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A roadmap for required technological advancements to further reduce onshore wind turbine noise impact on the environment

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Abstract

The noise emission of wind turbines and farms can be an important and limiting factor for future cost reductions and growth of wind energy. Closing scientific and technological gaps on wind turbine noise is thus directly supporting the further development of renewable energy while reducing adverse reactions toward wind farms. The present article is providing guidance on the most relevant research directions from an engineering perspective, namely: simulation methods, wind tunnel testing, and wind turbine design. Each topic is addressed separately and specific scientific challenges are identified. Future research directions that may improve our physical understanding of wind turbine noise, as well as facilitate the deployment of wind energy, are outlined. It is concluded that future scientific research on the topic of wind turbine noise should be conducted in a multidisciplinary context to maximize its impact. The suggested topics shall be seen as a collection of what is seen as the most relevant topics across research and product development but shall not be seen as exclusive or interlinked with specific development plans.

This article is categorized under:

Sustainable Energy > Wind Energy

Human and Social Dimensions > Social Acceptance

KEYWORDS

noise and vibration, simulation methods, wind tunnel testing, wind turbine design, wind turbine noise

1 | INTRODUCTION

Onshore wind turbine noise is dominated by flow-induced noise sources on the blades and can thus be reduced by limiting tip speeds. However, lowering tip speeds limits the annual energy production and consequently increases costs (Clifton-Smith, 2010; Jianu et al., 2012; Leloudas et al., 2017). *Low-noise wind turbine design* allows to control noise at higher tip speeds and therefore, supports the important goal of lowering the costs of wind energy. *Noise simulation* *methods and wind tunnel testing capabilities* are important enablers for low-noise wind turbine design. The development of measures to control machinery noise also plays an important role.

This document attempts to summarize the necessary scientific and technological progresses that need to be achieved to enable the design and operation of low-noise wind turbines.

2 | CATEGORIES OF NEEDS

Wind turbine noise is a complex multi-physics phenomenon, ranging from noise generation either from aerodynamic or mechanical sources, to noise propagation with various types of interaction with the atmospheric flow and the surrounding terrain in an unsteady environment with continuously changing boundary conditions.

The future most probably lies in a better understanding of the coupling between the above phenomena, so that the noise emissions can be better controlled to meet regulations in terms of noise immission levels at the dwellings. To achieve that, we need to improve:

- noise (generation and propagation) simulation methods,
- wind tunnel testing capabilities,
- low-noise wind turbine design.

It is virtually impossible to address all these aspects at once, and further studies in each area are required to understand their mutual interactions. The particular needs are addressed in the following four chapters.

3 | NOISE SIMULATION METHODS

Many efforts concentrate on broadband airfoil trailing-edge noise which is recognized as the dominant noise source. Other sources are inflow-turbulence/leading-edge interaction noise, stall noise, and noise caused by the blade-tower passage (all at low frequencies) or tip noise (at mid- to high frequencies). Manufacturers routinely apply semi-empirical noise prediction methods that have been refined and calibrated to a satisfactory accuracy (Brooks et al., 1989; Lau et al., 2017). However, such empirical models are not necessarily well-suited for future technological developments as they only apply within known design spaces (Sucameli et al., 2018). Wind turbine aerodynamic noise prediction is highly linked to rotor flow simulations from which the main flow characteristics (e.g., relative velocity and angle of attack of the flow impinging onto a blade section) impacting the noise generation are derived and used as inputs for noise models. Rotor flow simulation methods provide indications on specific phenomena such as separation, unsteadiness and other relevant interactions (Greco & Testa, 2021; Laratro et al., 2014), but some may also have their limitations (Boorsma et al., 2018).

High-fidelity methods in computational fluid dynamics (CFD) and aeroacoustics (CAA) lead a step further toward the next generation of quieter turbines. Today's computational capabilities offer new perspectives to gain detailed insight into the physical phenomena (Arakawa et al., 2005; Delfs et al., 2018; Faßmann et al., 2019; Lele & Nichols, 2014) as illustrated in Figure 1. However, further research and development is needed to enhance reliability and efficiency of current CAA approaches so that they are applicable in the context of fast industrial design loops. On the one hand, non-empirical, yet fast prediction schemes are required as a tool to exploit the complete design space for low noise. On the other hand, highly accurate schemes are needed for the analysis of given designs. Future methods should consistently represent all relevant noise sources over the entire relevant frequency range, including the effect of complex noise reduction add-ons, and should also consider the unsteadiness of inflow and propagation conditions. Amplitude modulation and low-frequency noise are important aspects in this respect.

