WIND TURBINE NOISE PRIMER

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ABSTRACT

A wind turbine is a modern machine that generates electricity from wind. Wind turbines generate four types of noise: tonal, broadband, low frequency, and impulsive. Another way to look at wind turbine noise is to consider its sources. There are two fundamental categories, mechanical and aerodynamic. Mechanical noise is transmitted along the structure of the turbine and is radiated from its surfaces. Aerodynamic noise is produced by the flow of air over the blades. In the United States, wind farm siting often requires compliance with state and/or local noise regulations. Common practice is to determine minimum setback distances from residences to comply with the most stringent noise limit. Geographic Information Systems (GIS) is a valuable tool in this type of analysis, particularly when current aerial photographs are available in GIS-ready format. Although recent technology advances has decreased overall noise levels, tonal noise still remains a concern during the planning process. Detailed meteorological data is available for most portions of the United States, however it is not commonly used to evaluate wind turbine noise. The authors of this paper are studying the creation of a GIS-based model that utilizes detailed met data in the propagation of wind turbine noise.

RÉSUMÉ

Une éolienne est une machine moderne qui produit de l'électricité par le vent. Les éoliennes génèrent quatre types de bruit: tonal, à large bande, de basse fréquence et impulsif. Une autre façon de voir le bruit des éoliennes est de considérer ses sources. Il y a deux catégories fondamentales, soit mécanique et aérodynamique. Le bruit mécanique est transmis le long de la structure de la turbine et est émis de ses surfaces. Le bruit aérodynamique est produit par le flot d'air à travers les pales. Aux États-Unis, les nombreuses centrales d'éoliennes doivent être conformes à la réglementation sur le bruit de l'état et/ou de la région. Une pratique commune est de déterminer la distance minimale des résidences pour mettre en application la limite de bruit la plus sévère. Les Systèmes d'Information Géographique (SIG) (« Geographic Information Systems ») représentent un outil valable pour ce type d'analyse, particulièrement lorsque les photographies aériennes actuelles sont disponible sous des formats 'GIS-ready' (GSI-ready format). De plus, des progrès technologiques récents ont fait décroître le niveau de bruit total, mais le bruit tonal reste toujours une inquiétude lors du procédé de planification. Des données météorologiques détaillées sont disponibles pour la majorité du territoire américain, cependant ces données ne sont pas utilisées couramment pour évaluer le bruit des éoliennes. Les auteurs de cet article ont étudié la création d'un modèle basée sur les SIG qui utilise des données détaillées pour la propagation du bruit des éoliennes.

1. INTRODUCTION

A wind turbine is a modern machine that generates electricity from wind. Wind turbines may or may not be a familiar sight in your area, but their image is not unfamiliar. It is easy to envision a tall, slender, yet massive tower capped with a box-like structure. Propeller blades are held in place by an aerodynamic noise cone. The image is reminiscent of windmills in Holland, though more modern-looking. Rather than harnessing wind energy to drive pumps or to grind grain, modern wind turbines generate electricity.

A wind turbine consists of numerous components. There is a tower or mast that is typically between 50 and 80 meters tall and made of tubular steel. The tower rests on a footing, generally made of reinforced concrete, and often nine feet tall (thick) and 20-feet wide. At the top of the tower is the nacelle, the box-like housing. Inside the nacelle are the electrical generator, the gearbox, and other control equipment. The blades make up the propeller-like structure called the rotor. Typically there are three blades on a rotor; each blade may exceed 30 meters long (SEDA, 2002, 1). When a group of wind turbines exist together in an area, it is called a wind farm.

2. CHARACTERIZATIONS

2.1 Wind Turbine Noise Types

Wind turbines generate several types of noise: tonal, broadband, low frequency, and impulsive.

Tonal: Tonal noise is defined as noise at discrete frequencies.

It is caused by wind turbine components such as meshing gears, non aerodynamic instabilities interacting with a rotor blade surface or unstable flows over holes or slits or a blunt trailing edge (non-pointed wing tip).

Broadband: This is noise characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is often caused by the interaction of wind turbine blades with atmospheric turbulence. A more tangible way to describe this type of noise is to describe it as a characteristic "swishing" or "whooshing" sound.

