Wind turbines: clean, renewable and quiet?

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In the United States, officials responsible for energy policy have been exhibiting renewed interest in wind energy as an alternate power source that is clean and renewable. Despite the new public enthusiasm for this option, wind turbine installations and wind farms must comply with U.S. Federal Environmental Protection Agency and Occupational Health and Safety guidelines and be approved by state and city regulators. Several recent news stories have indicated that turbine noise levels have become a factor in deciding whether to approve these installations—in part because they affect quality of life for nearby residents.

Although wind is clean and renewable, wind turbine noise may impede extensive use of wind energy. The perception of wind turbine farms has both visual and acoustic criteria. Recent reports by Oerlemans and Schepers[1] and Van den berg et al.[2] confirm that "sound is one of the most annoying aspects of wind turbines." Three recent examples highlight how important the problem has become, but I refrain from commenting on technical/legal merits of specific cases.

The Bismark Tribune (North Dakota; July 9, 2009) reported that officials approved a wind farm despite noise complaints. State regulators approved the location of a wind farm in east central North Dakota despite noise complaints but recommended that operators move one of 80 turbines to an alternate site. Commissioners approved installation because it complied with U.S. Federal guidelines that turbine noise was not expected to exceed 50 dB outside the homes. To put this noise level in perspective other commonly encountered sounds are shown in Figure 1. In a second example, reported by KMBC-TV (Kansas City), a Missouri man is suing over wind turbine noise. His 20-acre farm is surrounded by 27 turbines (seven within ½ mile of his house). He noted that on a bad day "it sounds like a helicopter or a train coming that never arrives." A third example comes from Libertyville, IL (*Chicago Sun Times*; June 4, 2009) where residents protesting noise related to installation of a single wind turbine in a suburban setting close to residences obtained a temporary restraining order.

These incidents clearly illustrate the need for noise reduction technologies and for metrics beyond

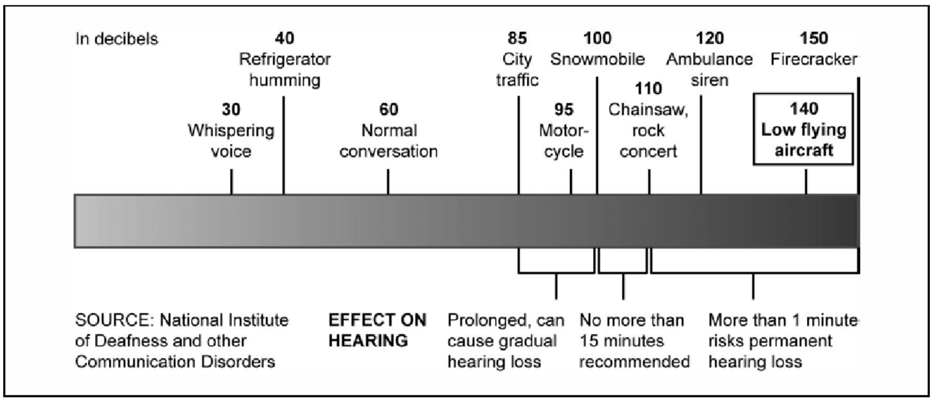

Figure 1. How loud is 50 decibels (dB)?

Figure 2(a). Test set-up for Turbine 1 (left) and Turbine 2 (right). Turbine 1 was a GE 2.3 MW prototype test turbine (Netherlands test site) with a rotor diameter of 94 m, tower height of 100 m. Turbine 2 was a GAMESA G58 850 kW turbine (northern Spain wind farm) with a rotor diameter of 50 m, a tower height of 55 m. (from Oerlemans and Schepers,[1] used with permission.