Because of the important aerodynamic noise reductions achieved so far, mechanical noise can emerge more distinctly over aerodynamic noise in certain circumstances. Thus, its accurate prediction has become more critical. Mechanical noise, which is characterized by tonal noise as opposed to broadband for the above-considered aerodynamic noise sources, presents also challenges in terms of numerical prediction (Citarella & Federico, 2018; Kam, 2010). Indeed, the many structural components of the nacelle (where most of vibrations are generated because of rotating machineries, fans, and coolers) constitute a complex system which is difficult to model. In addition to the mutual

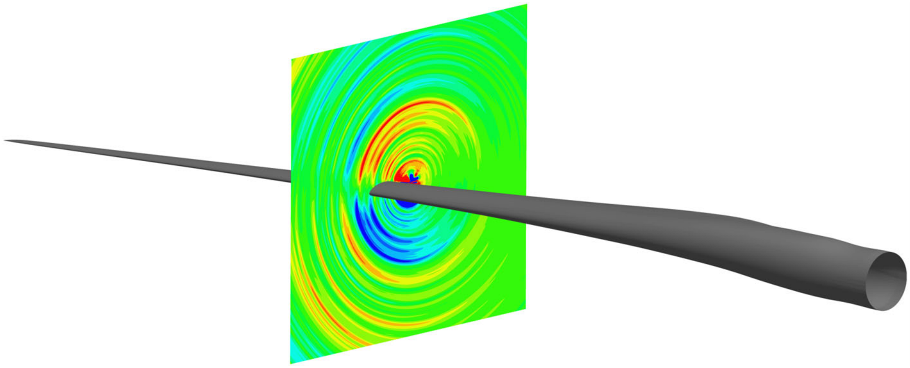

FIGURE 1 Instantaneous sound field around a wind turbine blade section as calculated by computational aero-acoustic (CAA) simulation (Source: Faßmann et al., 2019).

interactions between components, it is difficult to accurately characterize the various structural excitation loads and their path within the above complex system. Full-scale Finite Element Analysis of the entire system is a daunting task, and current research efforts focus on Modal Analysis and Reduced Order Modeling. Furthermore, the vibro-acoustic transfer phenomenon itself requires dedicated techniques that are still the subject of active research (Kirkup, 2019).

Noise propagates in the far-field to dwellings. Understanding and quantifying this propagation phase is critical to evaluate the noise immission. A better understanding of sound propagation under atmospheric conditions is of particular importance here (Attenborough, 2014; Wilson et al., 2015). Models used in the industry are typically based on empirical or semi-analytical ray methods and work well for standard and typical conditions but may lack accuracy for specific terrains and atmospheric conditions. Numerical methods to improve the prediction of sound immissions are emerging but still confined to the academic world (Blanc-Benon et al., 2001; Lee et al., 2000). Deepening the understanding of sound propagation along with the industrialization of advanced numerical methods for sound propagation for arbitrary (potentially complex) site conditions is one of the keys for better planning and acceptance of wind parks. A globally and commonly accepted fast engineering propagation model would certainly further help to reduce uncertainty while improving efficiency in the planning processes.

So far, little focus has been set on the aspect of prediction uncertainties. A detailed assessment and documentation of uncertainties, data validity ranges, and parameter sensitivities (e.g., associated to model assumptions or related aspects) would help defining constraints for overall robust designs.

4 | WIND TUNNEL TESTING CAPABILITIES

Today's capabilities to quantify typical wind turbine noise sources in wind tunnels are limited due to the generally very low sound intensity of airfoil noise with relation to test rig and wind tunnel self-noise. It is possible to measure trailing-edge noise in several wind tunnels, but additional research is needed to correctly extract the lower frequency content of the spectrum at industrially relevant scales and velocities, that is, an important part of the trailing-edge noise emission (Merino-Martínez et al., 2019).

In addition, there exist only few testing capabilities today for inflow-turbulence interaction noise, stall noise, and tip noise. Wind tunnel testing capabilities need to be extended to gain knowledge on the impact of atmospheric turbulence on aerodynamics or aeroacoustics (Figure 2).

