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Wind Turbine Noise 2023

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ABSTRACTS BOOK

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Schall_KoGe - measurements, simulations, and validation of wind turbine noise in complex terrain

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The project that was carried out from 2018-2022 was aimed at the realistic forecast of wind turbine noise and tested methods based on comprehensive long-term measurements of meteorology and sound as well as operational data from wind turbines at two sites. Precise flow models were used, as were various sound forecast and propagation models, and all results were compared with the measurement data.

This article presents the main results and problems of the project. The propagation conditions were classified, which allows the comparison of measurement results and model calculations. The source parameterization of the wind turbine was extensively examined so that a simplified yet realistic noise forecast is possible.

Finally, a scientific model was compared with conventional calculation methods and the differences are presented.

Exploring the effect of wind farm flow on wind turbine noise propagation through numerical simulations

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Wind turbine noise is a significant obstacle to the expansion of wind farms. To understand the generation and propagation of wind turbine noise, various models have been developed in recent years. They are generally used to compute the noise generated by a wind turbine according to its geometry and the characteristics of the surrounding flow, and to consider topographic and meteorological effects on sound propagation. The flow around the turbine is known to have a significant effect on wind turbine noise propagation. Although the flow inside a wind farm has been thoroughly studied, insight into the effect of this flow on sound propagation is limited. However, the flow inside and around a wind farm, including the interaction between different wind turbine wakes, can significantly impact wind turbine noise production and propagation.

This study aims to investigate this phenomenon through numerical simulations. A method for coupling several models is employed to predict the noise produced by the wind farm. It uses large eddy simulations to determine the mean flow in and around the wind farm, an extended source model to predict the sound generated by each turbine, and a propagation model to consider the effect of the flow on sound propagation. Two idealized wind farm configurations are studied under neutral atmospheric boundary condition. The wind turbine noise produced and propagated inside a wind farm is compared to an isolated turbine case.

High resolution analysis of measurements, and comparison of models for ong distance noise propagation over water for an elevated height-adjustable sound source

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This paper compares the results of a measurement campaign for downwind noise propagation over water for elevated sound sources with different relevant propagation models. The analysis of the measurements utilizes a technique that increases the signal-to-noise ratio when analysing tone sweeps, that were propagated from the sound source, compared to the common 1/3 octave band analysis previously used. Comparison of these results are made to a number of models and methods, both non-country specific models like the Nord2000 model, WindSTAR-Pro and ISO 9613-2, but also country specific models like the models used in Denmark and Sweden. Noise propagation over water for elevated noise sources is specifically relevant for offshore wind turbines, near shore wind turbines or wind turbines on land close to large water bodies. The measurement setup uses a height-adjustable sound source (81 m, 50 m and 30 m above ground) and microphones positioned downwind (at shore and ~100 m inland) from the sound source (~3 km, ~5 km and ~7 km distance over water). The meteorological conditions (wind speed, wind direction, atmospheric stability, temperature, humidity, etc.) were monitored continuously at both ends of the setup, utilizing both a tall met mast, a wind profiler and sonic anemometers at multiple heights.

Do measured immission data support the accepted norms on wind turbine propagation directivity as reported by the IoA GPG and is wind speed a significant variable?

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This paper provides analysis of directivity effects on wind turbine sound propagation from a far field perspective, and assesses the influence of wind speed. The study draws from more than 8 years' worth of post-completion measurements conducted by Green Cat Renewables (GCR) since the current Institute of Acoustics (2013), 'A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise' guidance1 (IoA GPG) was issued in full. The study highlights where results support or contradict the studies referenced in the IoA GPG; particularly: Wind Turbine Acoustics, NASA Technical Paper 3057, (1990). The 'NASA' results reproduced in the IoA GPG indicate that, for distances of up to 5.25 tip heights, attenuation of 2dB relative to downwind propagation can be expected for directions ±10° from cross-wind but with no attenuation shown for upwind conditions.

Influence of atmospheric boundary layer characteristics and source height on sound propagation from a 5 MW wind turbine

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In response to the growing concern over noise pollution generated by wind turbines and its adverse impact on living organisms, the current research endeavours to contribute to the wind energy industry by improving our understanding of sound propagation. The investigation focuses on the transmission of monotonic sound waves of 100 Hz and 300 Hz through a neutral turbulent atmospheric boundary layer (ABL). Variability of the ABL has been investigated by describing two different surface roughness values that effectively influence ABL characteristics. This study examines the influence of sound source height, viz. 25m, 88m and 151m, distribution of sound pressure level (SPL) in the vicinity of a 5MW wind turbine (1km upwind and 2km downwind). These source heights correspond to hub height and extreme blade tip heights of a typical 5MW wind turbine. The velocity fields have been generated using an actuator-line on the spatial model embedded in a large-eddy simulation (LES) domain Difference Time Domain (FDTD) acoustic propagation solver, developed in-house, The spatial derivatives in the governing linearized Euler equations are discretized using an 11-point central differencing scheme while explicit time stepping is performed using an optimized low-dispersion and low-dissipation 4th order Runge-Kutta method. The ground surface is set as a perfectly reflecting boundary and a porous absorbing layer with a width of 20m is implemented on the remaining boundaries to minimize spurious reflections. Contours describing the distribution of relative sound pressure levels (RSPL) and SPL over the two-dimensional domain of size 3000 m x 1000 m is reported in the study. The transmission Loss at different locations along the ground for the test cases are also presented. The study indicates that the characteristics of the atmospheric velocity field, such as turbulence intensity and inflection point, have the potential to change sound pressure levels at far field regions up to 2 km in the downwind direction.