Low frequency: Noise dominated by frequencies in the range of 20 to 100 Hz is mostly associated with downwind turbines (turbines with the rotor on the downwind side of the tower). It is caused when the turbine blade encounters localized flow deficiencies due to the flow around a tower.

Impulsive: This noise is described by short acoustic impulses or thumping sounds that vary in amplitude with time. It is also caused by the interaction of wind turbine blades with disturbed air flow around the tower of a downwind machine (Rogers and Manwell, 2004, 2).

2.2 Wind Turbine Noise Sources

Another way to look at wind turbine noise is to consider its sources. There are two fundamental categories, mechanical and aerodynamic. Mechanical noise is transmitted along the structure of the turbine and is radiated from its surfaces. Aerodynamic noise is produced by the flow of air over the blades. A summary of each of these noise mechanisms follows. A more detailed review is included in the text of Wagner, et al. (1996, 3).

2.2.1 Aeroacoustical noise

Aeroacoustical noise refers to noise created by the rotor blades. Quite a bit of research has been performed to evaluate how noise is generated by the blades. This is comparable to research performed on aircraft wings, propeller blades, and helicopter blades. It is fundamentally an issue of viscous flow across an airfoil. Aeroacoustical noise can be categorized into six types, and noise emissions occur when the blade interacts with turbulent layers of air.

- Laminar boundary layer vortex – laminar flow occurs where the air streamlines are smooth and regular, and air flow moves smoothly along a streamline. This results in a zone behind the blade that produces shedding noise.
- Turbulent boundary layer trailing edge noise occurs at the down-wind edge of the blade. A turbulent layer of air occurs where the air streamlines break up, and a fluid element moves in a random, irregular fashion.
- Leading edge inflow turbulence noise occurs in front of the blade. An area of turbulence exists in front of the blade as it moves through the air. As the blade moves toward and into this turbulent layer, scattering occurs at the leading edge of the blade, radiating noise.
- Blunt trailing edge noise occurs as a result of air movement past the blunt end of the blade tip creating turbulent vortices.
- Separation noise arises due to very high angle of attack (of the rotor blade) relative to the air flow (high incidence angle). When the incidence angle is flat, air pressure on rotor blades is perpendicular to the surface and balances on the top and bottom surface of the blade. Air flow over a rotor blade is smooth. But as the angle of incidence increases, air flow over the top of the blade becomes separated from the blade itself, creating a zone of turbulence over the top of the blade. This zone of turbulence creates noise.
- Blade tip noise occurs when air flows across the blade tip interacts with turbulence created at the trailing edge of the blade (Anderson, 1978, 4) – (Milgiore, 2002, 5).

Rogers and Manwell (2004) summarized wind turbine noise aerodynamic noise mechanisms in Table 1.

Table 1. Wind Turbine Aerodynamic Noise Mechanisms

Type or Indication	Mechanism	Main Characteristics and Importance
Low-frequency Noise		
Steady thickness noise; steady loading noise	Rotation of blades or rotation of lifting surfaces	Frequency is related to blade passing frequency, not important at current rotational speeds
Unsteady loading noise	Passage of blades through tower velocity deficit or wakes	Frequency is related to blade passing frequency, small in cases of upwind turbines/possibly contributing in wind farms
Inflow turbulence noise	Interaction of blades with atmospheric turbulence	Contributing to broadband noise; not yet fully quantified
Airfoil Self-noise		
Trailing-edge noise	Interaction of boundary layer turbulence with blade trailing edge	Broadband, main source of high frequency noise (770 Hz $< f <$ 2 kHz)
Tip noise	Interaction of tip turbulence with blade tip surface	Broadband; not fully understood
Stall, separation noise	Interaction of turbulence with blade surface	Broadband
Laminar boundary layer noise	Non-linear boundary layer instabilities interaction with the blade surface	Tonal, can be avoided
Blunt trailing edge noise	Vortex shedding at blunt trailing edge	Tonal, can be avoided
Noise from flow over holes, slits and intrusions	Unstable shear flows over holes and slits, vortex shedding from intrusions	Tonal, can be avoided

Researchers study airfoil design to minimize friction and turbulence. Blade tip design is also a research topic, as it also creates turbulence and noise. Recent research efforts evaluated serrated blade tip edges in an attempt to minimize turbulence and noise. Researchers have also focused on how to maximize the conversion of wind energy to rotational energy and minimize blade noise emissions.