Similarly, to noise simulation techniques, the issue of the uncertainty of measurements is relevant to comprehensively validate the above simulation methods. Indeed, without such information, it is difficult to infer the actual uncertainty of the noise emission of the final wind turbine design. There is a significant research need in filling these gaps. Here, the combined supportive application of both simulation and measurement technologies is recommended to push existing wind tunnel capabilities beyond the limits. A larger collaboration across industry and academia is desirable to cope with these challenges.

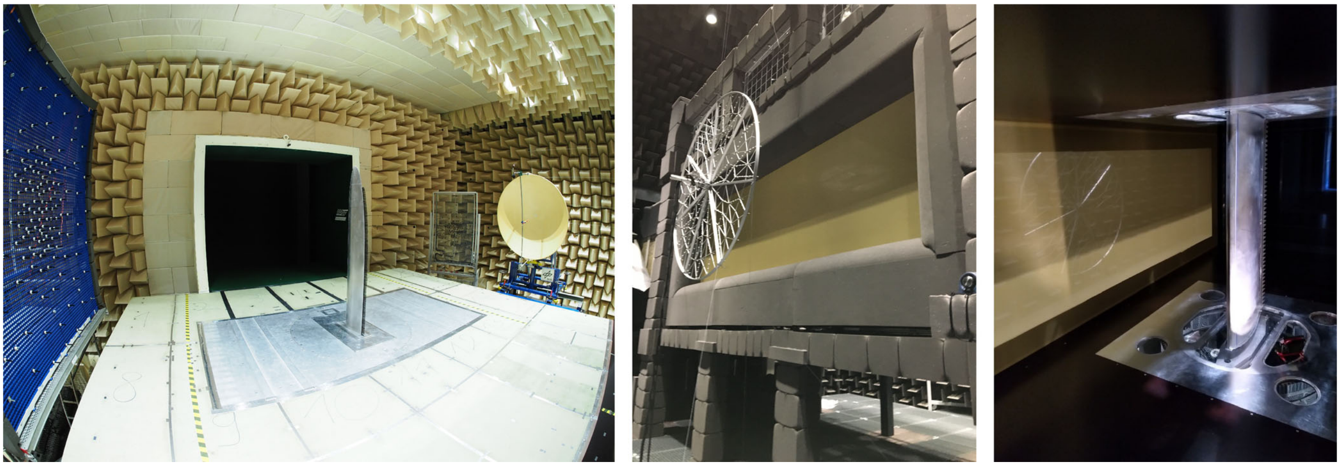

FIGURE 2 Two possible configurations of anechoic wind tunnel test facilities for aero acoustic measurements (left picture: The DNW-NWB wind tunnel in Braunschweig, Germany, here with 3/4-open test section setup. The microphone arrays and the directional microphone system (elliptic reflector) on the sides of the chamber, out of the way of the air flow, are used to measure the sound pressure emanating from the object at the center of the chamber in the air flow; middle and right pictures: The PLC closed-section wind tunnel at DTU Wind and Energy Systems, Roskilde, Denmark. A Kevlar wall contains the air flow inside the section, but is transparent to acoustic waves. The microphone array is located outside and can measure sound pressure emanating from inside the test section).

