

Wind turbine noise: A review of measurement, modelling, and mitigation strategies

Abstract

This review provides a structured and comprehensive analysis of wind turbine noise, covering the full chain from sound generation to measurement, modeling, and mitigation. Aerodynamic and mechanical noise sources are examined alongside their spectral and temporal characteristics and their implications for human perception. Standardized acoustic metrics and measurement procedures, including IEC 61400-11 and ISO 9613-2, are discussed in the context of field and wind-tunnel methodologies. The paper further reviews experimental and computational approaches, including semi-empirical models and high-fidelity simulations based on computational fluid dynamics (CFD) and computational aeroacoustics (CAA), highlighting their capabilities and limitations for noise prediction. Existing mitigation strategies are analyzed, with emphasis on passive solutions such as aerodynamic blade modifications, porous materials, and vibration-damping systems. Despite significant progress, current approaches remain predominantly passive and often involve trade-offs with aerodynamic performance. A critical gap is identified in the limited development of active noise mitigation strategies, particularly for small and micro wind turbines operating in proximity to residential environments. While active control systems are widely used for power optimization, their application to aeroacoustic noise reduction remains

largely unexplored. This review highlights the need for integrated methodologies combining measurement, modeling, and control, and outlines future directions toward adaptive, multidisciplinary solutions aimed at improving acoustic performance, social acceptance, and sustainable deployment of wind energy systems.

Keywords: Wind turbine noise, Acoustic impact, Noise mitigation, Noise measurement, Acoustic metrics

Nomenclature

AM	Amplitude Modulation
ANN	Artificial Neural Network
CAA	Computational Aeroacoustics
CFD	Computational Fluid Dynamics
DDES	Delayed Detached-Eddy Simulation
DNS	Direct Numerical Simulation
FWH	Ffowcs Williams–Hall
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LES	Large Eddy Simulation
MBS	Multi-body Simulation

OAM	Other Amplitude Modulation
RANS	Reynolds-Averaged Navier Stokes
PWL	Sound power level
SPL	Sound pressure level
SST	Shear Stress Transport
SVR	Support Vector Regression
TBL-TE	Turbulent-boundary-layer Trailing Edge
TLCD	Tuned Liquid Column Damper
TMD	Tuned Mass Damper
URANS	Unsteady Reynolds-Averaged Navier-Stokes
WHO	World Health Organization
WTs	Wind turbines
L_{Aeq}	A-weighted equivalent continuous sound pressure level
L_{Beq}	B-weighted equivalent continuous sound pressure level
L_{Ceq}	C-weighted equivalent continuous sound pressure level
L_{Geq}	G-weighted equivalent continuous sound pressure level
L_{Zeq}	Z-weighted equivalent continuous sound pressure level
L_{min}	Minimum sound level reached

L_{eq} Equivalent continuous sound pressure level

L_{max} Maximum sound level reached

1. Introduction

Wind energy is a low-emission renewable source with the potential to complement or replace fossil-based energy systems. It exhibits one of the lowest carbon footprints in the energy sector, with kgCO₂/kWh values even lower than those of solar energy [1]. Its rapid consolidation within the global energy transition is reflected in an installed capacity of 1,174 GW in 2024 [2], as shown in Fig. 1. This sustained growth highlights the increasing need to diversify the energy mix and reduce greenhouse gas emissions through both large-scale wind farms and distributed generation systems closer to consumption centers.

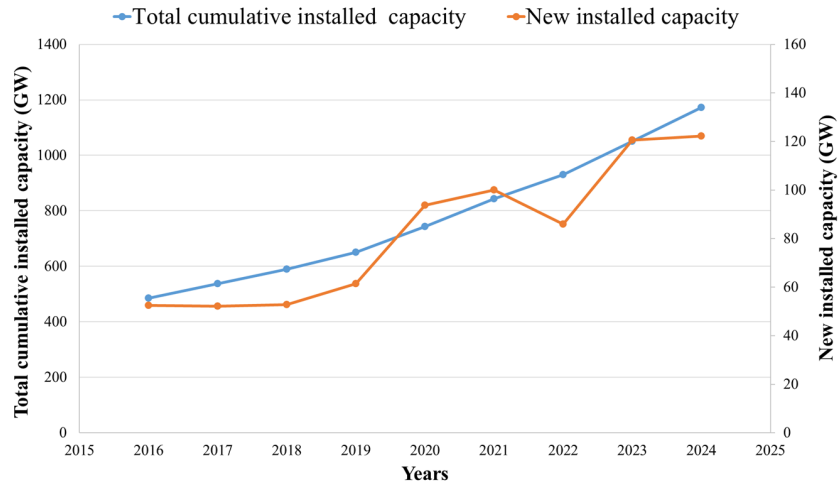


Figure 1: Progress in worldwide installed wind energy capacity since 2016 [2].

The increasing population and urbanization have led to the construction

12 of residential areas with high energy demand, encouraging the installation
13 of wind turbines (WTs) near human settlements [3] and their integration
14 into self-generation systems in single-family houses [4] and marine vessels
15 [5]. However, this proximity has revealed one of the main drawbacks of
16 wind power: aerodynamic and mechanical noise emissions, which can affect
17 nearby residents' quality of life [6], limit social acceptance [7], and hinder the
18 deployment of new projects [8]. Therefore, assessing and mitigating noise
19 levels prior to turbine installation is essential [9].

20 Several studies have addressed wind turbine noise from different perspec-
21 tives. Doolan et al. [10] provided a systematic review of experimental and
22 numerical investigations on trailing-edge noise, while Saavedra & Samanta
23 [11] examined noise and vibration sources, their effects, and relevant interna-
24 tional regulations. Xu et al. [12] analyzed vibration and noise in drivetrain
25 systems, emphasizing the importance of mechanical contributions.

26 Another major research line concerns noise mitigation strategies. Ahmed
27 et al. [13] and Doolan [14] identify passive methods as the predominant ap-
28 proach, particularly through aerodynamic modifications that alter boundary-
29 layer behavior and reduce turbulent fluctuations near the trailing edge. Ac-
30 tive methods, such as Active Noise Control (ANC) [13] and blade-rotation
31 coordination [14], have also been explored, although to a much lesser extent.

32 Despite these advances, the literature remains fragmented, often address-
33 ing noise generation, measurement, modeling, and mitigation separately. In
34 addition, limited attention has been given to small wind turbines, which
35 are typically installed closer to populated areas and are subject to stricter
36 acoustic constraints.

37 In general, existing studies underline the multidisciplinary nature of wind
38 turbine noise, involving aerodynamic, structural, acoustic, and perceptual as-
39 pects, and highlight the need for integrated reviews that consolidate advances
40 across these domains.

41 This paper focuses exclusively on acoustic noise generated by wind tur-
42 bines, specifically aerodynamic and mechanical sources, while excluding elec-
43 trical noise due to its comparatively minor contribution [15, 16]. The review
44 covers noise generation mechanisms, spectral and temporal characterization,
45 and key acoustic metrics, as well as their relationship with human perception
46 and annoyance. Furthermore, it analyzes experimental and computational
47 measurement techniques—including standardized procedures, semi-empirical
48 models, and numerical simulations—and evaluates current mitigation strate-
49 gies based on aerodynamic design and mechanical isolation.

50 The aim of this work is to provide a structured and comprehensive synthe-
51 sis of the current state of knowledge, identify key limitations, and highlight
52 research opportunities, particularly in the application of active control meth-
53 ods for noise reduction.

54 Unlike existing review studies, which typically address isolated aspects
55 such as noise generation mechanisms [17], numerical modeling, or mitiga-
56 tion strategies [18], this work integrates these perspectives within a unified
57 framework. In particular, it establishes connections between aerodynamic
58 phenomena, acoustic emissions, and engineering design considerations, offer-
59 ing a cross-disciplinary perspective that is often lacking in the literature.

60 Furthermore, this review provides an updated and critical assessment of
61 recent advances, including emerging approaches such as biomimetic blade

62 design and hybrid computational methods, thereby enhancing its relevance
63 for current research. By consolidating dispersed knowledge and identifying
64 key research gaps, this work aims to serve as a valuable reference for both
65 researchers and engineers involved in wind turbine design, noise prediction,
66 and mitigation.

67 The paper is structured as follows: Section 2 describes the characteri-
68 zation of wind turbine noise, including its sources, underlying mechanisms,
69 and relevant acoustic metrics. Section 3 examines the impact of wind turbine
70 noise on humans, covering perception, potential health effects, and implica-
71 tions for regulation and social acceptance. Section 4 presents experimental
72 and numerical methods for noise measurement and simulation, together with
73 an overview of the international regulatory framework. Section 5 analyzes
74 noise mitigation strategies, with a focus on aerodynamic design and acoustic
75 control approaches. Section 6 discusses the main research gaps and out-
76 lines future directions in the field. Finally, Section 7 summarizes the main
77 conclusions of this review.

78 **2. Characterization of wind turbine noise**

79 Characterizing wind turbine noise enables assessment of environmental
80 and social impact, especially in communities near wind farms [19]. This sec-
81 tion first addresses noise generation (mechanical and aerodynamic sources),
82 then radiation patterns and propagation by source directivity, followed by
83 acoustic classification (by origin and physical traits). Finally, it presents key
84 metrics quantifying intensity, frequency content, and perception, providing a
85 technical basis for analysis and mitigation.

86 2.1. Noise generation mechanisms

87 Sound is a pressure disturbance that propagates through an elastic medium
88 as a longitudinal wave and is perceived by the human auditory system [20].
89 Noise, i.e., unwanted sound, is a major environmental concern for wind en-
90 ergy.

91 In wind turbines (WTs), noise arises from multiple physical processes
92 associated with the operation of mechanical components and the interaction
93 between airflow and turbine blades. These processes generate sound over
94 a broad frequency range, including both tonal and broadband components,
95 which contribute differently to overall noise perception.

96 Accordingly, wind turbine noise is commonly classified into two main
97 categories: *mechanical* and *aerodynamic* sources. The relative contribution
98 of each depends on turbine design and operating conditions, making wind
99 turbine acoustics intrinsically complex.

