to rotor rotation. This distinction is essential for understanding the nature of turbine-related emissions.

To describe the characteristic, recurrent temporal structure of these impulse-dominated pressure signals in a concise and integrative manner, the term *wind turbine emission signatures* is used in this manuscript. This term refers to the reproducible time-domain and spectral features arising from discrete aerodynamic events associated with rotor operation. For brevity, these wind turbine emission signatures are hereafter referred to as WTES.

3. Results: Aerodynamic Wind Turbine Emission Signatures (WTES)

Wind turbine rotor systems do not generate continuous oscillatory sound sources but instead produce sequences of discrete aerodynamic events whose periodic repetition gives rise to impulse-dominated pressure signatures. These airborne emissions emerge from a multi-stage energy cascade involving aerodynamic, flow-mechanical, and acoustic processes.

3.1 PERIODICITY VERSUS HARMONICITY

Periodic repetition of an event does not imply harmonic oscillation. Wind turbine emissions arise from discrete aerodynamic events without an intrinsic oscillation frequency. Although periodic repetition produces discrete spectral components in Fourier representations, these components reflect mathematical periodicity rather than a harmonic generation mechanism.

3.2 IMPULSE-DOMINATED PRESSURE SIGNATURES

Figure 1 illustrates the fundamental difference between impulse-dominated wind turbine emission signatures (WTES) and harmonic sinusoidal signals with identical periodicity.

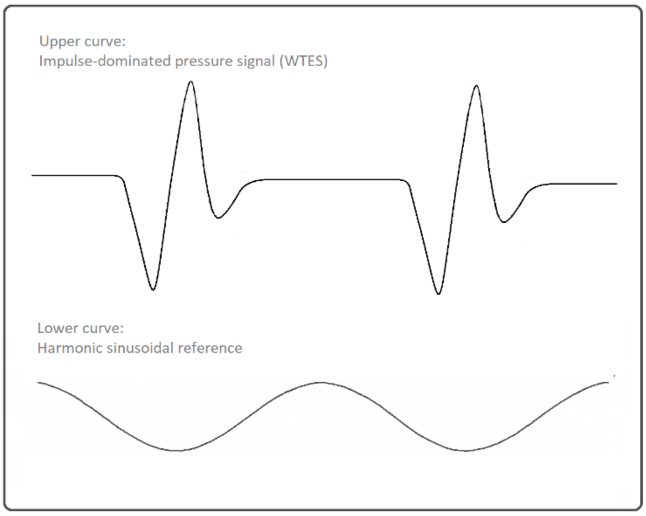

Figure 1. Schematic comparison of an impulse-dominated wind turbine emission signature (WTES) and a harmonic sinusoidal signal with identical periodicity. Vertical scales are schematic and not intended for amplitude comparison.

3.3 ENERGY CASCADE AND DIFFERENTIATION OF AIRBORNE EMISSION FORMS

Airborne emissions from wind turbines emerge from a multi-stage energy cascade involving aerodynamic, flow-mechanical, and acoustic processes. For analytical clarity, four airborne emission forms can be distinguished along this cascade. These categories do not imply strict separation in real-world exposure but serve to structure the underlying physical processes and their resulting wind turbine emission signatures (WTES).

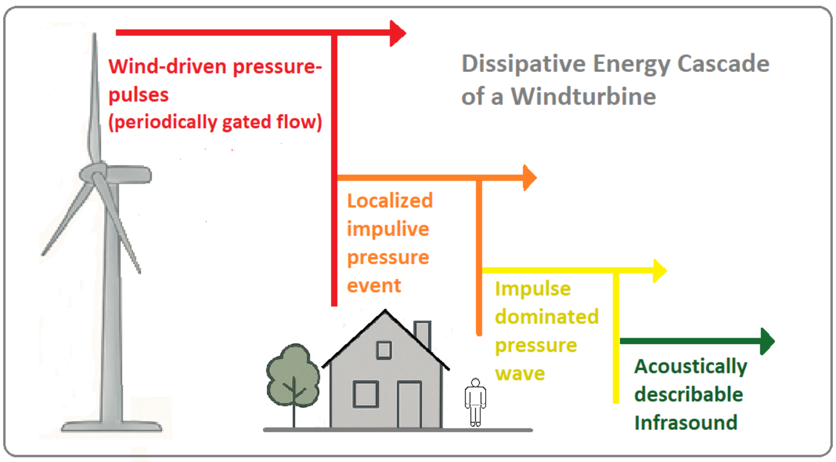

Figure 2. Conceptual illustration of the dissipative energy cascade of wind turbine emissions, showing successive airborne emission forms and transformation pathways from flow-bound dynamics to impulse-dominated pressure signals.

