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Review

Recent Advances in Wind Turbine Noise Research

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Abstract: This review is focussed on large-scale, horizontal-axis upwind turbines. Vertical-axis turbines are not considered here as they are not sufficiently efficient to be deployed in the commercial generation of electricity. Recent developments in horizontal-axis wind turbine noise research are summarised and topics that are pertinent to the problem, but are yet to be investigated, are explored and suggestions for future research are offered. The major portion of recent and current research on wind turbine noise generation, propagation and its effects on people and animals is being undertaken by groups in Europe, UK, USA, Japan, Australia and New Zealand. Considerable progress has been made in understanding wind turbine noise generation and propagation as well as the effect of wind farm noise on people, birds and animals. However, much remains to be done to answer many of the questions for which answers are still uncertain. In addition to community concerns about the effect of wind farm noise on people and how best to regulate wind farm noise and check installed wind farms for compliance, there is considerable interest from turbine manufacturers in developing quieter rotors, with the intention of allowing wind farm installations to be closer to populated areas. The purpose of this paper is to summarise recent and current wind farm noise research work and the research questions that remain to be addressed or are in the process of being addressed. Topics that are the subject of on-going research are discussed briefly and references to recent and current work are included.

Keywords: wind turbine noise; wind farm noise; aerodynamic noise

1. Introduction

Scholarly research on wind turbine noise has been on-going since the early 1980s, with much of the early work undertaken by the United States National Aeronautics and Space Administration (NASA) on horizontal-axis wind turbines, with the rotor downwind of the support tower ("downwind turbine"). The location of the tower upwind of the rotor resulted in very turbulent flow being incident on the turbine blades which, in turn, resulted in the generation of thumping sounds as the blades passed close to a leg of the tower that generated the flow disturbance. The thumping noise disturbed nearby residents and caused cause rattling of dishes and annoyance for a number of residents living within 3 km of a single turbine [1]. Some residents reported feeling the sound more than hearing it, which resulted in a sensation of uneasiness and personal disturbance.

In modern turbines, the rotor location has been changed to upwind of the support tower, as less thumping noise is generated in this configuration, resulting in this type of turbine being used in all modern wind farms that generate electricity for commercial use. Thus, this review is focussed on large-scale, horizontal-axis wind turbines.

Wind farm noise research can be divided into a number of distinct categories: turbine noise generation, turbine designs to minimise noise generation, noise propagation to surrounding communities, effects of noise on surrounding communities (including fauna) and regulation (including compliance checking).

Turbine noise research includes work on understanding noise generation mechanisms, control of these mechanisms to reduce overall noise levels, as well as calculation and rank ordering of the sound power output of various wind turbine noise sources. Research also includes work on quantifying problems such as tonality and amplitude modulation; measurement of turbine noise emission, such as directional characteristics; and quantifying the effect of topography and meteorological conditions on the sound power emission. Understanding of noise generation mechanisms is fundamental to the development of quieter blade and turbine designs that do not significantly reduce overall performance.

Noise propagation from turbines to surrounding communities includes work on the development of better propagation models that can provide more accurate predictions of noise levels at near and distant communities. Of particular interest is the calculation of worst case noise levels as well as the range of noise levels that will be experienced at any location as a function of weather conditions and time of day as well as the expected duration of particular levels over the longer term. Whenever predicted noise levels are provided by developers, it is important that they are accompanied with uncertainty estimates and this is an area of research requiring more effort. The more accurate prediction of noise propagation of off-shore wind farms to nearby on-shore communities is also of interest. As most disturbance caused by wind farms is at night after residents have retired to bed. For this reason, there is considerable interest in translating outdoor predicted noise levels to indoor predicted levels for various housing constructions with and without open windows. In addition to developing better noise prediction models, it is also important that measurements of environmental noise before and after a wind farm is constructed are undertaken and that ambient noise from other noise sources are properly taken into account when estimates of the contribution of wind farm noise to the overall noise level are made. This is an active area of research at the moment, with a number of procedures currently under investigation. As most noise measurements are undertaken with microphones exposed to a significant wind level, the development of measurement systems that are insensitive to wind noise is a research area that attracts a significant level of interest. As many community complaints are centred around low-frequency noise and the possibility of the presence of infrasound, it is particularly important that any measurements of ILFN (infrasound and low-frequency noise) are well isolated from the effects of wind disturbance.