100 2.1.1. Mechanical noise

101 Mechanical noise primarily originates from drivetrain components (gear-
102 box, couplings, bearings, generator), braking, and yaw systems. Vibrations
103 from moving parts transmit through the nacelle and tower [21] and may be
104 amplified by structural resonance. Although typically smaller than aerody-
105 namic noise, mechanical emissions can be significant depending on design
106 and operating conditions. Noise magnitude depends on maintenance, cou-
107 pling design, and material quality. Gear defects, bearing imbalances, or other
108 faults substantially increase vibration transmission [22], while generator cool-
109 ing and ventilation can add steady background noise. While these effects
110 are often studied in large-scale wind turbines, similar mechanisms apply to

111 smaller systems. In the case of microturbines installed on building rooftops,
112 structure-borne vibrations transmitted to the building can become one of
113 the main sources of annoyance for occupants, often exceeding the impact of
114 aerodynamic noise [9].

115 2.1.2. Aerodynamic noise

116 The acoustic emission of WTs is primarily aerodynamic in origin, arising
117 from air-blade interaction during rotation. These aeroacoustic mechanisms
118 are distributed along the blade profile and depend on flow conditions as well
119 as the blade surface state. Inflow turbulence at the leading edge induces
120 pressure fluctuations that radiate as sound, predominantly at low frequen-
121 cies and potentially including infrasonic components [23]. At high angles of
122 attack, flow separation generates turbulent structures that produce irregular
123 broadband noise. Under laminar conditions, periodic vortex shedding within
124 the boundary layer gives rise to tonal components [24].

125 As the boundary layer transitions to turbulence, its interaction with the
126 sharp trailing edge becomes a dominant broadband noise source, typically
127 within the range of approximately 250 to 1000 Hz and characterized by
128 a cardioid radiation pattern. Surface degradation or trailing-edge blunt-
129 ness further increases shedding instability, thereby enhancing acoustic ra-
130 diation. Additionally, tip vortex formation contributes to noise generation,
131 although at a comparatively lower magnitude [25]. Impulsive noise, associ-
132 ated with pronounced amplitude modulation (“thumping”), may occur under
133 certain conditions and is particularly perceptible and disturbing. Overall,
134 the trailing-edge and blade-tip regions dominate acoustic radiation under
135 normal operating conditions, while wind speed, angle of attack, and surface

roughness are key parameters governing noise intensity.

The Figure 2 summarizes the main aeroacoustic sources distributed along the blade, highlighting how different flow regimes and geometric features contribute to distinct noise generation mechanisms. In particular, it illustrates the spatial localization of leading-edge, trailing-edge, and tip-related sources, as well as their dependence on boundary layer behavior and vortex dynamics. This distribution explains why trailing-edge noise is typically dominant, while other mechanisms contribute under specific operating conditions.

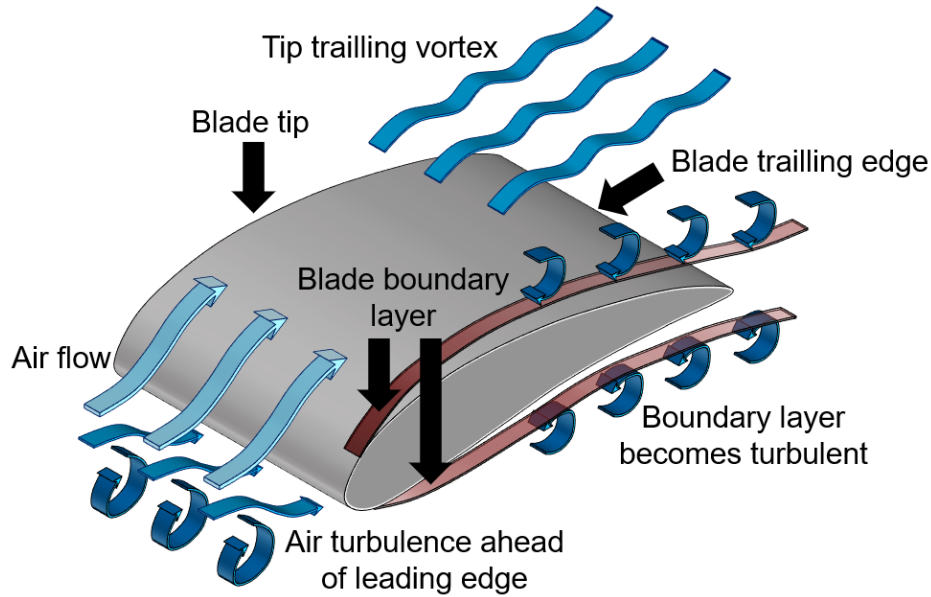


Figure 2: Aerodynamic noise sources along a wind turbine blade, adapted from [26].

Finally, the interaction between the rotating blades and the tower should also be considered within this group of aerodynamic sources, as it generates a periodic noise component associated with blade passing events. This blade–

148 tower interaction produces fluctuations in the local flow field and pressure
149 distribution, leading to amplitude-modulated sound that can enhance the
150 characteristic “swishing” or “thumping” perceived in wind turbine noise.

151 *2.2. Noise radiation and propagation*

152 Following the identification of the main noise generation mechanisms, it
153 is necessary to analyze how acoustic energy is radiated from the source and
154 subsequently propagates through the environment. These two aspects involve
155 different physical processes: while radiation is governed by the nature of the
156 source and its interaction with the surrounding flow, propagation depends on
157 atmospheric conditions, terrain characteristics, and distance from the source.

158 In wind turbines, both processes play a crucial role in determining the
159 spatial distribution and perceived levels of noise. The following subsections
160 therefore distinguish between source radiation mechanisms, which define the
161 directionality and strength of acoustic emission, and propagation effects,
162 which control how sound is transmitted and modified before reaching the
163 receiver.

164 *2.2.1. Source radiation patterns*

165 The acoustic radiation of wind turbine noise sources can be described us-
166 ing simplified source models based on their directivity and underlying physi-
167 cal mechanisms. In aeroacoustics, sound generation is commonly represented
168 in terms of equivalent *monopole*, *dipole*, and *quadrupole* sources [27, 28],
169 which provide a conceptual framework for interpreting radiation patterns
170 rather than a direct description of propagation.

171 A *monopole* source radiates sound uniformly in all directions and is typ-
172 ically associated with mass fluctuations. A *dipole* source, formed by two
173 out-of-phase *monopoles*, exhibits directional radiation and is linked to un-
174 steady forces acting on solid surfaces. *Quadrupole* sources, composed of two
175 opposing dipoles, are associated with turbulence-induced stress fluctuations
176 within the flow. These idealized source types are widely used to describe the
177 directionality and scaling of aerodynamic noise [14].

178 In wind turbines, aerodynamic noise is predominantly *dipolar* in na-
179 ture [29], as it originates from unsteady pressure loads acting on the blade
180 surfaces. Two primary mechanisms can be identified: leading-edge noise,
181 generated by the interaction between incoming atmospheric turbulence and
182 the blade, and trailing-edge noise, produced by the scattering of turbulent
183 boundary-layer fluctuations at the sharp trailing edge. The latter is gener-
184 ally considered the dominant broadband noise source in horizontal-axis wind
185 turbines.

186 Additional sources such as blade–tower interaction noise, tip-vortex noise,
187 and tonal components associated with periodic flow phenomena may also
188 contribute to the overall acoustic signature, although their impact is generally
189 more case-dependent.

190 *Quadrupole* sources, associated with turbulence within the flow field, typ-
191 ically contribute less to the overall acoustic emission of wind turbines due
192 to their lower radiation efficiency compared to dipole sources [30]. Conse-
193 quently, their impact is typically secondary in aeroacoustic analyses, where
194 surface-generated dipole noise remains dominant.

195 2.2.2. *Sound propagation and environmental effects*

196 Once generated, turbine noise propagates through the atmosphere, mod-
197 ified by environmental conditions, geometric spreading, and ground inter-
198 action [31, 32]. Atmospheric absorption attenuates high frequencies due to
199 molecular relaxation processes [33], while geometric spreading reduces sound
200 levels with distance, following spherical or cylindrical divergence depending
201 on source configuration.

202 Atmospheric stratification and wind gradients bend sound waves, enhanc-
203 ing or reducing levels at the receiver [31, 34]. Downwind or stable conditions
204 tend to increase noise exposure, whereas upwind or convective conditions
205 decrease perceived levels. Turbulence and obstacles introduce scattering,
206 further modifying local SPL and spectral content [35].

207 Ground properties strongly influence propagation. Direct and reflected
208 waves interfere according to surface impedance [36]. Porous or soft surfaces
209 enhance attenuation, while hard, reflective surfaces amplify levels. Standard
210 engineering models, such as ISO 9613-2 [37], account for atmospheric absorp-
211 tion, ground effects, and meteorology, providing practical SPL predictions
212 but not fully capturing complex wake and refraction phenomena.

213 High-fidelity studies illustrate these limitations. Sun et al. [38] sim-
214 ulated a 10 MW turbine with large-eddy simulations for rotor, tower, and
215 nacelle wakes, combined with a wide-angle Parabolic Equation solver. Wake-
216 induced velocity gradients and asymmetric refraction amplify near-ground
217 noise, while upward atmospheric bending reduces exposure. Standard PE or
218 ISO 9613-2 predictions can underestimate SPL by up to 5 dB at 500–1000 m,
219 highlighting the need to integrate wake and atmospheric effects for accurate

220 assessment and farm layout optimization.

221 2.3. Acoustic classification of wind turbine noise

222 Wind turbine noise exhibits complex features depending on frequency
223 distribution and time-based behavior [39]. Considering both domains yields
224 a complete description that links measurable physics with perception.

225 2.3.1. Spectral classification

226 Wind turbine noise spans *infrasound*, *low*, *mid*, and *high* frequencies [40],
227 each possibly *tonal* or *broadband*. Infrasound (0.1–20 Hz) arises mainly from
228 airflow leaving the blades and interacting with the tower; it is weak and of
229 low audibility, even nearby, and poses no significant acoustic risk [41, 42].
230 Low-frequency noise (20–200 Hz), perceived more as vibration, is associated
231 with mechanical components and local flow disturbances near the tower [43,
232 44] and can propagate long distances. Mid (200–1000 Hz) and high (1–
233 16 kHz) frequencies relate to structural resonances, mechanical vibrations,
234 and aerodynamic turbulence.