2.2.2 Mechanical Noise

Mechanical noise originates from the relative motion of mechanical components and the dynamic response among them. There are several sources: Wagner, et. al. (1996) provides estimates of their relative structure-borne (sb) and air-borne (ab) sound power (Lw) contributions for a sample 2 MW turbine whose total sound power is 102.2 dBA. These sources include:

- Gearbox – the hub rotates on an axle that connects to the gearbox. The gearbox converts rotational energy into mechanical energy. The gearbox is considered one of two dominant sources of mechanical noise. Gearbox noise is radiated through the nacelle and through the tower (Lw sb = 9 7.2 dBA). It is also radiated directly through vents or openings in the nacelle (Lwab = 84.2 dBA).
- Generator – the second of two dominant sources of mechanical noise (Lwab = 87.2 dBA).
- Auxiliary Equipment – including hydraulics used to control pitch and yaw of the rotors, cooling fans used to regulate the temperature of the generator inside the nacelle, and yaw drives used to control the rotational speed of the rotor, yaw drives adjust the angle of individual blades relative to the direction that the wind is blowing from (Lwab = 76.2 dBA).
- Hub – the axle upon which the rotors turn (Lwsb = 89.2 dBA).

Since the emitted noise is associated with the rotation of mechanical and electrical equipment, it tends to be tonal (of a common frequency), although it may have broadband components. For example, pure tones can be emitted at the rotational frequencies of shafts and generators, and the meshing frequencies of the gears.

In addition, the hub, rotor, and tower radiate the mechanical noise. They act as loudspeakers, transmitting the mechanical noise and radiating it. The transmission path of the noise can be air-borne or structure-borne. Air-borne means that the noise is directly propagated from the component surface or interior into the air. Structure-borne noise is transmitted along other structural components before it is radiated into the air (Rogers and Manwell, 2004)

3. PRACTICAL CONSIDERATIONS

3.1 Range of Regulatory Programs

In the United States, wind farm siting often requires compliance with state and/or local noise regulations. Often, wind turbine noise emissions are evaluated during both daytime and nighttime hours at the nearest noise-sensitive receptors which are typically rural residences. In the authors' experience, noise limits often range from 60 to 70 dBA during the daytime and 45 to 55 dBA during the nighttime, where nighttime compliance is the biggest concern. Common practice is to determine minimum setback distances from residences to comply with the most stringent noise limit. For example, modern wind turbines with a hub height of approximately 80 meters could have an overall noise level of 50 dBA predicted at distances between 600 to 1000 feet from the turbine. Buffer zones are often greater than 1000 feet, making compliance with regulatory levels obtainable in most cases.

3.2 Evaluation Strategies and Issues

Geographic Information Systems (GIS) is a valuable tool in this type of analysis, particularly when current aerial photographs are available in GIS-ready format. In this instance, the noise model calculates the distance to the threshold noise level, which is used as a noise contour or buffer distance. The noise analyst then uses GIS to plot buffers around each wind turbine. This allows confirmation that each wind turbine has been sited in a location that does not have a noise-sensitive land use within the minimum noise contour distance.

Strategies for evaluating wind turbine noise are driven by the analysis goal. The authors deal with one of two primary strategies - compliance with local noise regulations (maximum allowable noise levels) or controlling increases of background noise levels at nearby noise-sensitive receptors (residences) in rural locations.

Common practice in evaluating the wind turbine noise for compliance with noise regulations is to use simple propagation equations to predict setback distances. Because regulatory limits are typically broadband levels, demonstration of compliance does not require a spectral analysis or an in-depth analysis of wind profiles, temperature gradients, and terrain features. Other than simple propagation equations, wind speed and temperature profiles aren't included in typical calculations and variations in wind noise/turbine noise aren't simulated by current algorithms.