Intensive research on human response to wind farm noise has been on-going for many years. Although much has been accomplished, there is still no end to controversy and disagreement among researchers as to the extent of the effects. Although most agree that wind farm noise can be annoying to a significant number of people, there is disagreement regarding whether wind farm noise can cause sleep deprivation and adverse health effects. Recent research on this topic is discussed at length in this review.

Of considerable interest to farmers and environmentalists is the possible effect of wind farm noise on animals. Do wind farms near national parks cause wild animals to avoid their vicinity and, if so, is this a permanent effect or do animals grow used to them and are different species affected differently? From the agricultural viewpoint, farmers are interested to know whether or not wind farms affect reproductive performance as well as rate of growth of various species of livestock and the quality of their produce.

Legislation is an important area of current research. There seems to be no agreement between various countries and jurisdictions in the same country concerning acceptable A-weighted noise levels, acceptable wind turbine set-back distances from residences and how to account for special acoustic characteristics of wind farm noise such as tonality, amplitude modulation, enhanced low-frequency content and infrasound. The establishment of reliable procedures for compliance monitoring is also of importance and, to date, none that have been proven reliable have been available to regulatory authorities.

Work that has been undertaken in the past few years and work that is continuing in each of the above categories, as well as community engagement and ground vibration, are discussed in the remainder of this paper, along with suggestions for future research directions.

2. Mechanisms and Control of Wind Turbine Noise Generation

It is well understood that the main noise generating mechanisms of a wind turbine are associated with the drivetrain (usually vibration transmitted to the tower and blades and radiated as noise) and the passage of the blades through the air (aerodynamic noise) [2]. However, an understanding of the details of the noise generation mechanisms, their rank-ordering in terms of contribution to the overall level, and their control remain active areas of research. The end goal is to develop design changes that result in the minimum possible noise generation with minimal reduction (preferably an increase) in performance. Substantial progress has already been made, with modern wind turbines generating considerably less noise than earlier versions. The precise amount of noise reduction is difficult to quantify as it is dependent on the models being compared.

Some of the design modifications to the rotor and blades that have been implemented or are under consideration include the following [2]:

- low-noise airfoil designs for the blades;
- serrated blade trailing edges (TEs);
- blade trailing-edge brushes;
- porous blade surfaces;
- blade tip treatments (such as making the tip pointed rather than blunt);
- use of vortex generators on the blades;
- boundary layer suction applied to the blades;
- reduced rotor rotational speed; and
- use of blade angle of attack control systems to continually optimise the blade angle of attack for minimum noise and maximum performance.

Although much has been achieved in the development of quieter turbine blades and rotors [3], research is continuing with the aim of developing even quieter blades without sacrificing performance [4,5]. The work involves computer models [6–11] and theoretical studies [12], as well as experimental measurements on full-size rotors in the field [13,14] and model rotors in wind tunnels [12,15]. Part of the experimental work includes the use of an acoustic camera to identify noise source locations on wind turbine blades [16] and experiments have also been undertaken using loudspeakers attached to a turbine blade to verify the accuracy of the acoustic camera method [17]. This work is useful for developing an understanding of the physical mechanisms involved in any noise reductions that are achieved by modifications to the blades and their angle-of-attack control system.

Turbine blade generated aerodynamic noise consists mainly of trailing-edge generated noise, although leading-edge noise may also be important [18,19]. Considerable effort has been expended by a number of researchers in designing and testing various trailing-edge treatments using both numerical modelling [8,12,20–23] and experimental work [4,24–29]. As the performance of turbine blades in terms of generating energy is important in addition to minimising noise generation, most designs are compromises. However, design guidelines for low-noise but high performance turbine blades do exist [5], although there is always scope for improvement. More work is needed to determine the relative importance of the various parts of the blade so that design effort can be focussed on solving the problems in order of importance to the overall noise generation.