235 *Tonal* noise yields discrete spectral peaks from rotating components (gear-
236 box, generator, cooling fans), mechanical imbalance, or small aerodynamic
237 instabilities [45]. *Broadband* noise is continuous, mainly due to turbulent
238 inflow, trailing-edge interactions, vortex shedding, and flow separation [46].

239 2.3.2. Time-based classification

240 The time-based classification of noise generated by WTs focuses on how
241 acoustic emissions vary according to operating conditions and wind charac-
242 teristics.

- 243 • Continuous noise from WTs originates mainly from the constant ro-
244 tation of the blades and internal mechanical operation, such as the
245 gearbox and generator. It is perceived as a steady hum or murmur
246 whose intensity varies with wind speed. Its constant nature makes it
247 easier to distinguish from other environmental noises.
- 248 • Intermittent or impulsive noise arises from sudden variations in aero-
249 dynamic loading (blade interaction with the disturbed airflow around
250 the tower) [47], wind gusts (when the turbine is misaligned during
251 changes in wind direction), or specific mechanical events. These are
252 short acoustic impulses or dull sounds whose amplitude fluctuates over
253 time.
- 254 • The Amplitude Modulation (AM) of wind turbine noise is a phenomenon
255 that produces periodic fluctuations in sound intensity (slowly changing
256 its amplitude over time), increasing the perceived annoyance [11, 48].
257 The “swish” or “thump” sounds heard near wind farms are the result
258 of AM. This is considered the most annoying aspect of wind turbine
259 noise for residents living near such installations.

260 The spectral and temporal classification presented above is complemented
261 by a spatial characterization of noise sources in the wind turbine. As illus-
262 trated in Fig. 3, acoustic emissions are distributed across different compo-
263 nents, with a dominant contribution from aerodynamic interactions along the
264 blades and mechanical sources within the nacelle. In particular, turbulent
265 trailing-edge noise and blade-tip noise are primarily associated with mid- to
266 high-frequency ranges, whereas phenomena such as blade-tower interaction

and airflow in the near-field region contribute to low-frequency and infrasonic components.

Furthermore, the figure highlights how specific mechanisms, such as yaw operation and the periodic passage of the blades in front of the tower, introduce amplitude modulation, thereby reinforcing the non-stationary nature of the noise. This representation enables a direct correlation between frequency bands and the underlying physical mechanisms, facilitating an integrated interpretation of the spectral and temporal classifications.

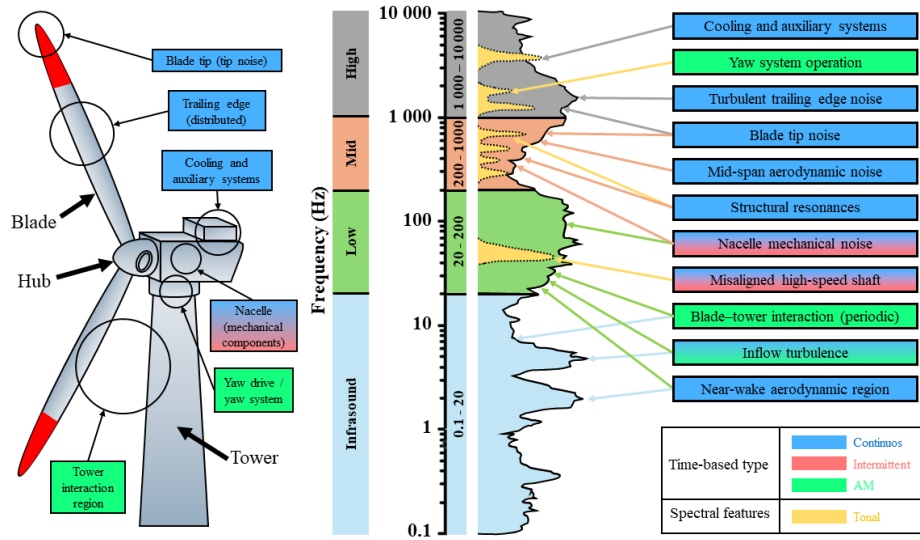


Figure 3: Distribution of the main noise sources in a wind turbine as a function of frequency and their temporal behavior.

2.4. Key acoustic metrics

Assessing wind turbine noise requires metrics that quantify magnitude, spectral content, and time-based variability. Basic levels provide global intensity; frequency weightings adjust for human sensitivity; spectral analy-

sis identifies dominant bands; time-based metrics capture variability. Together, these enable comprehensive characterization, objective comparison across studies [49], and compliance assessment [50].

2.4.1. Basic measurement levels

Human hearing typically spans 20 Hz to 20 kHz, with upper limits decreasing with age (presbycusis). *Sound power* is total acoustic energy emitted per unit time (W), distance-independent; *sound pressure* is the local pressure fluctuation (Pa) at a point.

In practice, Sound power level (PWL) and SPL are expressed in decibels (dB) to match the wide dynamic range of hearing [51]:

$$\text{PWL} = 10 \log_{10} \left(\frac{P}{P_0} \right) \quad (1)$$

$$\text{SPL} = 20 \log_{10} \left(\frac{p}{p_0} \right) \quad (2)$$

where $P_0 = 10^{-12}$ W and $p_0 = 2 \times 10^{-5}$ Pa.

2.4.2. Acoustic weightings

Equal-loudness contours, also known as isophonic curves, represent the human ear's perception of different frequencies when the perceived SPL is kept constant. These contours are expressed in phons, a psychoacoustic unit that quantifies loudness relative to a 1 kHz pure tone as a reference. These curves show that auditory sensitivity is not uniform across the entire frequency spectrum, but varies depending on the listening level.

From these curves, the International Electrotechnical Commission (IEC) defined the A, B, and C weightings, which simulate human sound perception across different ranges: low, medium, and high SPL, respectively [52]. These

weightings are applied in measurement instruments such as sound level meters, allowing sound pressure readings to more accurately reflect how people perceive noise, in accordance with IEC 61672-1 [53].

The A-weighted equivalent continuous sound pressure level (L_{Aeq}) corresponds approximately to the 40-phon equal-loudness contour and applies to the human ear’s response to low to medium sound levels. It is the current acoustic standard for sound and noise measurements. The B-weighted equivalent continuous sound pressure level (L_{Beq}) corresponds approximately to the 70-phon contour and applies to medium sound levels. The C-weighted equivalent continuous sound pressure level (L_{Ceq}) corresponds approximately to the 100-phon contour and applies to relatively high sound levels. For all these reasons, L_{Aeq} and L_{Ceq} are the most commonly used when performing measurements related to wind turbine noise [54, 55]. In addition to these, other weightings exist, such as G-weighted equivalent continuous sound pressure level (L_{Geq}), used for infrasound applications (below 20 Hz), and Z-weighted equivalent continuous sound pressure level (L_{Zeq}), which applies when no frequency weighting is used.

2.4.3. Temporal metrics

The equivalent continuous sound pressure level (L_{eq}) is one of the most relevant metrics in wind turbine noise studies, as it integrates the variable acoustic energy over a given period into a single value, widely used in regulations [56, 43]. Unlike instantaneous measurements, L_{eq} captures natural fluctuations in noise caused by blade rotation and atmospheric conditions, providing a representative measure of overall sound impact. It enables comparison between studies and supports consistent regulatory assessment of

community exposure over extended periods (e.g., daily, seasonal, or annual timescales), reflecting cumulative acoustic energy.

Complementarily, maximum sound level reached (L_{max}) and minimum sound level reached (L_{min}) describe the dynamic range of wind noise. L_{max} identifies sound peaks that may cause immediate annoyance or attract attention [57], while L_{min} indicates moments of minimal emission, useful for assessing acoustic variability. In WTs, where noise is intermittent and modulated by blade passage, these metrics complement L_{eq} , enabling a more comprehensive noise characterization that includes both average energy and extreme variations.

Acoustic percentiles (e.g., L_{10} , L_{50} , L_{90}) describe the sound pressure level exceeded during a specific percentage of the measurement time [58, 59]. L_{90} is typically associated with stable background noise, while L_{10} represents higher-intensity events [60]. In wind turbine applications, these indicators help distinguish between steady environmental noise and fluctuating turbine noise. Combined with L_{eq} , they provide insight into temporal variability and perceived annoyance in nearby communities.

2.4.4. Spectral analysis

Sound measurement in octave and one-third octave bands is one of the most widely used techniques in acoustics (standard IEC 61260-1) for characterizing the spectral distribution of noise in detail [61]. An octave band spans a frequency range in which the upper frequency is twice the lower one, grouping acoustic energy into broad and interpretable frequency ranges. One-third octave analysis further divides each octave into three narrower sub-bands, offering higher spectral resolution and improved accuracy in identifying tonal

351 components or specific peaks [62].

352 Octave and one-third octave band analysis is essential for understand-
353 ing the spectral distribution of acoustic components, as it represents noise
354 behavior in a manner consistent with human auditory perception, which is
355 also organized into non-uniform frequency bands [63]. Figure 4 presents a
356 representative one-third octave band spectrum of wind turbine noise mea-
357 sured near residential areas, including statistical descriptors (10th–90th and
358 median levels) and the human hearing threshold. The figure highlights that
359 most spectral components lie above the hearing threshold within the audible
360 range, while infrasonic contributions remain below it, despite their physical
361 presence.

362 Wind turbine noise includes low-frequency contributions such as infra-
363 sound and tonal noise from blades, along with mid- and high-frequency com-
364 ponents related to turbulence and aerodynamic effects [64]. This analysis en-
365 ables identification of the most perceptible or annoying frequency bands for
366 nearby communities, supports cross-study comparison, and aids in defining
367 regulatory criteria. Thus, frequency band analysis is a key tool for objectively
368 assessing the acoustic impact of WTs.