Emission 1: Primary aerodynamically gated volume -flow emission

The causal origin lies in rotor-induced modulation of the incoming wind. Rotor blades act as temporal modulators of an otherwise continuous flow, producing a periodically gated wind. This emission is flow-bound, non-acoustic, and propagates predominantly advectively with wind speed along the rotor wake, rather than radiating isotropically as an acoustic field.

Transition: pressure-difference neutralization by interaction When this gated flow interacts with obstacles or structures that disrupt the local flow field—such as the turbine tower itself or house-roofs within the rotor wake—flow-bound energy can be locally decelerated and converted into alternating compression and decompression work. This process reflects the interaction of windward stagnation overpressure, leeward stagnation underpressure, and dynamic pressure variations generated at the rotor blade upwind profile. The resulting pressure-difference neutralization marks a transition from advectively transported flow phenomena toward pressure-dominated dynamics.

Emission 2: Initial impulsive, volume-flow–driven pressure transients

At locations where the aerodynamically gated volume flow is abruptly decelerated or redirected, localized pressure transients arise from rapid volume-flow neutralization. These events remain closely coupled to the underlying flow field and represent short, highly impulsive pressure responses characterized by steep gradients and pronounced temporal asymmetry. They differ fundamentally from harmonic sound waves and resemble asymmetric, soft implosion-type pressure transients arising from localized energy conversion.

Emission 3: Transition to propagating, acoustically describable impulsive infrasound

With increasing distance and dissipation, these initially flow-bound pressure transients detach from the local volume-flow field and evolve into propagating pressure impulses. At this stage, the signals can be described within a classical acoustic framework in terms of sound pressure and frequency, although they remain strongly impulse-dominated and non-harmonic.

Emission 4: Dissipation, spectral transformation, and observational effects

With further propagation, high-gradient signal components are progressively attenuated, leading to temporal smoothing and frequency-dependent attenuation, resulting in a relative dominance of lower-frequency spectral components. Even at distances of several tens of kilometers, however, the impulse character often remains evident in the number and relative strength of spectral components.

3.4 CHARACTERISTICS OF WIND TURBINE EMISSION SIGNATURES (WTES)

Wind turbine emission signatures (WTES) are characterized by a predominantly non-harmonic, impulse-dominated temporal structure. In the time domain, they consist of asymmetric pressure events reflecting discrete aerodynamic and flow-coupled processes rather than continuous oscillatory sound generation. Their spectral appearance arises from the periodic repetition of these discrete events and does not imply harmonic oscillation.

Accordingly, wind turbine emission signatures are more appropriately described as sequences of temporally structured pressure impulses than as stationary acoustic waves. In real-world exposure scenarios, individuals may be simultaneously or intermittently exposed to multiple emission forms along this cascade, depending on distance, meteorological conditions, and site-specific propagation characteristics.

4. Discussion

The following discussion places the identified wind turbine emission signatures within the context of existing emission studies and examines their potential physiological relevance, with particular focus on vestibulo-cochlear and autonomic coupling.

4.1 RELATION TO ESTABLISHED EMISSION STUDIES

Large-scale interdisciplinary investigations have addressed wind turbine emissions with high temporal and spectral resolution. The German TremAc project provided detailed analyses of aerodynamic and structural emission components of modern wind turbines. Time-resolved measurements and simulations identified impulsive, blade-passage–related pressure fluctuations and their interaction with tower structures as dominant contributors to low-frequency emission patterns, particularly at the blade passage frequency and its harmonics[2,3].