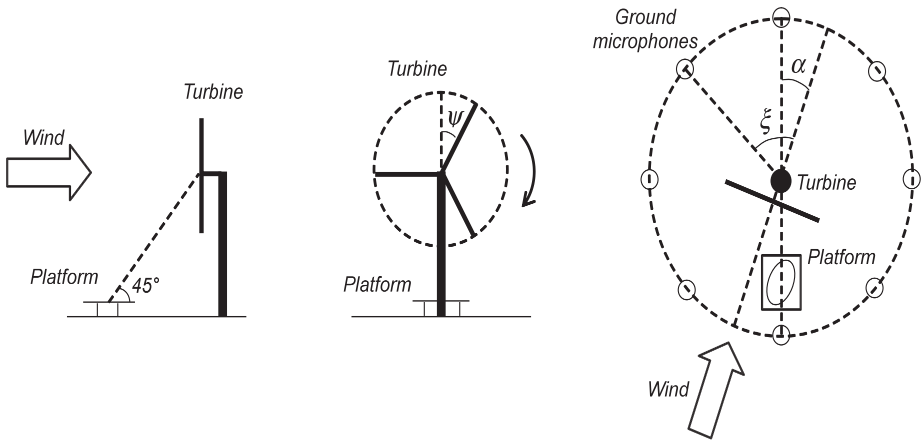

Figure 2 (b). Schematic picture of test set-up: side view (left), front view (middle), and top view (right). (from Oerlemans and Schepers,[1] used with permission).

existing Federal guidelines to eliminate public complaints.

To address these problems, we need careful studies of wind turbine installations to assess their acoustic characteristics. Oerlemans and Schepers2 conducted such a study recently, measuring noise on two turbines (see Figure 2 (a). Turbine 1 was a GE 2.3 MW prototype test turbine (Netherlands test site) with a rotor diameter of 94 m, tower height of 100 m. Turbine 2 was a GAMESA G58 850 kW turbine (northern Spain wind farm) with a rotor diameter of 50 m, a tower height of 55 m. Researchers took source localization measurements using a 148 mic acoustic array mounted on a horizontal wooden platform of dimensions 16 x 18 m^2 (Figure 2 (b)). The distance between the tower and platform was similar to tower height. The researchers also placed an acoustic array of eight ground microphones over a circle 240 m in diameter (45° intervals) around the turbine to measure the directivity.

Another study, by Van den Berg[3] involved nocturnal wind turbine noise in northwestern Germany near the

Dutch border. He examined the response to the strong protests from residents living near the17-turbine Rhede wind park. The 1.8 MW turbines had a 98 m hub height and 3-blade propellers of 35m blade span. The variable turbine speed ranges from 10 RPM at a wind speed of 2.5 m/s at the hub height to 22 RPM at wind speeds of 12 m/s and over.

Residents living between 500 and 1900 m away expressed annoyance about nocturnal sounds. There appeared to be a distinct audible difference between daytime and nocturnal sounds. In the daytime, residents heard a "swishing" sound within a few hundred meters. However, on quiet nights, they could hear a low pitched "thumping" sound at about 1000 meters, and when turbine blades rotated at high speed, they could hear the sounds for several kilometers. One resident living 1.5 km from the part described the sound as "an endless train." To assess the problem, Van den Berg conducted measurements over 400 night hours for over four months at distances between 400 and 1500 m. At night, the wind speed at hub height is up to 2.6 times higher than expected, causing a higher turbine rotational speed at night and a 15 dB increase in sound levels. He also confirmed that at high rotational speeds, the turbines produced a 'thumping' impulsive sound that aggravated the annoyance. This study emphasizes the importance of gathering data during the day and at night.

HAVE WE ENCOUNTERED THIS PROBLEM BEFORE?

As the world prepares for the proliferation of wind farms, it is worth noting that noise has always accompanied new technology. Modern man invented pulleys, gears, ploughs, crude carts without wheels and thereafter with wheels. This progress involved a lot of noise but beneficiaries overlooked the irritation because they appreciated the advantages of the new technology. Similarly, when the automobile was invented, despite the great noise that it made, people welcomed the advance. Likewise, when the Wright brothers invented powered flight, nobody worried about noise because we were fascinated by the endless possibilities air and space travel.

After the invention of flight, two world wars led to development of fighter and bomber aircraft (thousands of them). From 1915-1918, aircraft such as the De Havilland, Sopwith, Nieuport, Junker, and Fokker produced noise that caused panic among civilians. By the beginning of the World War II (1939-1945), significant advances in military aviation led to the era of the Messerschmitt, Mitsubishi, Mustang, Marauder, and MIG aircraft designed without consideration for the acoustic signature. (Source: The Timechart History of Aviation. Lowe & B. Hould, an imprint of Borders Inc. 2001).