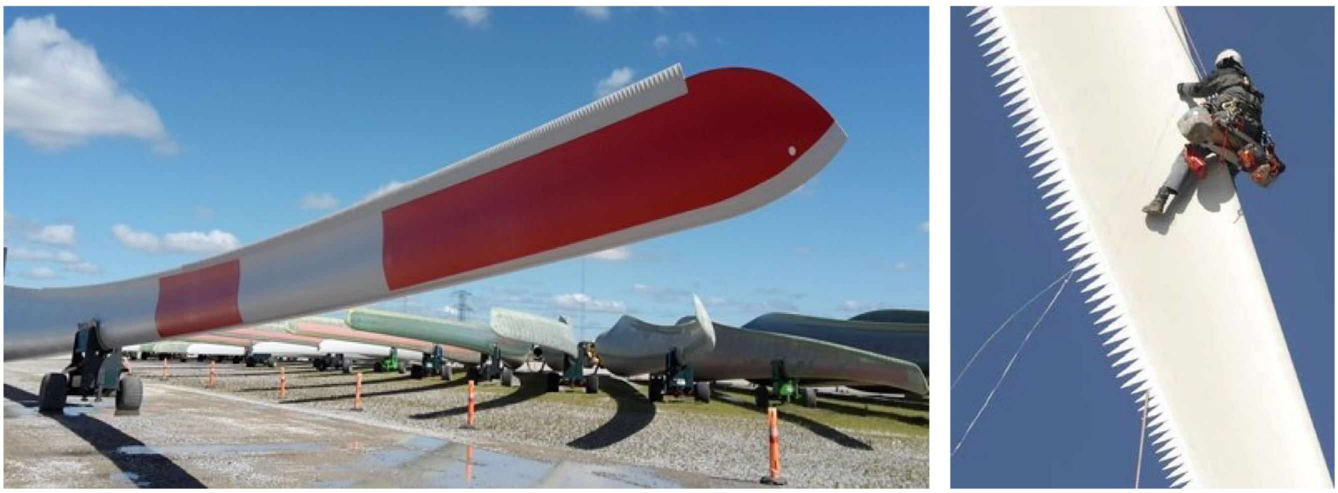

FIGURE 3 Serrations mounted on wind turbine blades (Source: Siemens Gamesa Renewable Energy (Oerlemans et al., 2009)).

5 | LOW-NOISE WIND TURBINE DESIGN

During the last few decades, better physical understanding and technological progresses have led to significant reduction of blade noise and thus, overall wind turbine noise. A recent important technological step is the now widespread use of low-noise airfoils and trailing-edge serrations (saw-tooth at the rear part of the blades, see Figure 3). These kinds of technologies can be utilized to reduce absolute noise levels or to allow higher tip speeds.

Even if large achievements have been already made, any further source noise reduction is an important additional contribution toward lowering the cost of wind energy. Indeed, a reduction of the noise emission directly translates into allowing higher tip speeds, and subsequently the energy yield. Future research should accordingly address more advanced low-noise solutions and enhance technology readiness of already proven concepts (Ai et al., 2016; Delfs et al., 2018; Finez et al., 2010; Geyer et al., 2010; Herr, 2008; Winkler et al., 2012).

The issue of amplitude modulation has been discussed for over a decade. Its origin and impact have been partly understood (Oerlemans et al., 2018), although its interaction with atmospheric effects (e.g., propagation), or in the context of a wind farm, are still poorly understood. Dedicated strategies may be implemented to mitigate its occurrences (Bertagnolio et al., 2014). Nevertheless, any mitigation approach would require further research, testing, and validation.

The reduction of overall aeroacoustic noise has put new focus on machinery noise contributions from, for example, gearboxes, generators, and cooling systems as they can be tonal and thereby, can be annoying, even if they are not contributing significantly to the overall noise emission levels. Continuous effort is made to control those noise sources by design and means of standard noise and vibration mitigation elements. A comprehensive, validated modeling approach that allows the quantification of tonal levels due to, for example, gearbox or generator internal vibrations is still under development and challenging due to the complexity of the problem (Gupta & Madsen, 2019; Vanhollebeke et al., 2012). Filling this gap is needed to find cost optimal solutions for tonality transfer to the surroundings and enable harvesting of the full potential of aeroacoustic noise reduction technology. In this context, the concurrent development of passive and active measures to control machinery noise must be more emphasized.

The modern 3-bladed rotor concept is the classical platform for MW-size turbines. However, new technological developments and economical context could open the road to innovative concepts (e.g., multirotors (van der Laan et al., 2019), tip-rotor (Leithead et al., 2019), and so on) which may change the soundscape as well.

6 | CONCLUSION

In parallel with the rapid development of wind energy over the last few decades and the relatively widespread deployment of on-shore wind turbines in the landscape, important progresses have been achieved to reduce their footprint in terms of noise emissions, and to properly evaluate noise immission levels and their impact on neighboring residents.

Nevertheless, the present document identifies a number of technological aspects for which further research advancements are necessary to even further reduce the acoustic environmental impact of wind energy.

It is shown that the above technological gaps range from practical engineering considerations to advanced computational methodologies. These different aspects of the problem are intertwined with more economical and societal issues such as the cost of energy and public acceptance, increasing its complexity as conflicting design constraints and interests must be fulfilled simultaneously. It can, therefore, be concluded that the above-mentioned required technological advancements and associated research should be conducted in a multidisciplinary perspective to maximize their effect.

AUTHOR CONTRIBUTIONS

Franck Bertagnolio: Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Michaela Herr:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal). **Kaj Dam Madsen:** Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the article and there is no financial interest to report.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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