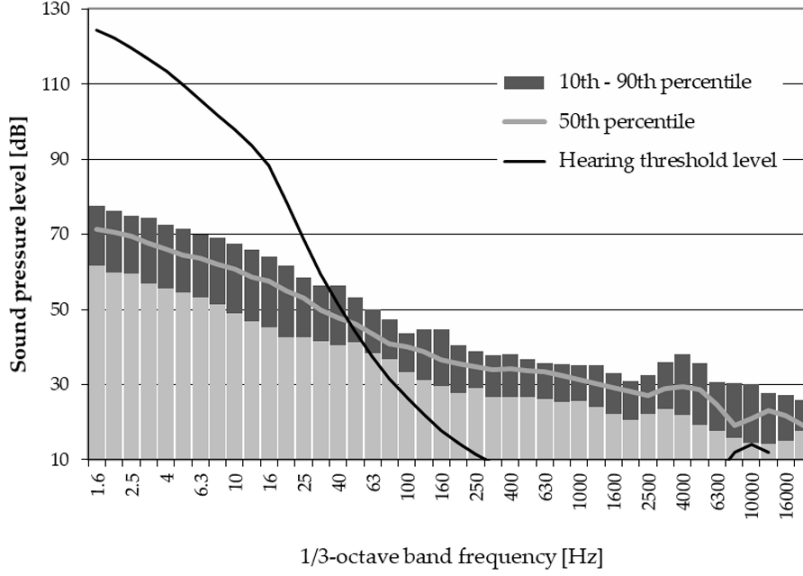


Figure 4: 1/3-octave band spectrum of wind turbine noise measured near residential areas, showing median (50th percentile) and variability range (10th–90th percentiles), together with the human hearing threshold. The figure illustrates the spectral distribution of noise across infrasonic and audible frequencies and highlights the relationship between measured levels and auditory perception. Reproduced from [65].

369 The spectral distribution highlights a dominance of low- to mid-frequency
370 components, with sound pressure levels generally decreasing at higher fre-
371 quencies. In addition to its spectral representation, the figure incorporates
372 statistical descriptors (e.g., percentile ranges), which capture the temporal
373 variability of wind turbine noise arising from atmospheric and operational
374 fluctuations. It also includes perceptual references, such as the human hear-
375 ing threshold, enabling a direct comparison between measured sound levels
376 and auditory sensitivity. Consequently, this representation provides a com-
377 prehensive view that integrates spectral content, variability, and perceptual

378 relevance, rather than a purely frequency-based description. In this context,
379 Table 1 summarizes the key acoustic metrics discussed in this subsection, out-
380 lining their respective roles and practical applications in the characterization
381 and assessment of wind turbine noise.

382 **3. Impact of wind turbine noise on humans**

383 The assessment of wind turbine noise (WTN) extends beyond its physi-
384 cal characterization, encompassing its perception by individuals, its potential
385 effects on health and well-being, and its implications for regulation and so-
386 cial acceptance. Unlike conventional environmental noise sources, WTN is
387 characterized by specific temporal and spectral features that influence how it
388 is experienced by nearby populations. Consequently, understanding its im-
389 pact requires an interdisciplinary approach that integrates psychoacoustics,
390 epidemiology, and policy considerations. The following sections review cur-
391 rent knowledge on human perception, associated health outcomes, and the
392 regulatory and societal challenges linked to wind turbine noise.

393 *3.1. Human perception and psychoacoustic characteristics*

394 WTN exhibits distinctive acoustic features that shape human perception,
395 differentiating it from other industrial or transportation noise sources [66].
396 In this context, perception refers not only to the physical detection of sound,
397 but also to the way acoustic stimuli are interpreted by the auditory system
398 and cognitive processes, including attention, expectations, and prior experi-
399 ence. As a result, sounds with similar sound pressure levels may be perceived
400 differently depending on their temporal and spectral characteristics.

401 Its dominant component is aerodynamic noise generated by blade–air
402 interaction, commonly described as a rhythmic “swishing” or “whooshing”
403 sound similar to that of a helicopter [67]. A key psychoacoustic characteris-
404 tic is amplitude modulation (AM), involving periodic fluctuations in sound
405 pressure levels as blades pass the tower, which can enhance annoyance and
406 hinder habituation [68].

407 WTN also contains low-frequency noise (LFN) and infrasound (IS), which
408 propagate over longer distances and penetrate building structures more ef-
409 fectively than higher frequencies [69]. From a perceptual standpoint, low-
410 frequency components may be experienced not only as audible sound but
411 also as a sensation of pressure or vibration, contributing to discomfort even
412 when levels are close to or below audibility thresholds. Although infrasound
413 levels from modern turbines are typically below human perception thresh-
414 olds and lower than those from natural or urban sources [6], WTN is often
415 perceived as more annoying than road traffic noise at equivalent levels. This
416 is largely attributed to its temporal variability and persistence during night-
417 time.

418 *3.2. Health effects and annoyance*

419 The effects of WTN are generally classified into subjective annoyance
420 and potential impacts on physical and mental health. Annoyance remains
421 the most robust and consistently reported outcome, increasing significantly
422 when outdoor levels exceed 35–40 dB(A) [70, 71]. Reported symptoms among
423 exposed populations include headaches, dizziness, nausea, and fatigue; how-
424 ever, large-scale epidemiological studies have not found statistically signifi-
425 cant associations with cardiovascular diseases, hypertension, or diabetes [72].

426 Sleep disturbance is another key concern. While self-reported data in-
427 dicate a clear association between WTN and reduced sleep quality [70, 71],
428 objective measurements using polysomnography (PSG) and actigraphy yield
429 more variable results [73]. Experimental studies suggest minor changes, such
430 as reduced REM sleep and increased latency under modulated noise exposure,
431 without major alterations to overall sleep structure [74]. Moreover, controlled
432 double-blind studies indicate that infrasound alone does not significantly af-
433 fect sleep physiology nor support the existence of “wind turbine syndrome”
434 [6]. These discrepancies highlight limitations such as self-reporting bias and
435 the difficulty of reproducing realistic exposure conditions [75].

436 *3.3. Implications for regulation and community acceptance*

437 The documented impact of WTN has led to the development of specific
438 regulatory frameworks, although many countries still rely on general envi-
439 ronmental noise limits [66]. Typical guidelines recommend outdoor limits
440 between 35 and 45 dB(A), consistent with World Health Organization recom-
441 mendations for nighttime exposure [69]. A value of approximately 43 dB(A),
442 based on annoyance indicators such as %HA, has been proposed as a bal-
443 anced planning criterion. Setback distances are also widely implemented,
444 ranging from about 550 m to 1.5 km depending on regional policies [71].

445 Beyond acoustic levels, social acceptance is strongly influenced by non-
446 acoustic factors [72]. Visual impact, in particular, can amplify perceived
447 annoyance, whereas economic benefits and community participation tend to
448 improve acceptance. These findings indicate that WTN perception is not
449 solely a physical phenomenon but also a socio-environmental one. Conse-
450 quently, combining technical mitigation measures—such as low-noise blade

451 designs and building insulation—with participatory planning strategies is es-
452 sential to enhance coexistence between wind farms and local communities.

453 Overall, the impact of wind turbine noise on humans is driven not only
454 by physical sound levels but also by its temporal and spectral characteristics,
455 as well as contextual and perceptual factors. Current evidence consistently
456 identifies annoyance as the primary effect, while direct health impacts remain
457 inconclusive. This highlights the need for improved assessment frameworks
458 that integrate psychoacoustic metrics and better represent real exposure con-
459 ditions. Future research should focus on bridging the gap between objective
460 measurements and subjective perception, as well as supporting more holistic
461 approaches to wind farm planning and community engagement.

462 **4. Noise measurement and simulation techniques**

463 Accurate assessment of wind turbine noise requires a combination of ex-
464 perimental measurements and computational modeling approaches to char-
465 acterize both source generation and sound propagation. While standardized
466 measurement procedures ensure consistency and comparability, each method-
467 ology presents inherent limitations related to environmental variability, scal-
468 ing effects, or modeling assumptions. Therefore, a comprehensive evaluation
469 of wind turbine noise relies on the complementary use of field measurements,
470 controlled experiments, and predictive simulations, each contributing differ-
471 ent levels of accuracy, control, and applicability.

472 *4.1. Regulatory framework and international standards*

473 International standards—primarily IEC 61400–11 [76]—define procedures to
474 measure and report wind-turbine noise [11]. They specify microphone place-

475 ment, reference distances, atmospheric corrections, and logging of overall
476 sound pressure levels, third-octave spectra, and operating parameters (wind
477 speed/direction, rotor speed, pressure, temperature). Recommended instru-
478 mentation includes microphones, digital recorders, calibrators, sensors, and
479 data acquisition systems to ensure precise, repeatable, and comparable mea-
480 surements across turbines and sites.

481 Beyond IEC 61400–11 for direct turbine noise measurement, ISO stan-
482 dards complement environmental assessment and propagation. ISO 9613–2
483 [77] provides outdoor sound attenuation methods (ground and atmospheric
484 absorption), while ISO 1996–1 [78] and 1996–2 [79] define procedures to de-
485 scribe, measure, and evaluate environmental noise. These allow extrapo-
486 lating IEC data to estimate acoustic impact in residential/industrial areas,
487 enabling comprehensive evaluations. However, these standardized methods
488 are typically based on simplified assumptions regarding atmospheric condi-
489 tions and terrain homogeneity, which may limit their accuracy under complex
490 real-world scenarios. In particular, effects such as atmospheric stratification,
491 turbulence, and wake interactions are not fully captured, potentially leading
492 to discrepancies between predicted and measured sound levels.

493 Several studies, e.g., Davy et al. [80], compare national noise limits
494 for WTs and propose evidence-based recommendations regarding annoyance.
495 Their review highlights discrepancies between legal limits and observed ef-
496 fects, underscoring the need to align standards with human perception and
497 to promote harmonized, evidence-based criteria for wind farm planning and
498 operation.

499 From a regulatory perspective, these standards are closely linked to en-

500 vironmental noise limits and land-use planning criteria. In wind farm sit-
501 ing, adequate setback distances from residential areas are essential to en-
502 sure compliance with recommended sound levels and to minimize annoyance.
503 Many national guidelines are informed by World Health Organization (World
504 Health Organization (WHO)) recommendations, which suggest that night-
505 time environmental noise levels should remain around or below 40 dB to
506 avoid significant disturbance [40, 81]. Nevertheless, the applicability of such
507 thresholds to wind turbine noise remains under discussion, given its distinct
508 temporal and spectral characteristics compared to conventional environmen-
509 tal noise sources.