While TremAc offered a comprehensive characterization of emission sources and propagation within an acoustic and engineering framework, potential physiological interaction mechanisms of temporally structured, sub-auditory pressure stimuli were not examined beyond questionnaire-based assessments. The present work builds upon these physical observations by addressing the physiological relevance of impulse-dominated wind turbine emission signatures (WTES), with particular focus on vestibulo-cochlear and autonomic pathways.

Site-specific aerodynamic and propagation effects—including wake dynamics, superposition, interference, and boundary interactions—can produce pronounced spatial variability of wind turbine emission signatures, resulting in localized exposure maxima at individual structures while nearby locations experience substantially lower levels[4].

Complementary to large-scale institutional investigations, independent high-resolution field studies have documented the temporal structure and functional relevance of low-frequency wind turbine emissions under real-world exposure conditions. In an independent acoustic case study, Ambrose, Rand and Krogh reported dynamically modulated low-frequency and infrasonic pressure fluctuations associated with blade-passage events, including pronounced amplitude modulation and impulsive pressure sequences detectable below auditory perception thresholds. Adverse effects, including sleep disturbance, were observed at indoor A-weighted sound levels well below commonly applied guideline values, while unweighted and infrasonic-weighted measures showed marked temporal variability and indoor amplification[5]. The authors did not propose a specific physiological mechanism.

Functional neuroimaging studies provide independent evidence that near-threshold infrasonic stimulation can elicit measurable central nervous system responses, even in the absence of conscious auditory perception[6]. These effects were more pronounced under near-threshold than supra-threshold stimulation, suggesting a distinct sub-perceptual processing pathway. Although the applied stimulus was a stationary sinusoidal tone rather than an aerodynamic pressure signature, these findings support the physiological plausibility that temporally structured, low-frequency pressure stimuli can engage vestibulo-cochlear and autonomic pathways without conscious perception.

4.2 VESTIBULO-COCHLEAR COUPLING AS THE PRIMARY PHYSIOLOGICAL PATHWAY

Among the possible biological interfaces for low-frequency and pulsatile pressure exposure, the vestibulo-cochlear system represents the most plausible and physiologically well-established transmission pathway. Within this framework, impulse-dominated signals may elicit transient sensory responses at amplitudes for which slowly varying harmonic signals of comparable magnitude remain physiologically ineffective. This principle is illustrated schematically in Figure 3.

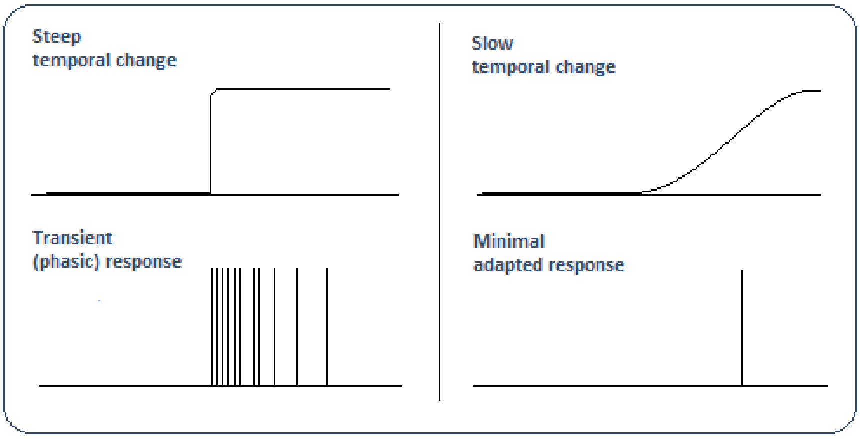

Figure 3. Schematic illustration of sensory adaptation and preferential encoding of temporal change. Steep stimulus transitions evoke transient responses, whereas slowly varying stimuli elicit minimal or adapted responses.

In audible-noise assessment, impulsive and tonal characteristics are routinely treated as additional descriptors beyond level-based metrics, reflecting the well-established fact that signal microstructure can be perceptually and biologically relevant even at comparable LAeq[7–9]. This principle provides a useful analogy for understanding the potential relevance of temporally structured, low-frequency pressure stimuli.

Unlike other mechanosensitive structures, the vestibular system is specifically designed to detect slow pressure changes, acceleration, and fluid displacement, and it maintains continuous, largely non-conscious interaction with the central nervous system.