On the civil aviation side, we were happy with the Viscount, Fokker-Friendship, and Avro. We were proud to fly in larger four-engine propeller aircraft such as the Viking. Then came jet- propelled aircraft such as the Comet, Boeing 707, and the Douglas DC-8. We considered it prestigious to travel in these noisy planes. Initially, people were not perturbed by the noise or the rattling of windows, and some were proud of living near a major airport. Then the era of environmental concern about noise pollution and damage to the human ear arrived. As time passed designers became more and more conscious about reducing noise. First, they tried to reduce cabin noise by barriers and lining; only later did they try to modify the noise source itself by going to aircraft with high bypass engines (Boeing 747, 777 and Airbus A380).

Aircraft and wind turbine noise are also connected because researchers can modify many experimental, analytical, and computational aircraft-noise study methodologies to study wind turbine noise. (especially for rotating blade and airframe noise). Some differences in blade design do exist since airplane propellers are optimized for thrust and wind turbines for torque.

WHAT PRODUCES WIND TURBINE NOISE?

Wind turbines generate both aerodynamic and mechanical noise from its various components (see Figure 3). Aerodynamic noise includes low-frequency sound, in-flow turbulence sound, and airfoil self-noise.[4-10] The cylindrical tower can produce additional noise due to vortex shedding in various regimes. Mechanical sources include sound from the gearbox, generator, yaw drives, cooling fans, and hydraulics. Even though wind turbines have gotten much quieter, their sound is still an important siting criterion.

Wind turbines can generate four types of sound: tonal, broadband, low frequency, and impulsive. Since the human ear is more sensitive to frequencies in a certain frequency range (typically 250 – 2500 Hz) the perceived noise levels (PNL) depend on the frequencies produced by the turbine. In addition, since tones are more annoying than broadband sound, a penalty needs to be assessed for the presence of tones. This is a term that is commonly used for aircraft fly-over noise assessment and is referred to as the tone corrected perceived noise levels (PNLT).

WHAT IS THE SOURCE OF MECHANICAL NOISE?

Mechanical sounds originate from the relative motion of mechanical components and dynamic response among them. Examples of mechanical sound sources include the gear box that houses gears that connect the low speed shaft to the high speed shaft. Typically the rotor blade rotations occur at 30-60 rotations per minute (rpm). These rotations are transmitted to the high speed shaft at 1000-1800 rpm and during the process noise is produced by the gears and the high speed shaft. Other examples of mechanical noise include sound produced by the yaw motor and drive that is used to keep the rotor facing into the wind as the wind direction changes. Since rotating shafts and gears exhibit periodic behavior, the

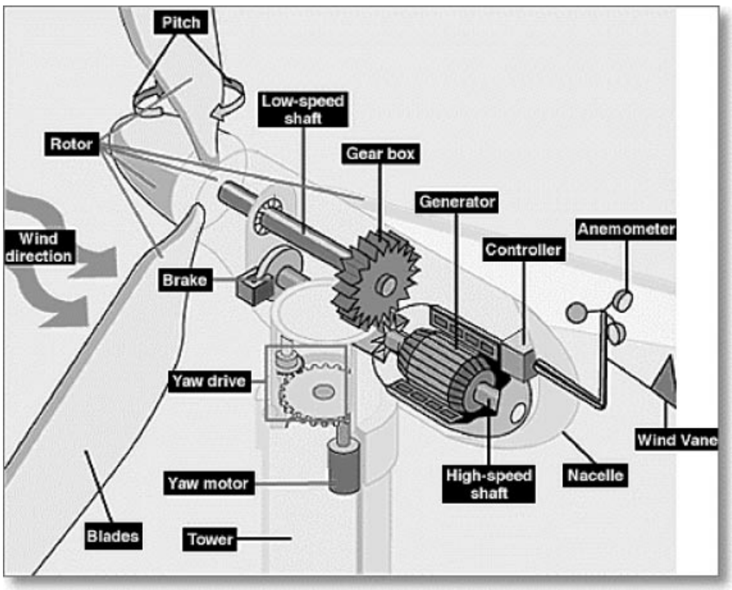

Figure 3. Components of a wind turbine. Source: US Department of Energy (http://www.eere.energy.gov/windandhydro/images/illust_large_turbine.gif

sound produce tends to include tonal components in addition to broadband sound. The mechanical noise produced by shafts and gears can be transmitted into the surrounding air (air-borne radiation of sound) or through the structure to various other parts of the wind turbine before it radiates out into the surrounding air. Parts of the turbine such as the casing, hub, rotor and tower can act as efficient broadcasters of sound to the surroundings.