510 *4.2. Experimental acoustic measurement techniques*

511 Wind turbine noise assessment relies on a combination of standardized
512 measurement procedures and experimental methodologies aimed at charac-
513 terizing both sound generation and propagation mechanisms. These ap-
514 proaches are implemented under either real operating conditions or controlled
515 laboratory environments, enabling the analysis of acoustic emissions across
516 different spatial and operational scales. While field measurements provide
517 direct insight into turbine noise under realistic atmospheric and environmen-
518 tal conditions, controlled experiments allow for systematic investigation of
519 specific aerodynamic noise sources. The integration of these complementary
520 approaches is essential for improving the reliability of acoustic characteriza-
521 tion and supporting the validation of predictive models and noise mitigation
522 strategies.

523 4.2.1. *Measurement setup and data acquisition procedures*

524 Standardized measurement of wind turbine noise is primarily conducted
525 according to IEC 61400–11 [76], which defines procedures to ensure con-
526 sistency and comparability of acoustic data, including microphone position-
527 ing, operating conditions, and validation criteria. Complementary standards,
528 such as ISO 3744 [82], ISO 3745 [83], and IEC 61672–1 [84], are also applied
529 to ensure measurement accuracy, calibration, and traceability.

530 In field measurements, IEC 61400–11 specifies a ground-based configu-
531 ration in which microphones are mounted on a reflective board to reduce
532 ground effects. The horizontal distance to the turbine is defined relative
533 to hub height, typically ranging from one to several hub heights depending
534 on the measurement objective. Microphones are positioned to avoid obsta-
535 cles and ensure representative propagation conditions, and are equipped with
536 windshields to minimize flow-induced noise.

537 Although this setup is standard, alternative microphone heights (e.g., 1.2–
538 1.5 m) are sometimes used in environmental or perceptual studies, potentially
539 affecting measured sound levels due to propagation effects. The standardized
540 measurement arrangement is illustrated in Fig. 5, showing both the geomet-
541 ric definition of the measurement distance and the spatial distribution of
542 microphone positions around the turbine.

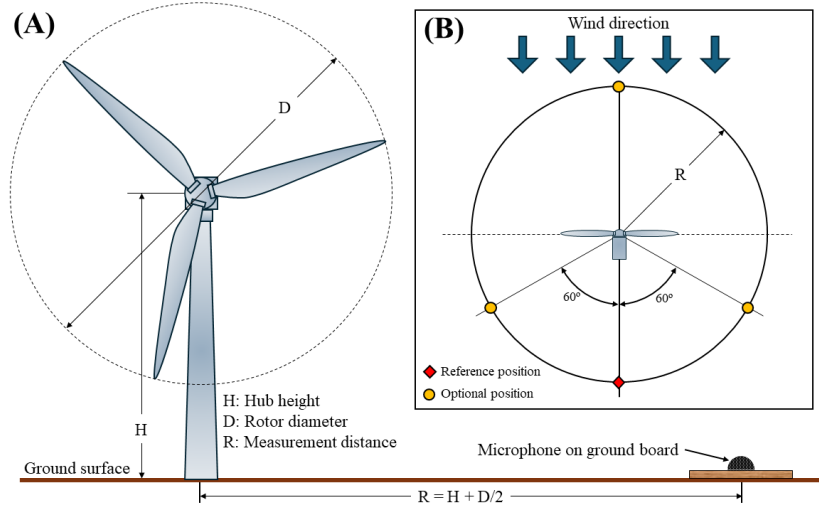


Figure 5: Schematic representation of wind turbine noise measurement configuration based on IEC 61400-11. (A) Side view showing hub height (H), rotor diameter (D), and measurement distance (R) with a ground-mounted microphone. (B) Top view illustrating the angular distribution of microphone positions around the turbine, including reference and optional measurement locations relative to wind direction.

543 Data acquisition includes continuous recording of L_{Aeq} and one-third oc-
 544 tave spectra, together with operational and meteorological parameters such
 545 as wind speed at hub height, rotor speed, and power output. Background
 546 noise is evaluated and filtered using reference measurements or statistical
 547 methods to isolate turbine-related contributions.

548 In contrast, wind-tunnel experiments are not governed by a single stan-
 549 dardized procedure, but instead rely on general acoustic standards (ISO 3744,
 550 ISO 3745), instrumentation requirements (IEC 61672-1), and experiment-
 551 specific methodologies adapted to the research objective and scaling condi-
 552 tions, enabling controlled investigation of aerodynamic noise sources.

553 4.2.2. *Field and wind-tunnel measurement approaches*

554 Field and wind-tunnel measurements constitute the two main experimen-
555 tal approaches for wind turbine noise assessment, providing complementary
556 perspectives in terms of environmental representativeness and experimental
557 control. Table 2 summarizes the key differences between both methodologies.

558 The comparison reveals a fundamental trade-off between environmental
559 realism and experimental control in wind turbine noise assessment. Field
560 measurements provide representative data under real operating conditions
561 but are affected by atmospheric variability and limited reproducibility. In
562 contrast, wind-tunnel experiments enable controlled and repeatable condi-
563 tions for isolating noise-generation mechanisms, although their results require
564 careful interpretation.

565 The main discrepancies between both approaches arise from three factors:
566 inflow turbulence, acoustic propagation, and geometric scaling. In wind tun-
567 nels, the lower and more homogeneous turbulence intensity can lead to an un-
568 derestimation of inflow-induced noise [85]. Sound propagation is also altered
569 by the confined test section, where wall reflections and limited measurement
570 angles deviate from free-field conditions. Additionally, reduced-scale models
571 modify Reynolds and Strouhal numbers [86], affecting both the amplitude
572 and frequency content of the emitted noise.

573 To address these limitations, correction strategies and signal-processing
574 techniques are applied, including background-noise filtering, spectral anal-
575 ysis, and time–frequency methods such as short-time Fourier transforms
576 (STFT) and wavelet analysis [87]. Consequently, combining field and wind-
577 tunnel measurements remains essential to achieve a comprehensive and reli-

578 able characterization of wind turbine noise.

579 These differences are illustrated in Fig. 6, which contrasts *in situ* mea-
580 surements with controlled wind-tunnel experiments.

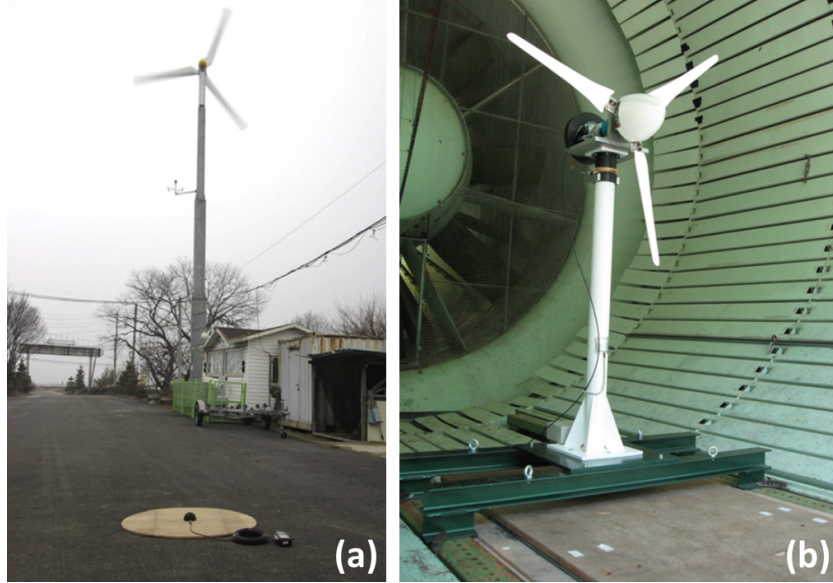


Figure 6: Noise measurement and logging: (a) wind turbine in field [88] and (b) in wind tunnel [89].

581 Beyond this general comparison, the literature reflects a wide range of
582 experimental methodologies and acoustic descriptors. Table 3 synthesizes
583 representative studies, highlighting instrumentation, evaluated parameters,
584 and measurement approaches used in wind turbine noise characterization.

585 The diversity of instrumentation and evaluated parameters reflects the
586 multidisciplinary nature of wind turbine noise assessment. While sound pres-
587 sure level and spectral analysis remain the primary descriptors, additional
588 parameters such as tonality, infrasound, and turbulence-induced fluctuations
589 are increasingly considered to better characterize perceived noise. This vari-

ability also highlights the lack of full standardization in certain measurement practices, particularly for low-frequency noise and perceptually relevant acoustic features, indicating the need for further harmonization to improve comparability and reproducibility.

4.3. Modeling and simulation

Modeling and simulation enable prediction of acoustic emissions under varying operating conditions without relying solely on costly measurements. Widely used approaches include *semi-empirical models*, which combine experimental data and theory to estimate noise levels, and CFD-based simulations to analyze detailed flow-blade interactions.

4.3.1. Semi-empirical modeling

Semi-empirical modeling provides a computationally efficient approach for predicting wind turbine noise by combining simplified physical formulations with empirical correlations obtained from experimental measurements. In general, these models estimate acoustic emission by relating key aerodynamic variables—such as inflow velocity, blade geometry, Reynolds number, and boundary-layer properties—to sound pressure levels. Because they avoid resolving the full turbulent flow field, semi-empirical models require significantly fewer computational resources than high-fidelity CFD-based aeroacoustic simulations, making them particularly suitable for preliminary design studies and comparative blade assessments.

Most semi-empirical formulations rely on several simplifying assumptions. Typically, the aerodynamic noise sources are modeled as statistically stationary processes associated with boundary-layer turbulence, flow separa-

tion, or vortex shedding. The blade sections are often approximated as two-dimensional airfoils, and the surrounding flow is assumed to be locally uniform. Additionally, these models generally treat different noise-generation mechanisms independently—such as turbulent-boundary-layer trailing-edge noise, separation noise, or tip-vortex noise—and then combine their contributions to estimate the overall acoustic emission.

The most widely adopted framework is the model developed by Brooks et al. [86], which was derived by applying the Ffowcs Williams–Hall (FWH) acoustic analogy to wind-tunnel measurements of two-dimensional NACA0012 airfoils [96]. This model provides empirical relations for several aerodynamic noise mechanisms and has become a reference methodology for predicting airfoil self-noise in many wind turbine studies.