The vestibular organs and the cochlea form a functional unit within the bony labyrinth and share the same fluid compartments (endolymph and perilymph). Pressure fluctuations acting on the middle and inner ear are therefore not selectively confined to auditory perception, but inevitably affect vestibular hair cells and their afferent pathways.

Sub-perceptual stimulation and autonomic coupling

Low-frequency and infrasonic pressure variations, particularly when pulsatile and repetitive, can induce subtle endolymphatic motion and cupula deflection without generating conscious auditory perception. Such stimulation preferentially activates otolithic and vestibular pathways, which are highly sensitive to low-frequency acceleration and pressure gradients. Importantly, vestibular activation does not require conscious perception; even sub-threshold stimulation can elicit reflexive and autonomic responses mediated via brainstem nuclei and their projections to hypothalamic and autonomic regulatory centers.

Functional manifestations of vestibulo-cochlear activation

This mechanism offers a coherent framework for understanding frequently reported, non-specific functional complaints such as inner restlessness, impaired concentration, sleep disturbance, or a diffuse sense of disequilibrium. Such manifestations are often difficult to verbalize and are poorly captured by standard acoustic assessment metrics.

Within this context, the relevant interaction is not determined by isolated sound pressure levels, but by the temporal structure and repetition of wind turbine emission signatures (WTES). These signatures act as structured mechanical stimuli rather than classical acoustic waves, providing a physiologically plausible link between aerodynamic emission processes and biological response. While other mechanosensitive pathways may contribute marginally, current physiological knowledge supports the vestibulo-cochlear interface as the dominant coupling mechanism for airborne low-frequency pressure emissions associated with wind turbine emission signatures (WTES).

4.3 Physiological relevance during periods of rest and sleep

Sleep disturbance represents a functional manifestation consistent with vestibulo-cochlear and autonomic activation and is among the most sensitive and consistently reported outcomes of low-level environmental exposure. Periods of rest and sleep are physiological states in which the relevance of low-level vestibular and autonomic stimulation is increased, as sensory masking by environmental noise and voluntary motor activity is reduced, while autonomic regulation shifts toward parasympathetic dominance. Under these conditions, even sub-perceptual pressure fluctuations may gain functional significance[10].

Vestibular activation does not require conscious awareness and can elicit reflexive responses via brainstem nuclei and their projections to hypothalamic and autonomic control centers. Repetitive, temporally structured pressure impulses, such as those characteristic of wind turbine emission signatures (WTES), may therefore interfere with sleep continuity without producing an explicit auditory sensation[11].

From a physiological perspective, sleep disturbance can be interpreted more coherently as a manifestation of vestibulo-cochlear and autonomic activation rather than classical auditory perception. Reported symptoms such as difficulties initiating or maintaining sleep, nocturnal arousals, or non-restorative sleep can be understood within this framework without invoking conscious sound perception or psychological attribution.

This interpretation aligns sleep disturbance with other frequently reported, non-specific functional complaints and situates them within a common mechanism of low-frequency, impulse-dominated mechanical stimulation acting on sensitive regulatory systems during vulnerable physiological states.

4.4 Integrative perspective

Framing the interaction in vestibular rather than purely acoustic terms helps to resolve several apparent contradictions in the existing literature and aligns reported health-related observations with established principles of sensory physiology and autonomic regulation.

5. Conclusion

This work introduces a physically consistent, aerodynamic classification of wind turbine–related airborne emissions and the concept of wind turbine emission signatures as an integrative descriptor of their characteristic temporal structure. By distinguishing impulse-dominated, non-harmonic pressure dynamics from classical acoustic sound generation, the proposed framework provides a coherent interpretation of wind turbine emissions beyond conventional acoustic concepts.

Framing wind turbine emissions in vestibular and autonomic rather than purely acoustic terms offers a plausible explanation for reported health-related observations that are not adequately captured by level-based acoustic metrics alone. The concept of wind turbine emission signatures supports a shift toward time- and structure-sensitive assessment approaches and may inform future measurement strategies, exposure evaluation, and interdisciplinary research on the environmental and health relevance of wind turbine emissions.

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