Recent work [30] has suggested that impulsive aerodynamic loading caused by the blades interacting with the wind speed deficit in the vicinity of the support tower (due to the blocking effect of the tower) can result in low-frequency aerodynamic noise generation. It was shown that this contribution was twice that of the noise caused by blades passing through the air. However, this work is the result of numerical investigations and needs to be verified with field measurements. If the presence of the tower is important for noise generation, then research may be needed to investigate possible modifications to the tower construction, such as changing the tower from a solid cylinder to a structure that is much less effective in allowing the air between the blade and tower to be compressed as the blade passes (for example, a lattice-type tower used for high voltage power lines [31]). Lattice towers were used to support the downwind turbines of the 1980s [1], and the interaction of the turbine blades with the flow disruption caused by the support legs was considered to be responsible for the thumping noise that residents complained of. However, for upwind turbines, there is no wake problem but there exists a wind velocity deficit in the vicinity of the support tower that leads to the generation of impulsive aerodynamic noise as discussed above. This impulsive loading is expected to be less for the smaller cross section support legs of a lattice-type tower and indeed Zagubień and Wolniewicz [31] found that upwind turbines supported on lattice-type towers produced about 10 dB less audible noise that turbines supported by cylindrical towers.

Amplitude modulation of wind turbine noise is the periodic variation of noise at the blade pass rate (usually between 0.5 and 2 Hz). That is, the noise amplitude varies from maximum to minimum and back to maximum again in the time it takes consecutive blades to be adjacent to the rotor support tower. Zagubień and Wolniewicz [31] showed that the variation in turbine noise level is less for a lattice-type tower, but more work is needed to determine whether this translates to lower levels of amplitude modulation. Another possible explanation for amplitude modulation is the change in sound radiation directivity as blades are moving downward compared to when they are moving upward. However, more investigation is required to determine which mechanism dominates.

Even with an optimised tower construction, a certain amount of amplitude modulation may be unavoidable due to the different mechanisms causing it as discussed above. However, a phenomenon exists where the amplitude modulation is much greater than expected and this is referred to either as "enhanced amplitude modulation" (EAM) or "other amplitude modulation" (OAM). As it is becoming more accepted that amplitude modulation, particularly EAM, is a significant contributor to annoyance, there is a corresponding interest in discovering what may be the cause of EAM [32]. It is generally accepted that EAM occurs under certain meteorological conditions and in-flow conditions, and could also be related to the blade experiencing high-speed stall due to its angle of attack being too high for the higher-speed air flow at greater heights above the ground [33]. It is hoped that, by understanding the physical mechanism, sensors may be employed to sense the incoming air flow and thus adjust the turbine blade angle of attack or orientation with respect to the direction and speed of the air flow, accordingly. This may require almost continuous adjustment of each blade as it rotates from relatively low-speed air flow to relatively high-speed air flow at the bottom and top of its trajectory, respectively. Although a considerable amount of research effort has been expended on attempts to understand the cause of EAM (see [32,34] for a summary), thus far, no definite cause seems to be agreed upon [32]. However, extensive work in this area is currently being undertaken as part of a French research project [28]. In addition to understanding the mechanisms producing EAM, future work may also be directed at optimising the control system that is responsible for continuous adjustment of each blade angle of attack using information from sensors mounted on all three blades.

Drivetrain vibration is transmitted through gearbox and generator mounts to the rotor support tower, which in turn vibrates and radiates noise [10]. This noise can be reduced by applying damping treatment to the tower (usually using vibration absorbers) to reduce its sound radiation [35], by improving the vibration isolation of the drivetrain from the tower, or by changing the tower construction as described above for reducing impulsive aerodynamic loading. The application of damping treatment to the tower is only effective if the tower is excited into resonant vibration. If the tower vibration is non-resonant (forced), damping treatment will be ineffective, as found by Schneider and Hanus [36]. This research area is still of interest in terms of developing retrofit technology for existing turbines and in the design of some new turbines [36]. Even turbines that are direct drive (and thus have no gearbox) exhibit vibration of the drivetrain, which is transmitted to the tower and blades [36]. More work is needed on tower design, drivetrain design and vibration isolation to mimimise the contribution of these sources to the overall sound radiation.

2.1. Future Directions for Research on Mechanisms and Control of Wind Turbine Noise Generation

Furthering the understanding of the physical mechanisms responsible for wind turbine noise emission is an essential part of designing low-noise turbines that can then achieve higher electrical power outputs for the same sound pressure levels at residences. Thus, considerable research work is on-going in this area and although much has been achieved (serrated TEs of blades, optimised blade shapes, vortex generators on the blade and sophisticated turbine control settings), there is scope for significantly more noise reduction. To properly understand the origins of wind turbine noise and how to control it in order to produce even quieter turbines, further work is needed in the following areas. Some of this work was discussed by Bowdler [37].