Evaluation of real noise effect inside the dwelling with open windows, a methodology

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In several countries, noise limits for wind energy depend on the comparison between background noise and total noise. Inside a dwelling with open windows a fundamental difference between background noise and turbine noise comes from the fact that background noise is omnidirectional while turbine noise has a definite direction. With background noise the difference between noise outside the dwelling and noise inside the dwelling with open windows is significant and literature has analyzed it. A different situation happens with turbine noise because the correction factor depends on the relative geometrical position between the window and the single turbine. The sum of the effects of all the different turbines on the single window creates a specific effect that is highly dependent on the direction of the window. To analyze the noise inside the dwelling with open windows we propose both an acoustic model that represents the situation and a measurement. We compare the results of three contemporary noise measurements of a real case. The three sound level meters are positioned inside the dwelling without direct visibility towards the turbines, on the window plane with direct visibility towards the turbines, and outside the dwelling. This allows the verification of the parameters of the acoustic model. The result is an assessment of the influx of the relative geometrical position between the window and the turbine. This result is later used to propose a methodology of calculation of the noise inside the dwelling that considers separately every couple turbine-window. A further result is a proposal of calibration of the parameters of this methodology.

WindTUNE: a new tool for modelling wind farm noise uncertainties

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Representative predictions of wind turbine noise require to accurately model the main mechanisms and characteristics of acoustic emission (i.e. extended sound source with aeroacoustic noise generation) and acoustic propagation in outdoor environment (i.e. ground effects and atmospheric properties). As these phenomena fluctuate over time and space, it leads to great uncertainty on Sound Pressure Level (SPL) estimated at local resident buildings/facades. Such uncertainty is not yet properly quantified by engineering noise prediction models. Thus, this paper presents a modeling tool developed in the framework of the French project PIBE, which aims at quantifying the SPL uncertainty involved in wind farm noise predictions. Ultimately, this modeling tool will be freely available online and will help to better understand the risk of noise pollution at each stage of a wind farm’s life, in order to guarantee compliance with the regulatory requirements concerning the exposure of local populations.

Noise curtailment plan optimization and manufacturer constraints

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To comply with acoustic constraints, wind farms are occasionally operated using predefined curtailment modes. The definition of optimal curtailment plans is a crucial point for wind farm developers and operators. Their implementation by the turbine manufacturer imposes the plan to satisfy some design rules that are not always accounted for in the optimisation process. This constraint introduces complexity in the optimisation process and thus increases significantly computational times. This paper proposes an approach to compute curtailment plans sacrificing a bit of optimality to favour the computation time. The idea is to first compute the optimal curtailment plan without the turbine manufacturer constraints and then fit it to the manufacturer constraints. Some illustrative applications are proposed suggesting that these constraints cannot be ignored within the optimization process, in particular when the number of commands is very limited (below 6) and that the command prioritization option is not possible. These cases are also a reminder that the availability of truly efficient noise reduction operational modes is key.

Wind turbine directional noise reduced operations – description and measurement

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Wind turbines can be placed into NRO (noise reduced operation) modes to reduce sound emissions. These modes can be implemented for all meteorological conditions and time periods, or for specific conditions (wind speed and direction) or time periods. The current paper describes how they work and provides measurement results from a project where they are applied.

Optimizing the locations of turbines in a wind farm according to acoustic and spatial constraints

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Within the framework of environmental impact studies of wind farms in France, acoustic propagation software are used to define the regulatory exceedances of the noise emergence criterion. Based on these results, the acoustician then proposes a noise curtailment plan which defines the operating mode of each machine at different wind speeds and wind directions. Experience shows that noise curtailment plans lead to losses in electricity production ranging from 4-5% on average to 10-12% - and even more for very sensitive projects. For this reason, we have developed an algorithm that optimises not only the operating modes of the machines, but also their position. This optimisation algorithm, called OPPIO, finds a layout that minimises production losses while considering the displacement constraints of each wind turbine. It is achieved by coupling the output of the acoustic model (CadnaA) to a Mixed-Integer Nonlinear Programming (MINLP) model.

A year in review: ANSI/ACP's new standard for wind turbine sound predictions

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Common methods for modeling wind turbine sound rely on sound power levels from International Electrotechnical Commission (IEC) 61400-11 and propagation algorithms from International Organization for Standardization (ISO) 9613-2. Typical approaches in the United States yield relatively similar results; nonetheless, standardization of prediction methods was pursued to facilitate a robust and repeatable process that increases regulatory confidence and comprehension. American Clean Power Association (ACP) is recognized by the American National Standards Institute (ANSI) as an Accredited Standards Developer. ACP established a wind turbine sound modeling standard working group and reached consensus on a preferred method for predicting sound levels during the siting and permitting process. ANSI approved this standard in April of 2022 and made it available on the ANSI website in the fall of 2022. A primary goal of this new standard was to establish a uniform method of predicting future project sound levels such that predevelopment sound assessment results and predictions used in research can be readily compared. Initial indications are that this goal and the corresponding goals presented in this paper are being achieved.

Practical application of standard 61400-11 : lessons learned on a case study

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This paper describes a measurement campaign to test the sound power level of a wind turbine following precisely the IEC 61400-11 standard. In a first step, an IEC compliant analysis is done. This is followed by a discussion on the practical implications and choices of the IEC methodology.

Guidelines for Environmental Assessment of Wind Farm Noise in Chile

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If investors plan to build a wind farm or other type of power plant in Chile, an Environmental Impact Assessment must be completed if the project produces more than 3 MW. This assessment must consider a noise and vibration impact study, among others. Related to the noise part, according to law 19.300, there are different environmental protection objects, such as population’s health, natural renewable sources (native wildlife), the system of life and customs of human groups, tourist value of an area, and cultural heritage. Therefore, an environmental assessment of wind farm noise must consider all these environmental protection objects. This work presents guidelines for assessing environmental noise in these protection objects, including an application to a real project in Chile. In this sense, the noise regulation decree DS38 enacted by the Chilean Ministry of the Environment is recommended for assessing the effects on the population’s health. For natural renewable sources (native wildlife), several international studies are used for different species. For the system of life and customs of human groups and cultural heritage, the Spanish Royal Decree 1367/2007 is recommended. Not exceeding background noise is advised to assess the tourist value. The results of several projects in Chile have shown that a wind farm project can have a potential noise impact area at a distance of 2 km around the wind farm, which is very similar to the potential impact area related to shadow flicker.

Wind energy and health: the Dutch case

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Tulips, wooden shoes, cheese and windmills form the classic image of the Netherlands. But Dutch policy is also focused on developing more sustainable forms of energy. To meet the challenge of producing more sustainable energy, wind turbines have become an increasingly common feature of the Dutch landscape in recent years.