WHAT IS THE SOURCE OF AERODYNAMIC NOISE?

Aerodynamic broadband sound is typically the largest component of wind turbine acoustic emissions. It originates from air flow around the blades. Figure 4 shows a number of complex fluid dynamic phenomena occurring, each of which might generate sound. Aerodynamic sound generally increases with rotor speed and the noise producing mechanisms can be divided into three groups[4]: *Low Frequency Sound*: sound in the low-frequency part of the sound spectrum generates when a rotating blade encounters localized flow deficiencies due to flow around a tower, wind speed changes, or wakes that shed from other blades. *Inflow Turbulence Sound*: depends on the amount of atmospheric turbulence that results in local force or pressure fluctuations around the blade. *Airfoil Self Noise*[7]: sound generated by air flow along the airfoil surface—typically broadband, but tonal components may occur because of blunt trailing edges or flow over slits and holes

Wind turbine noise is also very dependent on wind speed (see Figure 5 from Leloudas et al.[11]) . An increase in wind speed from 6 to 12 m/s can raise noise levels by 15 dB. Figure 6 (from Leloudas et al.[11]) shows the $^1/_3$ octave spectral distribution of sound from their wind turbine. Note that most of the noise occurs in the frequency range audible to the human ear.

Predicting wind turbine noise and validating it against experiments has always been challenging. Oerlemans and Schepers1 recently developed a semi-empirical method for estimating the trailing edge noise of two modern large wind turbines. If one inputs the blade geometry and turbine operating conditions, the model estimates noise. Using detailed acoustic array and

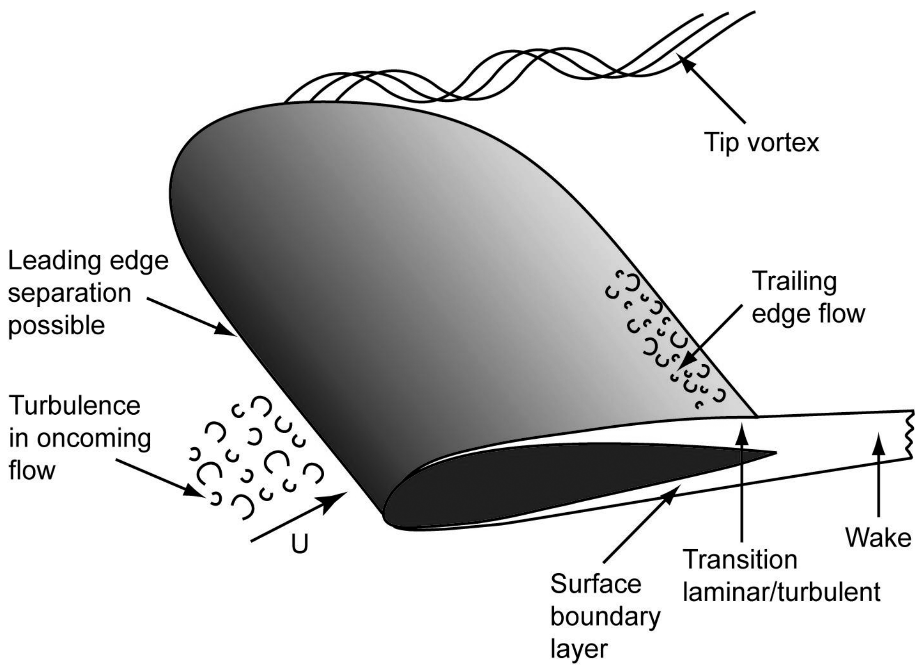

Figure 4. Noise producing mechanisms on a rotor blade (as described in Wagner[4])