Applications of semi-empirical models to wind turbines have been reported in several studies. Möllerström et al. [91] assessed the noise from a 200 kW vertical-axis wind turbine using measurements combined with a turbulent-boundary-layer trailing-edge (TBL-TE) semi-empirical model. Their results indicated that additional phenomena such as inflow turbulence and dynamic stall also influence acoustic generation, leading the model to underestimate field levels by approximately 15–20 dB. Zhu et al. [97] combined semi-empirical noise prediction with advanced simulation tools (WindSTAR-Gen and WindSTAR-Pro) to analyze sound propagation and support turbine design optimization. Similarly, Oerlemans [98] reported that wind shear can influence other amplitude modulation (OAM), increasing the variability and low-frequency content of the radiated noise.

638 4.3.2. Computational modeling and simulation

639 Computational approaches to wind turbine aeroacoustics aim to predict
640 noise generation and propagation through physics-based numerical meth-
641 ods. Within this framework, two main approaches are commonly distin-
642 guished: computational fluid dynamics (CFD) and computational aeroacous-
643 tics (CAA) [99]. CFD is primarily used to resolve the aerodynamic flow
644 field around the blades, capturing unsteady pressure fluctuations and flow-
645 structure interactions that act as noise sources. In contrast, CAA focuses on
646 the propagation of acoustic waves from these sources to the far field, often
647 using simplified acoustic equations.

648 Rather than being independent methodologies, CFD and CAA are typ-
649 ically combined in hybrid frameworks. In such approaches, CFD provides
650 detailed flow and source information, while acoustic analogies, such as the
651 Ffowcs Williams–Hawkings (FW–H) formulation, are employed to predict
652 far-field noise. This hybrid strategy enables a balance between physical fi-
653 delity and computational efficiency in aeroacoustic simulations.

654 A key aspect in CFD-based aeroacoustics is the turbulence modelling
655 strategy, which directly determines the accuracy of noise prediction and the
656 associated computational cost. CFD-based aeroacoustic analyses typically
657 rely on turbulence modelling approaches such as RANS, URANS, LES, and
658 DES.

659 From an aeroacoustic perspective, the main differences between these
660 methods arise from their ability to resolve turbulence-driven sound gener-
661 ation. As summarized in Table 4, RANS-based approaches are unable to
662 capture broadband noise due to the absence of resolved turbulent fluctu-

663 ations, and are therefore mainly used in conjunction with semi-empirical
664 models. This limitation is evident in studies such as Khaled et al. [100],
665 where RANS-based CFD was primarily employed for aerodynamic optimiza-
666 tion, and Hansen & Hansen [101], where aerodynamic noise predictions relied
667 on simplified turbulence representations.

668 URANS improves tonal noise prediction by resolving large-scale unsteady
669 structures, but still exhibits significant limitations in broadband noise pre-
670 diction due to the lack of small-scale turbulence resolution, leading to at-
671 tenuation of high-frequency content. For instance, Mohamed [102] applied
672 URANS with a κ - ω SST model coupled with FWH equations, demonstrat-
673 ing its capability for aerodynamic noise prediction while still constrained in
674 capturing broadband components.

675 High-fidelity approaches such as LES enable a more accurate representa-
676 tion of broadband noise by resolving the dominant turbulent structures re-
677 sponsible for acoustic generation. However, their applicability is constrained
678 by the high computational cost and resolution requirements. LES-based
679 studies [103] have shown improved broadband noise prediction, although of-
680 ten limited in frequency range (≤ 500 Hz) and lacking full tonal characteri-
681 zation or experimental validation, which can lead to discrepancies with field
682 measurements.

683 Hybrid methods such as DES or DDES provide a compromise between
684 accuracy and cost, capturing large-scale turbulent structures while mod-
685 elling near-wall regions. As indicated in Table 4, these approaches offer
686 improved broadband noise prediction compared to URANS, although their
687 performance may depend on grid resolution and model-switching strategies.

688 Ma et al. [104] demonstrated that DDES combined with FWH can achieve
689 good agreement with experimental data while maintaining feasible compu-
690 tational cost in wind turbine simulations.

691 In general, a trade-off between computational cost and acoustic accuracy
692 can be identified. While LES and DES provide improved broadband noise
693 prediction, their applicability is often limited by computational resources,
694 whereas RANS and URANS remain attractive for large-scale or industrial
695 applications despite their acoustic limitations.

696 To further quantify this trade-off, several studies report typical deviations
697 in noise prediction depending on the turbulence modelling approach. RANS-
698 based methods can underestimate broadband noise levels by more than 5–
699 10 dB due to the absence of resolved turbulent fluctuations [105]. URANS
700 improves the prediction of tonal components and low-frequency unsteadiness,
701 but still exhibits deviations on the order of 3–8 dB in broadband noise,
702 particularly at higher frequencies [106].

703 Hybrid approaches such as DES and DDES generally provide improved
704 agreement with experimental data, with reported discrepancies typically
705 within 3–5 dB, depending on grid resolution and model configuration. In
706 contrast, LES-based simulations can achieve higher accuracy [107], with de-
707 viations often reduced to within 2–5 dB when sufficient spatial and temporal
708 resolution is ensured. However, this level of accuracy requires significantly
709 higher computational resources, often increasing computational cost by one
710 to two orders of magnitude compared to RANS-based approaches.

711 These quantitative differences highlight the importance of selecting an
712 appropriate modelling strategy based on the specific objectives of the study,

713 whether focused on preliminary design, detailed aeroacoustic analysis, or
714 high-fidelity validation.

715 Beyond turbulence modelling, accurate noise prediction requires careful
716 consideration of numerical aspects. Low-dissipation and low-dispersion nu-
717 merical schemes are essential to avoid artificial attenuation or distortion of
718 acoustic waves. Furthermore, appropriate boundary conditions must be im-
719 plemented to prevent non-physical reflections, including non-reflecting bound-
720 ary conditions, buffer zones, or perfectly matched layers (PML). The compu-
721 tational domain must also be sufficiently large to capture wake development
722 and acoustic propagation without contamination from boundary effects.

723 Recent studies also highlight the integration of CFD with data-driven
724 and design-oriented approaches. Kim & Cheong [44] used CFD combined
725 with FWH-based acoustic prediction to design low-noise Savonius turbine
726 configurations. Anicic et al. [108] coupled CFD with support vector re-
727 gression (SVR) to predict noise as a function of wind speed and frequency.
728 Similarly, Merino et al. [109] investigated noise reduction strategies through
729 trailing-edge modifications, such as serrations and porous treatments, using
730 CFD/CAA frameworks to assess perceived annoyance.

731 At a larger scale, Kongprasit et al. [62] simulated a 90 MW wind farm,
732 reporting noise levels between 35 and 45 dB(A), demonstrating the applica-
733 bility of CFD-based approaches to wind farm-scale assessments.

734 Despite these advances, several limitations remain in computational aeroa-
735 coustic modeling. Most approaches rely on simplified inflow conditions and
736 may not fully capture the effects of atmospheric turbulence, wind shear,
737 and stability, which significantly influence noise generation and propagation

738 in real environments. In particular, the accurate prediction of broadband
739 noise remains challenging due to the complex interaction between turbulent
740 structures and blade geometry. Furthermore, although high-fidelity methods
741 such as LES and hybrid approaches improve prediction accuracy, their high
742 computational cost limits their applicability in industrial design processes.
743 Consequently, there is a need for reduced-order and hybrid modeling strate-
744 gies that can provide a better balance between computational efficiency and
745 predictive capability.

746 **5. Noise mitigation strategies and techniques**

747 Noise mitigation in wind turbines represents a complex optimization prob-
748 lem that necessitates a strategic balance between acoustic performance, aero-
749 dynamic efficiency, and structural integrity. While noise characterization
750 identifies sources and propagation pathways, mitigation strategies focus on
751 suppressing emissions at the source without compromising energy yield or
752 economic viability.

753 A key difficulty lies in the inherent trade-offs between noise reduction
754 and turbine performance. Measures that effectively attenuate aerodynamic
755 or mechanical noise may introduce penalties in terms of power output, struc-
756 tural complexity, or maintenance requirements. Consequently, the selection
757 of mitigation strategies must be guided by the specific operating conditions,
758 turbine design, and regulatory constraints.

759 The following subsections examine the main approaches to noise reduc-
760 tion, focusing on aerodynamic and mechanical strategies, and discuss their
761 effectiveness, limitations, and practical implications.

762 5.1. Aerodynamic blade design

763 Blade aerodynamics plays a dominant role in wind turbine noise genera-
764 tion, as unsteady flow features such as boundary-layer turbulence, separation,
765 and vortex shedding directly determine the intensity and spectral character-
766 istics of aerodynamic noise. Consequently, mitigation strategies focus on
767 modifying the blade geometry to alter flow structures and reduce acoustic
768 source strength.

769 Among the most widely investigated approaches are trailing-edge serra-
770 tions, airfoil optimization, add-on flaps, and bio-inspired geometries. These
771 techniques primarily act by weakening coherent turbulent structures and
772 smoothing pressure fluctuations at the trailing edge, thereby reducing broad-
773 band noise and, in some cases, tonal components. In particular, serrated
774 trailing edges have been shown to mitigate both vortex shedding noise and
775 laminar separation bubble noise across a broad frequency range [110]. This
776 reduction is associated with a decrease in the power spectral density of tur-
777 bulent velocity fluctuations in the wake, as serrations disrupt large-scale co-
778 herent vortices and promote faster turbulence breakdown. As a result, the
779 acoustic source strength is reduced without significantly altering far-field di-
780 rectivity patterns, although the effectiveness remains sensitive to angle of
781 attack and airfoil geometry.

782 However, their effectiveness is strongly dependent on operating conditions
783 and involves trade-offs with aerodynamic performance. While serrations can
784 achieve noise reductions of up to 10 dB [111, 112], their impact on lift-to-drag
785 ratio and power coefficient (C_P) varies significantly depending on geometry,
786 Reynolds number, and inflow conditions. Recent experimental and numerical

787 studies indicate that optimized serrated configurations can achieve substan-
788 tial broadband noise attenuation while maintaining or even slightly improv-
789 ing aerodynamic performance [113]. Nevertheless, other configurations may
790 induce performance penalties or modify wake structures [114], leading to in-
791 creased low-frequency noise or altered directivity. These discrepancies high-
792 light the strong coupling between aeroacoustic behavior and flow conditions,
793 which remains a key challenge for design optimization.

794 Similarly, trailing-edge flaps can enhance aerodynamic efficiency (up to
795 +8.79% in C_P [100]) while reducing noise levels, but their effectiveness de-
796 pends on control strategy and structural integration. Hybrid configurations
797 combining serrations and flaps have shown improved attenuation of both
798 broadband and tonal noise, although their complexity may increase manu-
799 facturing and maintenance costs.