As a result of the national energy strategy, the expansion of wind energy (number, output) on land will increase in the coming years. This raises concerns and questions about the safety and health of local residents and the need for accessible information on the subject. For these reasons, the Wind Energy and Health Competence Centre (2021) has been established at the RIVM.

The aim of our center is to build, secure and share knowledge about wind turbines and health (e.g. noise, shadow, external safety risks, visual aspects, erosion). This includes relevant factors that influence this relationship (such as non-acoustic and non-visual aspects, e.g. level of participation, noise sensitivity, attitudes towards wind turbines). In the competence centre, we also work with the municipal health services (GGDs) in the Netherlands, who receive many questions from citizens and local governments on the topic of wind turbines and health. Examples of our knowledge building and dissemination activities include quarterly alerts of new scientific and grey literature (published on the RIVM website), structured literature reviews, conference visits and conducting research (perception research, exposure-response research). The presentation will cover the background, structure and activities of the Wind Energy and Health Competence Centre. Furthermore, the content of some of our current projects (e.g. literature review, research studies) will be explained in more detail.

Standards for regulating environmental impact of wind turbines

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As a result of a motion in the Dutch House of Representatives and the intention in the Dutch coalition agreement 2021-2025 to set clear distance standards for wind turbines, the Dutch Ministry of Economic Affairs and Climate Policy commissioned Arcadis to conduct research into standards for regulating the environmental impact of wind turbines. The goal of the study was to describe effects of different distance standards on nuisance for residents and to go into the advantages and disadvantages of a distance standard compared to specific standards for noise and shadow flicker. As a result of a court verdict in June 2021 the Netherlands currently has no national regulation for wind farms. A literature search has been carried out into the previously applicable standards for wind farms in the Netherlands, how these were established and the underlying considerations. This research has also been carried out for seven other European countries. The research focused on distance standards and standards for noise and shadow flicker. The noise and shadow flicker impact at different distances to a wind farm has been portrayed.

Study on the Capabilities of a TNO-Based Trailing Edge Noise Pre- diction Tool Applied to Boundary Layer Suction on a NACA 64-418 Airfoil

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Recent improvements to the TNO-based IAGNoise+ trailing edge noise prediction tool better capture the noise emissions for angles of attack up to moderate flow separation. This improved prediction capability is of particular use in studies on the efficiency of boundary layer suction as a trailing edge noise mitigation measure. As a method of active flow control this can delay the onset of flow separation along the airfoil surface and reduce the turbulence kinetic energy and turbulent length scales of the flow when passing the trailing edge, where turbulent energy is then scattered into sound. In order to predict the decrease in noise achieved by this kind of boundary layer control, an accurate prediction of the baseline sound emissions without suction is essential. Wind tunnel measurements are available for a NACA 643 − 418 airfoil with and without boundary layer suction through a porous plate for angles of attack of 0°, 3° and 6° and can be used for validation of the predictions. Based on steady Reynolds-Averaged Navier Stokes computations, the previous as well as the improved IAGNoise+ implementation will be compared to these wind tunnel results. First, the boundary layer parameters related to trailing edge noise generation will be examined, followed by the resulting sound spectra.

Numerical Study on the Reduction of Blunt Trailing Edge Noise by the Use of Vortex Generators

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The size of horizontal axis wind turbines will continuously increase leading to new challenges in aerodynamics and aeroacoustics. One of these challenges is the design of the blade root section: For structural reasons, a very high blade thickness in the root area is necessary which results in strong adverse pressure gradients and potentially flow separation. In order to delay these separations, so-called flatback airfoil shapes can be used. The flat back shape decreases the strong adverse pressure gradients. In the wake behind the blunt trailing edge, as the airfoils are bluff bodies, a von Kármán vortex street forms and induces strong pressure fluctuations on the surface of the blunt trailing edge. These periodic fluctuations are the reason for blunt trailing edge noise. The following work shows that very cheap and easily retrofittable vortex generators are able to reduce these noise emissions. To investigate this effect, Delayed Detached Eddy Simulations on an extruded DU97-W-300 flatback airfoil are conducted. From an aerodynamic point of view, it is shown that vortex generators placed at a relative chordwise position of 20% or 45% have a positive effect on the boundary layer velocity distribution through a momentum transfer from the upper parts of the boundary layer towards the lower parts. In contrast, vortex generators placed at a chordwise position of 70% reduce slightly the velocity inside the boundary layer compared to the case without vortex generators. By means of Proper Orthogonal Decompositions of the flow fields, it is demonstrated that the very dominant first mode, arising from the von Kármán vortex street, is reduced by up to 15%, for the chordwise vortex generator position at 20%, and redistributed into higher modes by the effect of the vortex generators. Lastly, with regards to aeroacoustics, the use of a Ffowcs-Williams and Hawkings Code showed that the reduction of the tonal hump resulting from blunt trailing edge noise is reduced by up to 7 dB when using vortex generators.

Experimental investigation of noise from a wall-mounted swept tip blade in a wind tunnel

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A wall-mounted swept tip segment of a wind turbine blade (tip model) is tested in an acoustic Kevlar-walled wind tunnel at free stream velocities ranging from 20 to 80 m/s (corresponding to chord-based Reynolds numbers 4.9 · 105 to 2.0 · 106). The tip model used is the result of a design optimization focused on tip extensions for wind turbine blade upscaling. The trailing edge and tip vortex noise spectra are determined by integration of acoustic images generated with a microphone array using beamforming techniques. Aerodynamic lift and drag coefficients are determined from 128 s urface pressure tabs on the model and related to the acoustic results. The results indicate, that tip vortex noise is dominant at high angles of attack (corresponding to high lift coefficients) and low flow- speeds. At higher flow speeds, trailing edge noise is the dominant source of acoustic output. This suggests, that tip vortex noise is important to take into account when wind turbines are operating in low wind speeds or noise curtailment. Additionally, the acoustic spectra dependence on velocity is estimated for trailing edge and tip vortex noise. The results indicate, that trailing edge noise scales with a power between 5 and 6, and similar for tip vortex noise, but only at high lift coefficients. Despite the special model used, the presented methodology clearly shows the benefit of using acoustic imaging techniques to distinguish noise sources in a wind tunnel, and can pave way for improved tip vortex noise models in the future.