Wind turbine noise analyses can get interesting when the goal is to ensure there is no net increase in noise levels at the nearest noise sensitive receptors. The quality of the noise monitoring data becomes very important, and the locations at which it is measured become critical. Sometimes indoor noise levels are also a concern. This raises the issue of whether or not a particular residence was constructed in a manner, and using materials, that provide adequate insertion loss to noise propagated from outdoors to indoors.

The authors have been involved in a project where site visits evaluated the type and materials used in the construction of homes in a project area. Concerns over potential increases of indoor noise levels required knowledge of the potential insertion loss of specific residential structures. This is more often associated with airport noise mitigation analyses than wind turbine noise analyses.

Air pollutant dispersion models utilize detailed meteorological data collected at a height of 10 meters. Those models use power laws to calculate wind speed profiles at different heights as a function of atmospheric stability. If, during a wind farm siting exercise, meteorological data were collected at the hub height, that data could be processed using the same power laws – and a wind speed and temperature profile could be determined (using the same algorithms used for air pollutant dispersion modeling). The authors currently are investigating the potential application of these resources in the development of a wind turbine noise model that incorporates detailed meteorological data and propagates noise on a spectral basis.

Such a model might alleviate the use of "apparent wind turbine sound power levels." Apparent wind turbine sound power levels exist because of the uncertainty caused by the relationship of wind noise and wind turbine noise. At low wind speeds, wind turbine noise is most noticeable. As wind speeds increase, wind noise increases, and wind turbine noise becomes less distinct. Apparent wind turbine sound power levels are calculated to account for this phenomenon.

This phenomenon contributes to the notion that there are benefits to modeling turbine noise rather than monitoring it because the modeled turbine noise levels eliminate contributions from non-turbine noise sources. Wind noise, vegetation noise, traffic noise, animal noise, and noise from anthropogenic sources compose the ambient acoustic environment in ways that sometimes complicate wind turbine noise analyses. It becomes difficult to isolate the wind turbine noise component of the overall acoustic environment.

For example, this becomes an issue when a noise complaint is filed. The development plans for some wind farms require noise monitoring when complaints are filed about wind turbine noise. Noise data collected in response to a complaint has potentially limited value, because it will be difficult to reproduce the meteorological conditions during the period when the noise complaint originated. Noise modeling can be a useful tool to assess what turbine noise levels may have been like when the complaint originated.

These notions illustrate the relative infancy of wind turbine noise assessment methodologies. While this is true, we note the early stages of an apparent paradigm shift. The emphasis on pre-construction and post-construction noise monitoring has dwindled as familiarity with wind turbine technology, and understanding of their effect on view shed, wildlife, property values, quality of life, and general acceptance grows.

3.3 Tonal Concerns

Although recent technology advances has decreased overall noise levels, tonal noise still remains a concern during the planning process. Evaluating tonal noise emissions has improved with the introduction of standardized methods for measurement. The International Electrotechnical Commission standard (IEC 61400-11) Wind Turbine Generator Systems – Part 11: Acoustic Noise Measurement Techniques provides methodology for measurement of wind turbine noise at incremental wind speeds from 6 to 10 m/s and for identification of dominant noise level frequencies. The standard has aided manufacturers and acousticians in evaluating wind turbine broadband and tonal noise for comparison with background noise levels. The standardized method tends to provide more consistent and accurate data allowing wind farm planners to more easily assess various turbine models.

4. CONCLUSIONS

Wind turbines are becoming increasingly common sources of energy. The mechanisms, sources and types of noise emitted by wind turbines are becoming better understood. The existing body of aerodynamic and aeroacoustic knowledge supplements the understanding of wind turbine noise. Research continues to expand that body. The dynamic nature of this knowledge suggests that the state of the art of wind turbine noise analysis is one of relative infancy.

An interesting area of research is the development of automated control systems to run turbines below nominal power during nighttime hours. This noise control strategy is not in widespread use, yet has potential to reduce turbine noise during low wind conditions while still allowing electrical generation. Improvements in structure (blade technology, rotors downwind of mast, etc.) are more common examples of the evolution of wind turbine design that also reduce turbine noise emissions.

5. REFERENCES

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