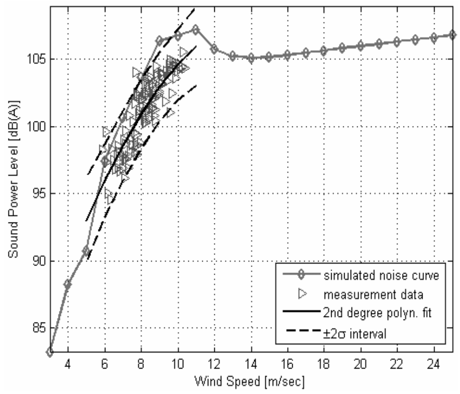

Figure 5. Sound power level variation with wind speed (from Leloudas et all.,[11] used with permission

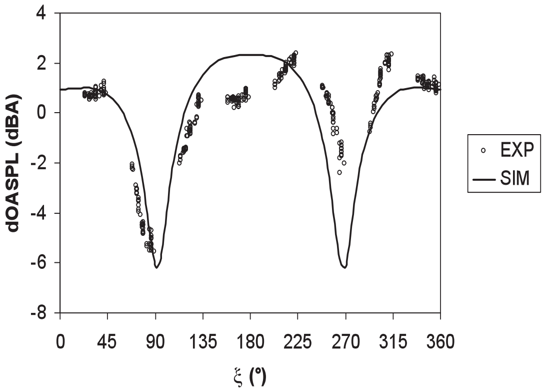

Figure 7 Measured and predicted directivity for Turbine 1. (from Oerlemans and Schepers,[1] used with permission

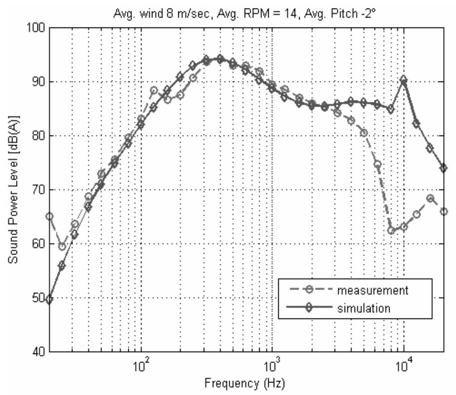

Figure 6. Sound power spectra for a wind turbine (from Leloudas et al.,[11] used with permission.

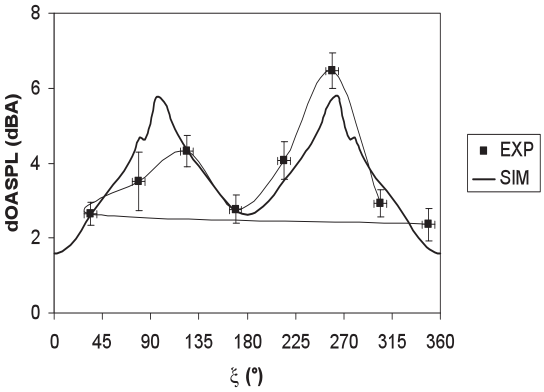

Figure 8 Measured and predicted swish ampli tude as a function of farfield position ξ. (from Oerlemans and Schepers,[1] used with permission.

directivity measurements, the authors validated their model. The work also addresses the annoying aspect of wind turbines caused by “swishing” (amplitude modulation). It appears that humans perceive this sound to be more annoying than others of equal level—e.g., air or traffic. Figures 7 and 8 show the measured and predicted directivity of overall sound and ‘swish’ amplitudes for a GE 2.3 MW test turbine. Note that the sound level directivities are presented as relative values since the absolute values depend on test conditions and measurement locations.

Oerlemans et al.[12,13] also studied location and quantification of noise sources on a wind turbine. They considered a three-blade rotor with a diameter of 58m and assessed the effect of blade roughness. Of the three blades tested, one was the untreated baseline, the second was cleaned, and the third tripped. The tripped blade is the noisiest. They also found that in addition to a minor noise source at the hub, most noise emitted to the ground was produced during the downward blade movement (Figure 9). The authors argue that convective amplification and trailing edge noise directivity cause the strongly asymmetric source pattern. For a review of phase array methodologies used for source location the reader is referred to Dougherty.[14]

Figure 9. *Location for Aerodynamic Noise Sources (courtesy of S. Oerlemans, NLR, used with permission.*

Another useful study is a review of the aeroacoustics of large wind turbines (Hubbard and Shepherd[6]). They summarize published information on aerodynamically generated noise from large horizontal axis wind turbines used to generate electric power. They present methods for estimating the discrete frequency rotational noise and the broadband components; they validate these methods by comparing measurements. They also discuss several important points such as distributed source effects and the role of building dynamics in sound perception.