Computational study on the aeroacoustics of the X-Rotor – a hybrid vertical - horizontal axis wind turbine

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This study presents a computational aeroacoustic analysis of the X-Rotor Offshore Wind Turbine. The X-Rotor is a new offshore wind turbine concept consisting of an x-shaped vertical axis wind turbine (VAWT) combined with two horizontal axis wind turbines (HAWT). In order to evaluate performance and noise emitted from the X-Rotor baseline concept, a full-scale high-fidelity computational fluid dynamics (CFD) simulation was carried out with the Lattice-Boltzmann very large eddy simulation (LB-VLES) solver 3DS PowerFLOW. The results from the numerical simulation were used to predict the far-field sound pressure using the Ffowcs-Williams & Hawkings (FW-H) acoustic analogy implemented in the Opty∂B® software. In the present study, the X-Rotor was operated at the designed maximum power extraction condition. The rotational tip Mach number of the VAWT and HAWT are 0.19 and 0.59, respectively. The corresponding Reynolds number (Re) based on the blade sectional chord and the local flow velocity of the VAWT and HAWT are over 10 and 1 million, respectively. The results show that the VAWT is the main noise source of the X-Rotor causing high amplitude noise in the low-frequency region. Additionally, the overall sound pressure level (OSPL) of the VAWT and HAWT at a virtual microphone located at an upwind location is higher than the one computed when the virtual microphone is located at a downwind location.

Noise prediction for wind energy turbines based on CAA methods

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The here presented work is part of the HGF (Helmholtz Association of German Research Centres) -funded DLR projects ViSion (Validation of Simulation Tools for the Description of Wind Turbines) and LAiSA (Lastadaptive & Aeroakustische Analyse). In both projects we take part at the IEA Wind Task 39 – Quiet Wind Turbine Technology, code benchmark (1). The initial goal is to predict the turbulent boundary layer trailing edge noise (TBL-TEN) and the turbulent inflow noise (TIN) dominating the overall sound radiation for a 2.3 MW NM80 wind turbine. A comparison with other codes within the framework of IEA Wind Task 39 benchmark is shown in Bertagnolio et al. (2).

A process chain, originally developed by Rautmann (3), is used that breaks down the 3D rotor into individual segments, for each of which 2D CAA (computational aeroacoustics) simulations are performed to calculate the TBL-TEN contribution of each slice. Here this tool chain was picked up and supplemented: The rotation of the rotor, the associated amplitude modulation and the variation of the distance to arbitrary evaluation points for the individual rotor blade sections are considered. With the spatial information of each 2D slice related to the chosen observer point and data about the atmospheric turbulence a turbulent inflow noise model is applied. The individual contributions of TBL-TEN and TIN of the blade segments of the entire rotor are finally summarized and averaged over the rotor revolution. In addition to, e.g. the certification position according to IEC-64100-11 standard, arbitrary positions distributed in space can be specified. Third octave spectra can be exported at single observer points varying over the rotor revolution and OASPL values at spatial distributed positions in order to evaluate noise signatures.

Wind turbine noise code benchmark: A comparison and verification exercise

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In a number of institutions and companies, researchers and engineers are developing numerical models and frameworks that are used to predict the aerodynamic noise emissions from wind turbine rotors. The simulation codes range from empirically tuned engineering models to high-fidelity computational ones. Their common feature is the fact that they all specifically model the main aerodynamic noise mechanisms occurring at the rotating blades (namely, the turbulent boundary layer): trailing-edge and turbulent inflow noise. Nevertheless, different modelling techniques and implementations may generate different results, even when assessed on the same rotor design and operating conditions, which raises the question of the actual fidelity and reliability of these models. Trailing-edge noise is put at the forefront of the present study, as it is recognized to be the main source of audible noise from modern wind turbines.

The present benchmark aims at comparing the results from different modelling approaches and drawing some conclusions from these comparisons. This effort, denoted as Wind Turbine Noise Code benchmark, was initiated in 2019 as a joint activity between the IEA Wind Task 39 (Quiet Wind Turbine Technology) and Task 29 (Detailed Aerodynamics of Wind Turbines, now Task 47).

In addition to the investigation of the noise emissions themselves, the rotor aerodynamic characteristics are investigated, as they are the source of the noise generation mechanisms discussed herein.

A number of test cases are defined, and the aerodynamic and aeroacoustic predictions from the various models are compared. A fair agreement between the aerodynamic predictions is observed. There exist some discrepancies between the different noise prediction methods, but it is difficult to conclude if one methodology is better than another in order to design a wind turbine with noise as a constraint.

Aero-acoustic prediction tool for complex wind turbine blade configurations

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A semi-empirical aeroacoustic prediction package was developed in LM Wind Power to compute the wind turbine blade noise emission with various aerodynamic add-ons, including serrations, Leading Edge Protection (LEP) and Lightening Protection System (LPS). Excellent agreement between the prediction and field measurement was achieved on both the apparent sound power level (Lwa) and the spectral shape. The serration and LEP noise prediction models are the foci of this paper and will be discussed further in detail.

Evaluation of acoustic measurements in relation to annoyance reports from residents in the vicinity of a wind farm

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Within the framework of the interdisciplinary project Inter-Wind, the annoyance of residents of a wind farm is related to acoustic, ground motion and meteorological data, as well as wind turbine (WT) operational data. Measurements were carried out at a wind farm in southern Germany and in parallel at residential sites in the vicinity of the wind farm, while residents were able to report different levels of annoyance with a noise reporting app. This paper focuses on acoustic measurements in the low and infrasonic frequency range. The parallel evaluation allows filtering and assessment of the acoustic, but also meteorological and WT-operational data in relation to the annoyance periods. It has been shown, that ratings with at least somewhat annoyance are present at maximum rotational speeds of a WT, higher wind speeds at hub height and stable atmospheric conditions. Wind direction, air temperature and humidity cannot be related with annoyance reports in this study.