800 Beyond conventional rigid serration designs, recent investigations have
801 also focused on the influence of geometry and structural adaptability on
802 noise reduction performance. Flexible serrations have been shown to provide
803 additional broadband noise attenuation (up to 2–3 dB at high frequencies)
804 compared to rigid configurations [115], as they can better align with the local
805 flow and reduce crossflow intensity near the serration roots. This behavior is
806 particularly relevant for high-frequency noise attenuation, which is strongly
807 influenced by small-scale turbulent structures that are not adequately con-
808 trolled by conventional rigid serrations. Furthermore, these studies reveal
809 that current analytical and semi-empirical models tend to overpredict the
810 acoustic benefits of serrations, as they often neglect the complex, non-frozen
811 turbulent interactions occurring near the trailing edge. This limitation un-

812 derscores the need for improved predictive models that accurately capture
813 the coupling between turbulence dynamics and acoustic emission.

814 In addition to conventional engineering solutions, bio-inspired designs, in-
815 cluding owl-inspired leading and trailing edges, have demonstrated potential
816 for noise reduction by disrupting coherent vortex formation. Nevertheless,
817 these designs may introduce aerodynamic penalties, such as reductions in
818 power coefficient (e.g., -2.13% [116]), highlighting the need for optimization
819 between acoustic and aerodynamic performance.

820 More recent studies have further advanced biomimetic approaches to aero-
821 dynamic noise reduction, moving beyond owl-inspired concepts toward multi-
822 scale and functionally integrated surface designs. For instance, fish scale-
823 inspired trailing-edge and tip structures have demonstrated significant noise
824 reduction by suppressing tip vortex formation and accelerating vortex dissi-
825 pation in the near wake [117]. High-fidelity simulations indicate that such
826 configurations can reduce both broadband and tonal noise components while
827 maintaining competitive aerodynamic performance. These findings suggest
828 that biomimetic concepts can achieve synergistic improvements by simul-
829 taneously targeting multiple noise-generation mechanisms. However, their
830 practical implementation remains constrained by manufacturing complexity,
831 scalability, and durability under real operating conditions.

832 Complementing geometric modifications, material-based solutions have
833 also been proposed to mitigate wind turbine noise through both acoustic
834 and structural mechanisms. In particular, bio-inspired porous materials,
835 mimicking the microstructure of owl wings, have been shown to attenuate
836 vortex shedding noise and smooth pressure gradients by equalizing surface

837 impedance [118]. These materials are especially effective in reducing low-
838 frequency broadband noise; however, under certain operating conditions,
839 they may introduce additional high-frequency noise components [119]. This
840 trade-off highlights the importance of optimizing material properties and flow
841 conditions simultaneously to achieve robust aeroacoustic performance.

842 At a more integrated level, acoustic treatments combining micro-perforated
843 casings with porous media have shown substantial acoustic attenuation. For
844 instance, Jiang et al. [120] reported reductions of up to 12 dB in the mid-
845 frequency range (1.5–6 kHz), highlighting the potential of integrated structural-
846 acoustic solutions for airfoil noise control. However, despite these benefits,
847 challenges related to durability, structural integrity, manufacturability, and
848 cost-effectiveness remain critical for large-scale implementation.

849 A comparative summary of these approaches, including their acoustic
850 benefits and impact on turbine performance, is provided in Table 5. The data
851 highlight that, although significant noise reductions are achievable, no single
852 solution universally optimizes both acoustic and aerodynamic performance,
853 and design choices must be tailored to specific operational conditions and
854 constraints.

855 From an engineering perspective, the implementation of aerodynamic
856 noise reduction strategies involves several practical trade-offs that are not
857 always fully addressed in the literature. Modifications such as trailing-edge
858 serrations, porous materials, or biomimetic geometries can increase manu-
859 facturing complexity, requiring advanced fabrication techniques and tighter
860 tolerances. This may lead to higher production costs, particularly for large-
861 scale blades.

862 In addition, durability represents a critical concern. Noise-reduction fea-
863 tures are often located at the blade trailing edge, where they are exposed to
864 erosion, environmental degradation, and cyclic loading. This can reduce their
865 effectiveness over time and increase the need for maintenance or replacement.

866 Maintenance requirements also play a key role in the overall feasibility of
867 these solutions. More complex geometries or add-on devices may complicate
868 inspection and repair operations, particularly in offshore environments where
869 access is limited and operational costs are high.

870 Despite the wide range of aerodynamic noise mitigation strategies pro-
871 posed in the literature, their practical implementation remains constrained by
872 several factors. In particular, the trade-off between noise reduction and aero-
873 dynamic performance is not yet fully optimized, and results obtained under
874 controlled conditions do not always translate to full-scale turbines operating
875 under realistic atmospheric conditions. Additionally, aspects such as long-
876 term durability, manufacturing complexity, maintenance requirements, and
877 economic viability remain insufficiently addressed. Quantitative assessments
878 of lifecycle costs and long-term performance degradation are still scarce,
879 highlighting the need for integrated experimental, numerical, and techno-
880 economic studies to support the large-scale deployment of these solutions.

881 5.2. *Mechanical isolation and damping*

882 Mechanical and structural vibrations, particularly those originating from
883 the drivetrain, gearbox, and nacelle, are a major source of low-frequency and
884 tonal noise in wind turbines. These vibrations are transmitted through the
885 structure and radiated as sound (structure-borne noise), making vibration
886 control a key strategy for noise mitigation. In addition to reducing acoustic

887 emissions, isolation and damping techniques contribute to improved struc-
888 tural reliability and component lifetime.

889 Passive mitigation solutions such as anti-vibration mounts, acoustic en-
890 closures, and sound-absorbing materials are widely implemented due to their
891 robustness and low maintenance requirements. However, their effectiveness
892 is often limited to specific frequency ranges and may introduce additional
893 mass or design constraints. Improvements at the source, such as high-
894 precision gear design [124], can significantly reduce excitation mechanisms,
895 while direct-drive turbines eliminate gearbox-related noise sources entirely,
896 at the expense of increased generator size, weight, and cost.

897 Advanced damping systems have been proposed to enhance vibration at-
898 tenuation without compromising structural efficiency. Kapasakalis et al. [125]
899 demonstrated that KDamper configurations can increase the effective damp-
900 ing ratio up to 9.8% with minimal added mass (0.1%), outperforming con-
901 ventional tuned mass dampers (TMD, 2.7%) and nacelle isolation systems
902 (7.8%). This results in a significant reduction in structural loads and vibra-
903 tion amplitudes. Similarly, control-based strategies such as generator torque
904 modulation have proven effective in reducing drivetrain-induced excitation.
905 Windisch et al. [126] showed, through multi-body simulation (MBS), that op-
906 timized torque oscillations can reduce bearing forces by up to 60%, thereby
907 mitigating gear-mesh excitation and associated radiated noise.

908 Active and semi-active damping approaches provide additional flexibility
909 under variable operating conditions. Rahman et al. [127] reported that de-
910 vices such as TMD and tuned liquid column dampers (TLCD) can effectively
911 reduce vibration amplitudes under stochastic loading, although their perfor-

912 mance depends on tuning and control strategy. Compared to passive systems,
913 active solutions offer improved adaptability but at the cost of increased sys-
914 tem complexity, energy consumption, and maintenance requirements.

915 In general, mechanical isolation and damping techniques can effectively
916 reduce tonal and low-frequency noise emissions. However, their performance
917 depends on the complex interaction between structural dynamics, excitation
918 mechanisms, and control strategies. Therefore, effective noise mitigation
919 requires an integrated approach combining passive, active, and design-based
920 solutions, while balancing acoustic performance, structural constraints, and
921 economic feasibility.

922 **6. Future research directions and challenges**

923 Despite the significant progress achieved in the characterization, model-
924 ing, and mitigation of wind turbine noise, several key issues remain open.
925 These limitations point to the need for a more integrated and multidisci-
926 plinary framework to address aerodynamic noise under realistic operating
927 conditions. In particular, shortcomings persist in predictive modeling accu-
928 racy, the practical implementation of mitigation strategies, and the effective
929 incorporation of noise reduction within the overall turbine design process.

930 This section synthesizes the main research gaps identified in the literature
931 and outlines key directions for future work, with particular emphasis on
932 improving predictive capabilities, enhancing the effectiveness and feasibility
933 of mitigation strategies, and advancing emerging approaches such as active
934 noise control.

935 *6.1. Modeling and prediction challenges*

936 One of the main limitations in wind turbine aeroacoustics is the accu-
937 rate prediction of noise under realistic atmospheric conditions. Most current
938 computational approaches rely on simplified inflow assumptions and do not
939 fully capture the effects of atmospheric turbulence, wind shear, and stability,
940 all of which play a critical role in noise generation and propagation.

941 In particular, the prediction of broadband noise remains a major diffi-
942 culty due to the complex interaction between turbulent flow structures and
943 blade geometry. Although high-fidelity numerical methods such as LES and
944 hybrid approaches provide improved accuracy, their high computational cost
945 restricts their applicability in industrial design and optimization processes.

946 Future efforts should therefore focus on the development of reduced-order
947 and hybrid modeling strategies that achieve a better balance between com-
948 putational efficiency and predictive capability. In parallel, the availability
949 of high-quality experimental datasets under realistic operating conditions is
950 essential for the validation and improvement of existing models.

951 *6.2. Aerodynamic and passive noise control limitations*

952 A wide range of passive noise mitigation strategies has been proposed,
953 particularly in the context of aerodynamic blade design. These include
954 trailing-edge modifications, serrations, and biomimetic geometries inspired
955 by natural flyers. While these approaches have demonstrated noise reduc-
956 tion potential under controlled conditions, their performance in real operating
957 environments remains uncertain.

958 A key limitation lies in the trade-off between noise reduction and aero-
959 dynamic efficiency. In many cases, improvements in acoustic performance

960 may result in penalties in power output or increased structural complexity.
961 Moreover, practical aspects such as manufacturing feasibility, material dura-
962 bility, and maintenance requirements are often insufficiently addressed in the
963 literature.