HOW CAN WE REDUCE NOISE LEVELS?

We can alleviate mechanical noise with relative ease using acoustic barriers and vibration isolation systems. However, aerodynamic noise is more difficult to reduce. Researchers have done significant work on single airfoils and aircraft propellers—in aeroacoustics, earlier work applied to commercial aircraft. However, basic principles of aerodynamic noise generation, characterization, measurement, and analysis are fundamentally the same. We can also use aeroacoustics principles to calculate noise radiation from unsteady aerodynamic sources.[15-19]

Since wind-turbine noise can affect the health and quality of life of nearby residents and animal populations, for widespread growth of wind turbine farms to be feasible, we must optimize blade designs for flow characteristics and minimum noise under various conditions, including gusting.

Methods for reducing aerodynamic noise include variable speed operations and lower tip speed ratios and blade angles of attack; for mechanical noise, we use baffles, acoustic insulation, and vibration isolators.

NEED FOR EDUCATION

For use of wind farms to become widespread, we must educate the public at various levels:

1. General population about noise produced by wind turbines as compared to the noise from other sources (traffic, aircraft, industrial operations, etc.)
2. Residents living near wind turbines about the types of noise to expect and about misconceptions and fears about being near wind turbines
3. Next-generation workforce about dealing with needs of the wind turbine community, including education of scientists, engineers, and other professionals in designing quiet wind turbines and developing methods to predict the noise and its propagation characteristics. Education should also focus on developing metrics to experimentally measure and assess noise sources, acoustic levels, frequencies of sound, and other qualitative sound characteristics that affect human annoyance.

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KEEPING AN EAR OUT FOR NOISE

Stanford Hospital (CA) is working to reduce noise,to help patients rest and sleep more effectively in order to more quickly recover their health. Night time noise is reported as a particular problem by patients. So the Stanford noise team has installed “SoundEar ” noise sensors at nursing stations; the meter, shaped like a human ear, has lights that flash green, yellow and then red as noise escalates – visual reminders to lower the volume.

NEIGHBOURS TO SUE AIRPORT OVER NOISE

Some neighbors are demanding compensation for what they call excessive noise and plane traffic at the new third runway of the Seattle-Tacoma International Airport. A class-action lawsuit will be filed, said attorney Darrell Cochran, who said 10,000 people live in affected areas. Besides money, the lawsuit seeks to restrict air traffic at night. The $1 billion third runway, which opened recently on the airport ’s west flank, was justified as a relief runway to help in bad weather conditions — but plaintiffs claim the port reneged on its word by using it all the time.

COURTS DISMISSES NOISE CASE AGAINST SUVARNABHUMI AIRPORT

Thailand ’s Supreme Administrative Court has ruled that Airports of Thailand (AoT)should continue to be responsible for solving the problem of noise pollution of residential areas around Suvarnabhumi airport, as set out in a cabinet resolution of May 29, 2007. The court dismissed the petition submitted by a number of people living near the airport, who said the cabinet resolution was unfair to them and AoT was not doing the job properly. In its judgement, the court upheld the cabinet resolution, saying it was legitimate, and said the AoT, which operates the airport, had actually taken measures to solve the noise problem, in line with the cabinet resolution. Wanchart Manasombat, a representative of the community, said the residents have not received fair treatment in the two years since the cabinet passed the resolution. They wanted the government to revert to the Nov 21, 2006 cabinet resolution,which was more favourable to the affected residents than the one passed in May 2007. The November resolution stated the would AoT buy houses in areas where the sound level was 35-40 noise exposure forecast (NEF) units if the owners wanted to sell. The May resolution said the AoT would buy only houses suffering from noise of over 40 NEF units.NEF is a method developed by the US Federal Aviation Agency to predict the degree of community annoyance caused by aircraft noise and airports.