The masking effect of vegetation- and wave noise on wind turbine noise audibility

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In Denmark and several other countries noise is regulated as absolute levels, hence the audibility of the noise source is not directly handled.

In most countries, including Denmark, wind turbines are often set up in rural areas. Denmark is a flat, windy and in general densely populated country, but the rural areas are less populated and has longer distances between dwellings, and so it is easier to comply with the setback distances and noise demands. Coincidently some of the windiest parts of Denmark are also rural areas.

In the rural areas some of the common sources of noise is vegetation or waves, which masks other environmental noise sources. The effect of masking from vegetation and/or waves has not been studied in much detail in Denmark.

The aim of this project is to gather data from vegetation noise and wave noise and use this to form simple models for both vegetation noise and wave noise. The models are used to estimate the audibility of wind turbines erected in rural areas, considering both temporal effects, spectral effects and effects of wind turbine size, distance and wind shear.

This paper introduces the background and current status of the project, which is based on the Danish noise regulation for wind turbines and a number of investigations/projects.

Noise forecast app: positively impacting non-acoustic factors

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Literature shows annoyance by wind turbines is related to the sound level. The higher the exposure to wind turbine noise, the more annoyance occurs. However, between communities and between individual persons large differences occur in the annoyance level at a specific sound level. This is caused by a number of factors including non-acoustic factors like situational, personal and contextual factors. The interactive noise forecast app aims to positively impact a number of non-acoustic factors in the operational phase of a wind farm. Also, it aims to create more insight into the conditions in which annoyance occurs, so a more effective noise management and communication strategy is possible. The app has been and is being used in multiple projects comprehending over 100 turbines, over 500 MW wind capacity and over 17,000 addresses. This paper describes the non-acoustic factors the app is targeting, what information is presented and what the interactive part comprehends. General findings, preliminary insights and results generated by application of the app in various projects are presented.

No discernible effect of wind farm infrasound exposure on electroencephalographic markers of sleep disturbance

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There has been protracted community debate arising from unknown impacts of wind farm generated infrasound (<20 Hz noise) on human health and sleep. This study tested for acute wind farm infrasound exposure effects on electroencephalographic (EEG) markers of sleep disturbance. Sixty-eight adults underwent in-laboratory sleep studies over 7 nights, including one night with repeated 3-minute exposures to full-spectrum wind farm noise (WFN) and wind farm infrasound alone, derived via low pass filtering to remove frequencies ≥20 Hz. Noise samples were replayed in random order throughout established sleep to achieve sound pressure levels (SPLs) equivalent to 30 and 35 dBA (without the low pass filter). For infrasound, this corresponded to 71 and 77 dBG, above 90th centile levels previously measured outdoors at residences >1 km from a wind farm. To examine EEG changes relative to the pre-stimulus baseline, sleep disturbance effects with each noise type and SPL were evaluated using logistic regression analyses applied to EEG arousal and K-complex probabilities in each 5-sec window from 20-sec before to 20-sec after each 3-min noise exposure. Changes in EEG spectral power in sleep-related frequency bands over time were also evaluated. Fifty-four participants (mean±SD aged 48±20 years, 31 females and 23 males) had sufficient replicates of WFN and infrasound exposure data for analysis. Full-spectrum WFN exposure produced an abrupt and acute increase in arousal probability within the first 5-sec of noise onset (odds ratio, 2.9 [95%CI 1.6 to 5.4], p= 0.018). In contrast, infrasound exposure produced no discernible changes in arousal or K-complex probabilities, or EEG spectral power. These findings do not support that acute wind farm infrasound exposure produces any discernible EEG changes during sleep.

Socio-psychological effects of wind turbine noise: Research activities of IEA Wind TCP Task 39 (Work Packages 4 & 5)

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This paper presents a report of some of the activities of the International Energy Agency's (IEA) Wind TCP Task 39. By identifying best practices in an international collaboration, Task 39 hopes to provide the scientific evidence to inform improved regulations and standards, increasing the effectiveness of quiet wind turbine technology. Task 39 is divided into five separate work packages, which address the broad wind turbine noise topic in successive steps; from wind turbine noise generation (WP2), to airborne noise propagation over large distances (WP3). The assessment of wind turbine noise and its impact on humans is addressed in WP4, while WP5 is dealing with other aspects of perception and acceptance, which may be related to noise. All WPs contribute to a dedicated Work Package on dissemination (WP1). This paper provides an updateof activities primarily associated with the socio-psychological aspects of wind turbine noise (WP4 and WP5). Through the consideration of a wide variety of factors, including measurement technologies, auralisation and psychology, the effects on noise perception, annoyance and its impact on wellbeing and health is being further investigated. This paper presents a discussion of the activities of each member country and highlights some of the key research questions that need to be further considered.

Wind farm compared to road traffic noise onset induced arousal responses during sleep

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Despite rapid growth in wind farms globally, and community concerns regarding noise impacts, potential effects of wind farm noise exposure on sleep remain poorly understood. This study compared wind farm noise (WFN) versus road traffic noise (RTN) effects on electroencephalographically (EEG) defined arousal responses during sleep. Sixty-eight adults underwent in-laboratory sleep studies over 7 nights including, for this study, one night with repeated 20-sec WFN and RTN exposures. Following at least 2 minutes of established sleep and ≥20-sec between noise exposures, pre-recorded WFN or RTN samples were reproduced at sound pressure level (SPLs) of 30, 40 and 50 dBA in random order. The primary outcome was the probability of EEG-defined arousal events (>3 sec EEG shifts to faster frequencies) following the onset of each noise exposure. Awakening responses (≥15 sec EEG frequency shifts) were also evaluated. Noise type, sleep stage and SPL effects on arousal and awakening response probabilities were evaluated using mixed effects logistic regression analyses. Sixty-two participants (mean±SD aged 49±20 years, 35 females and 27 males) had sufficient replicates of noise exposure data for analysis. Arousal response probabilities were low, particularly in deep sleep, but showed a significant noise type-by-SPL interaction (x2=13, p=0.001), with marginally but significantly lower WFN compared to RTN arousal probabilities at 40 dBA (mean [95%CI]: 2.1 [1.5, 2.9] vs 3.2 [2.4, 4.2]%, p=0.016) and 50 dBA (5.0 [4.0, 6.2] vs 8.6 [6.9, 10.6]%, p<0.001). Awakenings were infrequent (<4% at 50 dBA) but showed similar effects. These findings support that acute wind farm noise onset events are marginally less sleep disruptive than road traffic noise events of equivalent SPL ≥40 dBA.