964 Future research should aim to incorporate noise reduction as a primary
965 objective within multi-objective design frameworks, while also integrating
966 techno-economic considerations. In addition, large-scale experimental vali-
967 dation is required to assess the long-term performance and feasibility of these
968 solutions under realistic conditions.

969 *6.3. Active noise control and emerging strategies*

970 Active noise and vibration control methods, based on real-time sensing
971 and actuation, have received comparatively less attention than passive mit-
972 igation strategies in wind turbine applications. Existing studies mainly ad-
973 dress specific approaches, such as active noise control (ANC) [13] and aeroa-
974 coustic concepts proposed by [14], with limited integration into comprehen-
975 sive noise-mitigation frameworks.

976 Although active methods can adapt to varying operating conditions and
977 target both tonal and broadband noise, as well as structure-borne vibrations,
978 their implementation remains constrained by system complexity, energy de-
979 mand, and scalability.

980 Recent work by Moska et al. [128] shows that active control in wind
981 turbines is primarily applied to operational optimization, such as yaw control
982 to maximize power output and adapt to wind conditions, rather than to noise
983 reduction. Similarly, active control strategies in wind energy systems have
984 been extensively developed for power and grid management. For example,

985 Saki et al. [129] propose a hierarchical control scheme for microgrids, while
986 Khosroshahi et al. [130] focus on voltage and frequency regulation using
987 power electronics.

988 Despite these advances, active control remains largely disconnected from
989 aeroacoustic applications. Noise mitigation continues to be primarily ad-
990 dressed through turbine design choices, such as the use of VAWTs [131] and
991 BIWTs [132] in urban environments, or through aeroacoustic considerations
992 during the design phase.

993 This situation reveals a clear research gap in the development of ac-
994 tive control strategies specifically aimed at noise reduction. Future work
995 should explore the integration of active and passive approaches, particularly
996 in small-scale and microturbine systems, to improve acoustic performance
997 and enhance the social acceptance of wind energy.

998 Furthermore, the lack of experimental validation and large-scale imple-
999 mentation highlights a significant gap between theoretical developments and
1000 practical application. Addressing this gap will require interdisciplinary efforts
1001 combining control theory, aeroacoustics, and system integration, as well as
1002 the development of robust and energy-efficient actuation mechanisms suitable
1003 for real operating conditions.

1004 **7. Conclusion**

1005 This review has provided a comprehensive synthesis of wind turbine noise,
1006 integrating its generation mechanisms, characterization methods, measure-
1007 ment techniques, numerical modeling, and mitigation strategies within a uni-
1008 fied framework. The analysis highlights the multidisciplinary nature of the

1009 problem and the need for coordinated approaches that link aerodynamic,
1010 acoustic, structural, and perceptual aspects.

1011 First, wind turbine noise is governed by complex interactions between
1012 aerodynamic and mechanical sources, with trailing-edge turbulence, blade–
1013 tower interaction, and drivetrain components identified as dominant contrib-
1014 utors. Accurate characterization requires the combined use of spectral, tem-
1015 poral, and psychoacoustic metrics, supported by standardized measurement
1016 procedures to ensure consistency and comparability across studies.

1017 Second, experimental and computational approaches provide complemen-
1018 tary capabilities for noise assessment. While wind-tunnel measurements en-
1019 able validation under controlled conditions, numerical methods such as CFD
1020 and CAA allow detailed analysis of flow–acoustic interactions. However,
1021 challenges remain in bridging the gap between the results of these experi-
1022 ments/model predictions and real operating conditions, particularly in rela-
1023 tion to turbulence representation, scaling effects, and acoustic propagation.

1024 Third, current mitigation strategies are predominantly based on passive
1025 approaches, including aerodynamic blade design (trailing-edge serrations,
1026 winglets, and bio-inspired designs) and structural damping techniques. Al-
1027 though effective, these solutions often involve trade-offs with aerodynamic
1028 performance and energy efficiency. In contrast, active control systems are
1029 widely used in wind energy for operational optimization but are rarely ap-
1030 plied to noise mitigation.

1031 This disparity reveals a critical research gap in the development of active
1032 noise-control strategies, especially for small and micro wind turbines operat-
1033 ing in proximity to residential environments. Future research should focus on

1034 integrating active and passive approaches, advancing hybrid modeling tech-
1035 niques, and incorporating adaptive control systems capable of responding to
1036 variable operating and environmental conditions.

1037 Addressing these challenges is essential to improve acoustic performance,
1038 enhance social acceptance, and support the sustainable expansion of wind
1039 energy in both large-scale and distributed applications.

1040 **Declaration of competing interest**

1041 The authors declare that they have no known competing financial inter-
1042 ests or personal relationships that could have appeared to influence the work
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Table 1: Acoustic indicators and their application in the analysis of environmental noise generated by wind turbines.

Acoustic metric	What it measures / How it is interpreted	Application
SPL	Sound Pressure Level as an absolute physical quantity	Foundation for all other metrics
L_{Aeq} , L_{Beq} , L_{Ceq}	Weighted levels adjusted for human hearing sensitivity	Environmental impact regulations and perception
L_{eq}	Equivalent continuous level; average acoustic energy over a period	Comparison of exposure over time
L_{max} , L_{min}	Instantaneous maximum and minimum levels; salient values from the measurement	Identification of discrete noise events
L_{10} , L_{50} , L_{90}	Acoustic percentiles; sound pressure level exceeded for a given percentage of the measurement time	To assess fluctuations and background noise at installation sites
Octave and 1/3-octave bands	Spectral distribution by frequency; it allows for the identification of dominant or tonal frequencies	Diagnosis of aerodynamic and mechanical components

Table 2: Comparison between field and wind-tunnel acoustic measurements.

Criterion	Field measurements	Wind-tunnel tests
Flow generation	Natural wind: uncontrolled speed/direction, atmospheric turbulence	Artificial flow: controlled speed, direction, and turbulence
Experiment scale	Full-scale turbine	Scaled models; acoustic scaling required
Acoustic environment	Open: propagation effects, ground reflections, meteorology	Closed: acoustically treated; tunnel background noise
Experimental objective	Characterize overall acoustic behavior and real environmental impact	Analyze local generation mechanisms; validate predictive models
Experimental control	Limited: non-replicable due to environmental variability	High: reproducible and parameterizable conditions
Representativeness	High: real operating environment	Limited: requires scale/condition corrections
Primary application	Assessment of overall noise emission and environmental impact	Investigation of specific noise-generation mechanisms and model validation
Main limitations	Uncontrolled external influences; weather dependence	Results may differ from real field behavior

Table 3: Comparison of experimental techniques and evaluated parameters in wind-turbine noise studies.

Setting	Measurement instruments	instruments	Evaluated parameters	Author(s), year, ref.
Field	SVAN 958 analyzer and SV22L microphone		SPL, perception and annoyance; distance effects	Pawlaczyk et al., 2018 [71]
	GRAS Type 40PH microphone, B&K 4231 calibrator		Turbulent inflow noise; overall spectra; IEC 61400–11 compliance	Buck et al., 2016 [90]
	BSWA MP201 microphone, B&K 4231 calibrator		Trailing-edge turbulence noise; IEC 61672–1 compliance	Möllerström et al., 2015 [91]
	SVAN 912AE analyzer, SV 02/C4L microphone		Infrasound and acoustic noise; background at microphone and nacelle	Zagubien & Wolniewicz, 2019 [40]
	Prepolarized B&K 4189 microphone, 2250 analyzer, windshield		SPL, 1/3-octave bands; IEC 61400–11; background analysis	Ryi et al., 2014 [88]
Wind tunnel	GRAS 46AE microphone, NI PXIe-1082 system		SPL, acoustic spectra; peri-odogram method; tunnel background check	Li et al., 2022 [92]
	1/2" capacitive microphone, windshield		Airfoil trailing-edge noise; background-noise subtraction	Solís et al., 2018 [93]
	Panasonic WM-61A microphone, PXI-1042Q with PXI-4472, optical camera		SPL; source analysis by blade geometry	Ocker et al., 2021 [89]
	GRAS 40PH microphone		SPL, tonality, broadband levels, tonal peak shifts	Zhang et al., 2023 [94]
Field and tunnel	B&K 4006 microphone		Measurement vs. simulation comparison; IEC 61400–11 compliance	Merino et al., 2019 [95]

Table 4: Comparison of turbulence modelling approaches for aeroacoustic applications in wind turbines.

Criterion	RANS	URANS	LES	DES
Turbulence treatment	Fully modeled	Large scales resolved	Large scales resolved (SGS modeled)	Hybrid (RANS/LES)
Flow unsteadiness	No	Partial	Full	Partial
Computational cost	Low	Moderate	Very high	High
Broadband noise	Poor	Limited	High accuracy	Good
Tonal noise	Poor	Moderate	High	Good
Typical use	Aerodynamics	Unsteady flows	High-fidelity CAA	Full-scale compromise
Main limitation	No turbulence resolution (no broadband noise)	Missing small scales (high-frequency loss)	High cost (wall-resolved requirements)	Model-switch sensitivity (grid-dependent)

Table 5: Summary of aerodynamic blade modifications for wind-turbine noise mitigation and performance optimization.

Modification type	Feature	Main findings	Author(s), year, ref.
Geometry change	J-shape profile	Increased low-frequency noise; reduced high-frequency noise	Mohamed, 2019 [102]
	Solid vs. hollow	−1.9 dB (53%) noise; −1.6% power	Pourrajabian et al., 2023 [112]
Serrations	Triangular; porous material	−2.4 dBA (serration); −1.2 dBA (porous)	Merino et al., 2019 [95]
	Trailing edge	−10 dB noise; CP up to +72%	Sadeghimalekabadi et al., 2024 [121]
	Toothed geometry	Lower noise and power output	Volkmer et al., 2021 [111]
	Triangular teeth	+0.7% annual energy production	Zhou et al., 2022 [114]
Flaps	Trailing-edge add-on	CP increase (max. 8.79%)	Khaled et al., 2019 [100]
	Addition and modification	−10.2 dB noise	Ye et al., 2023 [122]
Serrations + flaps	Trailing-edge add-ons	−2.7 dB (low frequencies); −9.1 dB tonal components	Khalaf & Kennedy, 2025 [123]
Bio-inspired	Leading/trailing edges	+6.9 dB at mid/high frequencies; −2.13% CP	Feng et al., 2023 [116]