Analysis of Mitigation Measures for Wind Turbine Noise Annoyance – A field experiment in the interdisciplinary project Inter-Wind

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Due to the growing distribution of renewable energies, increasingly, people live in the vicinity of wind turbines (WTs). In this context, acceptance conflicts can arise due to annoyance caused by WT immissions. In the interdisciplinary project Inter-Wind on WT noise, objective measurement data were collected synchronously with subjective assessments of residents at a wind farm with three WTs in southern Germany. After strongly annoyed residents were identified in a survey, measurements were carried out at the WTs and in the municipality. Meteorological, acoustic, and ground motion measurement data as well as operational parameters of the wind farm were collected, while residents (n = 46) reported and described annoying WT noise using an app. Constantly high rotational speeds (rpm) as well as high variability in rpm, were associated with annoyance. To address these rotational patterns, mitigation measures with three different operational modes were tested in a following field experiment. During the experimental period, 36 residents used the app to log their noise perception every night. Compared to periods of normal operation (one WT noise reduced) noise reduction of all three WTs did not result in lower levels of sound perception and noise annoyance.

Closing in on the Wind Turbine “Sasquatch” – Whose Name is “Annoyance”

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A research project under way is described, the objective of which is to determine an objective measure to predict annoyance from wind turbines. Some would state categorically that there is nothing specific in the noise profile of wind turbines to cause annoyance. Claims have declared that wind turbine annoyance is the result of stress, and that stress is the result of misinformation about adverse impacts. Annoyance from wind turbines is perceived like the “Sasquatch”, a mythical being, for which there is no actual evidence. Yet, a fraction of credible individuals attest that when near operating wind turbines they are irritated, or annoyed, and suffer adverse impacts. When they separate themselves from wind turbines, or when the wind turbines shut down, the individuals find the adverse conditions diminish. However, when they are again exposed, the conditions reoccur. Over time a sensitivity seems to develop, so that the annoyance and adverse conditions occur with reduced exposure. This research project examines the acoustic, environmental, and wind turbine operational conditions existing when impacted individuals report annoyance. Factors such as wind turbine visibility, wind speed and direction, as well as the noise resulting from ambient winds are also considered. The project seeks to determine if the annoyance could be arising independent of the wind turbine noise profile, or from misinformation. Insights arising from the research are discussed, as the project circles closer, and closer, to substantiate a verifiable measure of the character of the wind turbine “Sasquatch.”

The many understandings of noise and the opportunities and pitfalls of interdisciplinary research

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The accelerated deployment of renewable energy generation is seen as the backbone of most energy transition policies around the globe. This continues to put pressure on finding space for wind farm development to fulfil the capacity targets. In turn, these deployments face increasing societal resistance in many countries (Cousse et al. 2020; Lintz and Leibenath 2020), constituting a grand challenge to wind energy (Kirkegaard et al. 2023; Veers et al. 2019). Recently, it has been argued that finding ways for how to tackle this challenge, so that wind energy is implemented in a just but timely manner, constitutes a grand challenge in itself and one that can benefit from interdisciplinary research (Kirkegaard et al. 2023)

In this presentation/session, we would like to explore how and whether an interdisciplinary approach to the 'social-technical grand challenge' of wind energy deployment is a viable solution to the entangled challenges of renewable energy deployment and social acceptance. For this, we have been working on using the case of wind turbine noise to explore the potential avenues, but also barriers, to conducting interdisciplinary research in the attempt to tackle this social- technical grand challenge.

A comparison of methods for identifying wind turbine sounds in big data sets

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For the investigation of long-term acoustic measurements in wind farms, methods for the selection of wind turbine noise are needed. In this paper, methods for identifying dominant wind turbine noise and for classifying sound scenes in a wind farm are presented, applied to a measured one-month data set and validated with manually labelled data.

For identifying dominant wind turbine noise, four methods given in the literature are applied. They are all based on statistical, acoustic criteria and differ in their complexity. Dominant wind turbine noise is correctly identified by all methods. In the case of low or no wind turbine noise, statistical criteria are not sufficient. Here, methods that also consider rotor speed show better results.

For the classification of sound scenes, two methods are used - a simple method based on acoustic and turbine-related criteria, and a more complex method using machine learning in the form of a convolutional neural network (CNN). In the examples of this work, the classes Wind Turbine, Wind and Silence are predicted well using simple criteria such as limiting the rotor speed. Bird sounds and other disturbing sounds are classified less good. The CNN-based method uses high-resolution time signals for classification, but coarse windowing was applied to the predictions for an easier comparison of the results to the other method. With normalized audio, the classes Wind Turbine and Aircraft are classified well. Broadband sounds, such as wind noise, are predicted less good. The classification of the class Bird did not yield good results for the given data, but it is suspected that it would work better with lower time scales than one minute. The prediction of the class Silence only works without normalization, such that further work needs to be done in this area.

A comparison of wind data sources for wind farm noise compliance assessments

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This paper considers a number of sources of wind data that can be used for wind farm noise compliance assessments with reference to the relevant guidance used in the UK and the Republic of Ireland.

A brief summary of existing guidance and previous papers of note is presented, and information detailing the impact of under estimating wind speeds with relevance to several different types of noise level limits is provided.

Analysis is presented which considers noise data collected during a noise compliance survey undertaken at four locations surrounding a wind farm (>10 turbines in size) situated in the UK. The noise data are correlated with various sources of wind data and the resulting average measured levels are then compared with predicted noise levels. Variation from the predicted levels is calculated and a commentary is provided on which sources correlate most closely, where the correlation is poor, consideration is given to why this may be.

The use of proxy monitoring locations to assess planning compliance at receptor distances.

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This paper reports an investigation to establish the ideal position for a proxy measurement, relative to a wind turbine or wind farm, from which the results could be extrapolated to receptor distances for the purposes of establishing planning compliance in the UK. The study draws from more than 8 years' worth of post-completion measurements conducted by Green Cat Renewables (GCR) since the current Institute of Acoustics (2013), 'A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise' guidance (IoA GPG) was issued in full, in particular 'Supplementary Guidance Note 5: Post Completion Measurements' (SGN5)1. Data collected at several distances from a variety of different turbines was compared with expected immissions according to SGN5 assuming the turbines were operating to manufacturers' expectations based on IEC-61400-11 measurements. Level difference (LD) between operational turbine noise and background noise was considered in relation to the validity of turbine immissions derived from measurements.

Continuous monitoring of wind turbine noise

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This paper presents the specificities and results of a cost-effective continuous monitoring system that was designed specifically for wind turbine noise analysis. The system utilizes Class 1 sound level meters, which are synchronized with other data sources such as audio/video recordings and meteorological data from local stations. The results are published on a web platform in near real-time, allowing for the identification of specific noise events and the automatic control of relevant parameters. The system can detect tonal characteristics using the ISO/TS 20065:2022 method and amplitude modulation, both of which are factors typically associated with wind turbine noise discomfort.

Apportionment of wind farm noise limits: Observations from using UK good practice guidance

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Wind farm noise limits in the UK are set in accordance with the guidance contained in ETSU-R- 97 'The Assessment and Rating of Noise from Wind Farms'. ESTU-R-97 establishes that noise limits should apply to the combined operation of all wind farms and when multiple wind farms are proposed, it may be necessary to apportion the noise limit.

In 2013, the Institute of Acoustics published 'A good practice guide to the application of ETSU- R-97 for the rating and assessment of wind turbine noise.' (IOA GPG). The IOA GPG provides a number of methods which can be used to consider cumulative noise such that Site Specific Noise Limits can be established for individual schemes. One of the options considered in the IOA GPG is 'apportionment of the ETSU-R-97 limits on an energy basis'.

By assuming apportionment on an energy basis relates to the acoustic energy of the noise predictions for each of the proposed schemes, noise limits would be created where each schemes share a proportionate amount with respect to their predicted noise levels. This approach can work well where predictions indicate that all schemes can coexist within the ETSU-R-97 limits. Where predicted levels exceed the limits apportionment on an acoustic energy basis, all schemes will need to reduce noise emissions (regardless of how acoustically dominant each scheme is).

An alternative approach is that the limits could be apportioned on the basis of the energy yield that will be generated by each scheme. This would result in limits being apportioned in such a way that energy generation is maximised.

Within this paper, example scenarios will be presented where limit apportionment using each method will be undertaken. Commentary will be made on the practicalities of each approach and the potential positive and negative impacts each approach can have on the proposed schemes.

Uncertainties on measured and predicted noise levels for wind farms. Do we need it?

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Assessment of the noise from a wind farm usually gives you a decibel value from which the authorities decide compliance with noise criteria or not. Not many considers the validity of this number or tries to make a qualification through an uncertainty evaluation. Measurement of noise from wind farms can be difficult owing to the dependence of wind speed and direction as well as other meteorological parameters. Most often the noise level is close to the noise limits and the noise limits are close to the background noise in the area. A series of measurement principles are listed in the coming Technical Specification IEC 61400-11-2 which also includes a proposal for an evaluation of the uncertainty. From the discussion behind this document, it is not clear if it is operational in all cases and practice on how to apply these uncertainties is different in different regions. This presentation will focus on the necessity of uncertainties and how to use them if at all.

Evolution of sound production of onshore wind turbines

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The sound power Lw of wind turbines (WTs) over time has developed in relation to their electric power P as Lw ∝ logP. The spectral distribution of the sound did not change significantly over time. This applies to the average performance of wind turbines, but there are differences between individual WT types. Because of the rapid and substantial growth of onshore wind energy, a greater number of people will be living close to wind farms. This sustains the need for WT sound power reduction. The use of sound reduction measures such as serrations, reduced tip speed and low noise modes, may counteract the development of higher sound power from ever bigger WTs. To investigate this, the sound production of WT types over the last decade is analysed in relation to their size and electric power and the application of sound reduction measures. The analysis includes the broad band A-weighted and the low frequency sound power levels.

Experience using the IOA AM method, and how the results may vary with distance and direction

Tom Levet (Hayes McKenzie Partnership)

A method for quantifying the amplitude modulation characteristics of wind turbine noise was proposed by a working group setup by the UK Institute of Acoustics. This paper provides a note on some of the in-field experiences using that method. Several measurement locations at various sites have been analysed. These locations are at a variety of receptor distances, and due to the nature of the surveys occurred in a variety of wind directions relative to the wind turbine(s). The results have been normalised to a relative direction in order to investigate trends within the results. The summaries provided are not intended to be exhaustive of the range of results that may be possible, and there would still seem to be a need to treat results on a site-by-site basis. Nevertheless, it is intended the results may be helpful in furthering the understanding of if, or how, it may be possible to predict where high levels of modulation may occur, for potentially undertaking risk assessments for future projects.

Detection and assessment of amplitude modulated noise of wind turbines

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Wind turbines are important for a sustainable energy supply and their expansion contributes significantly to achieving independence from fossil imports. The noise emitted by these turbines is often discussed in politics, the media and the public. In order to prevent harmful effects on human beings and the environment, various industrial and commercial installations are subject to licensing in Germany. This includes wind turbines with a height of more than 50 m (4. BImSchV). Principally, installations subject to licensing shall be established and operated in such a way that this does not involve harmful effects on the environment or other hazards, considerable disadvantages and considerable nuisance to the general public and neighbourhood (BImSchG). The sound from wind turbines is subject to both strong spatial and temporal fluctuations in its amplitude and frequency composition. It depends on meteorological conditions and the location of the wind turbine. In addition, it depends on the type of turbine, the rotational speed and the operating mode. In connection with wind turbines, it is often discussed that this kind of sound is perceived as whoosh noise. This is an amplitude-modulated sound generated by wind turbines. In this paper a research project commissioned by the German Environment Agency, the generation of amplitude-modulated sound and its influence on the noise perception of residents living near wind turbines is presented and discussed.

Investigation of the Low Frequency Noise from the Large Modern Wind Turbines

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WEC: Wind Energy Converter; LFN: Low Frequency Noise

Measurements have indicated that turbines generate vibrations during their operation which can be measured at significant distances [1]. The airborne energy can be heard as sound across a range of frequencies from infrasonic (0-20 Hz) up through LFN (generally below 200 Hz) and in the higher audible frequency range above 200 Hz [2]. As the demand for renewable energy increased, WEC grow in size. Large turbines produce a bigger percentage of their total noise emissions in the low frequency and infrasound range [3]. LFN may cause distress and annoyance to sensitive people. For this reason, LFN has been widely analyzed. In this study, low freq. noise emissions from a large modern wind turbine are investigated.

This study was performed at the AD8 8 MW, a large prototype wind turbine with rotor diameter of 180 m and hub height of 115 m. It serves as a suitable platform for measuring the LFN and infrasound noise emissions. The measurement campaign (acoustic and meteorological) ran over a period of 6 weeks in summer 2022 and covered both day and night times. Due to the water canal and nearby forest area (Figure 1) limited space was available for the microphone placement (Figure 2). The microphone was finally placed at approx. 205 m south side of the WEC. The measurements are conducted using a GRAS 47 AC, ½" microphone and IMC Cronos Flex 2000GP-I-ET and amplifier ICPU2-8-70mHz-ET module.

Wind data from a meteorological met mast located 400 m South of the WEC was used for the analysis. The A-weighted sound pressure level at 1/3rd -octave bands starting from low frequency band of 0.8 Hz till 20 kHz at different binned wind speeds (WS) from 8 m/s till 11 m/s were investigated. An example can be seen in Figure 3 for a wind speed bin of 9.5 m/s. The background and total noise levels show a decreasing trend till 10 Hz 1/3rd Octave band. Afterwards, it increases and then decreases again as we proceed towards the higher 1/3rd octave bands.

A-Weighted Narrowband measurements were synchronously measured with the sound pressure levels. The presence of tones in the noise at different wind speeds were determined based on the narrow band analysis acc. to IEC61400-11 [4]. For the measurements carried out the infrasound levels in the vicinity of WEC are well below the threshold of what humans can perceive in accordance with publication [5]. Only, at frequencies higher than 25 Hz the noise become perceptible (Figure 5).

A Study on Sound Propagation of Mid-Speed Drivetrains and how to avoid Tonality Issues

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Advances in aerodynamic noise over the recent years led to comparatively low sound emissions of wind turbines (WT). But, at low wind speeds or, in low-noise operating modes, reduced aeroacoustics masking energy makes mechanical sounds, noise originating from the drivetrain, audible. Excitations stem from the gearbox, predominately from the gear mesh of the second planetary carrier. The structure-borne sound propagates further through the drivetrain and finally to the surfaces of the wind turbine and is radiated to the ambient air.

Two basic ways of addressing tonalities are described by this paper, all drivetrain integrated. Tonalities can efficiently be mitigated by systematically decoupling excitations from sound emitting surfaces, like with a low-speed shaft coupling (LSSC). The load reducing effect of a LSSC on the gearbox had been well studied already (Kari, A., et al.). The work of this shall paper investigate the influence of a LSSC on the structure-borne sound propagation within an integrated drivetrain concept. Detailed numerical investigations by means of a modified generic model were performed to understand and to quantify the effect and the value of a LSSC to lower sound power levels of a wind turbine. The second part of this paper examines two other decoupling elements, but also a torsional damper, all integrated to the gearbox. Other than with the LSSC, these investigations were limited to torsional vibration analysis (TVA) to provide a good indication of their effect on tonality mitigation. This paper shows how different powertrain elements allow to tune the system in such a way to achieve tonality-free drivetrains.

Wind turbine tonality - A holistic approach to its prediction and mitigation

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Tonal noise in wind turbines is a result of vibrations at discrete frequencies which can be excited by different sources such as gearbox, generator, etc. This structure-borne sound propagates through the drivetrain to finally be radiated from blades, tower or large surfaces of the drivetrain housings. IEC61400-11 defines how to measure such narrow band sounds relative to the broadband noise emitted by the entire wind turbine. If the narrow band noise exceeds the wind turbine masking noise, this is referred to as a tonality and becoming increasingly a hot topic due to certain trends in the wind energy market. On the other hand, reducing the structure-borne noise is becoming increasingly difficult due to a cost pressure, increasing torque density and new integrated powertrain architectures.

This situation requires scanning of a wide design space at an early phase of the project to create risk maps for the powertrain and optimize the components thereof according to wind turbine operation and sensitivities. This paper aims to explain an wholistic approach to evaluating and optimizing tonality performance of its products throughout the design process. Based on example powertrain, a tonality risk assessment is carried out and optimizations on powertrain structures are done to reduce tonality risks.

Adaptive Tuned Mass Dampers for reduction of multiple resonances in variable speed wind turbine applications

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In this paper, the application of an adaptive tuned mass damper on a wind turbine gearbox is presented. After the motivation and the actual problem definition, the basics of regular tuned mass dampers and the functionality of adaptive tuned mass dampers are introduced. Thereupon the impact of the device and achievable reductions of the vibration amplitude is shown in an experimental environment. In a first experiment at a shaker test set-up, the principal functionality is assessed. Furthermore, the adaptive tuned mass damper is applied on a 13 MW gearbox test rig to achieve environmental conditions with respect to vibrations as in the real wind turbine.

Tone propagation and receptor levels

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A frequency component sticking out from the overall frequency spectrum shape leads to tonal characteristic. This is a concern as such noise could be annoying. There are standards which define how a tone is assessed and evaluated.

The current paper describes tone propagation to evaluate the consequences at receptor. The various considerations that are needed for advanced evaluation of the typical conditions at receptors are presented. The major parameters that influence the perceived tonal response at receptors are highlighted.

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