(a) Development of more accurate airfoil trailing-edge noise predictions using 3-D models.
(b) Rank ordering of the parts of the blades in terms of their contribution to noise radiation and using these results to inform optimal blade design.
(c) Development of a greater understanding of the effect of separating flow on noise generation.
(d) Development of new and better models for predicting transition and stall for stationary as well as rotating blades.
(e) Development of a better understanding of how turbine operating control strategies affect noise generation and how these may be optimised in conjunction with various blade add-on low-noise treatments.
(f) Development of blade shapes that make less aerodynamic noise but have minimal effect on performance.
(g) Development of turbine designs that are tonality free.
(h) Determining how best to relate wind tunnel tests to operating turbines.
(i) Development of efficient methods for the measurement of turbine sound power output for a range of wind speeds, meteorological conditions and topographical conditions.
(j) Increasing the quality of airfoil noise generation model validation, both in laboratory wind tunnels and on installed turbines.
(k) Development of a better understanding of the causes of AM and EAM and how to ameliorate them via better angle-of-attack control system design.
(l) Development of a better understanding of the effect of the tower on the impulse generated by the passage of blades past it.
(m) Design of better towers to minimise noise radiation.
(n) Development of improved drivetrains that do not produce so much vibration of the tower.
(o) Development of improved vibration isolation systems for the drivetrain to prevent it from exciting the tower and rotor blades.
(p) Development of models to estimate noise radiation from tower vibration (induced by the drivetrain as well as the blade passage past the tower).
(q) Assessment of the overall effect of using different tower designs that radiate noise less efficiently.

3. Characterisation of Wind Turbine Noise Emission

3.1. Calculation (Including Amplitude Modulation)

When modelling the wind turbine as a noise source, there is the choice of using a number of distributed point sources to simulate the sound radiation or a single point source. For the former choice, each blade is modelled as a number of point sources and then the contribution of each source to the sound pressure level at a particular receiver location is calculated. However, when receivers are sufficiently far away from a turbine, the error associated with treating the turbine as a single point source is insignificant. The error may be calculated approximately by considering the turbine as an incoherent plane source and using Figure 4.15 in [38] (which shows the difference in level radiated by a plane incoherent source compared to a point source in the same location) or by comparing the results obtained using the distributed vs. point source approaches. The approximate calculation would suggest that the error in receiver sound pressure level calculation resulting from considering the turbine as a single point source is less than 1 dB for distances from the turbine that are greater than twice the blade length and less than 0.1 dB at distances that are greater than six times the blade length. For receivers more than a few hundred metres from the turbine noise sources, a noise propagation model (which predicts noise levels at dwellings) also has to be used, so current work is also directed at combining a turbine noise source model with a propagation model [28,39–42].

Theoretical work (which is on-going) is directed at the construction of computer (numerical) models that can estimate the noise levels radiated by the turbine blade trailing edges (TEs) [9,11,14,15,18,28,43–47]. The purpose of the work is to provide means for calculating the noise reducing effects of various blade treatments (see Section 2) as well as being able to provide sound power levels of noise generated by turbine blade trailing-edge noise sources. These can be compared with sound power levels from other turbine noise sources to determine the relative importance of trailing-edge noise in various frequency bands and receiver distances. Work is also on-going on the development of a computer model for assessing LFN emission from the turbine rotor blades [48].

3.2. Measurement (Including Amplitude Modulation)

There is a well accepted standard method [49–51] for measuring the noise emission (sound power output) of any particular wind turbine. However, such measurements are always undertaken under ideal conditions of laminar air flow over flat ground prior to incidence on the wind turbine blades. In most wind farm cases, actual incident flow conditions are far from ideal. Turbulence is introduced as a result of irregular upstream terrain, other upstream turbines in the wind farm and meteorological conditions, and these phenomena have adverse effects on the turbine noise emission. Thus, there is on-going interest in measuring the sound power for turbines installed in a wind farm for various weather and terrain conditions, although little work has been reported on this topic.

3.3. Directional Characteristics

It is well known that turbine sound radiation is directional with respect to the rotor plane [33]. Efforts are on-going to quantify this for various turbine sizes and designs [52]. Although all wind turbine sound power measurements according to IEC61400 [49] are undertaken at ground level for convenience, it is suspected that the inherent assumption that the directivity in the vertical direction is uniform is not valid. Thus, work is being undertaken in an attempt to quantify this non-uniformity [53].

3.4. Effect of Topography and Meteorological Conditions

As mentioned in Section 3.2, topography and meteorological conditions can affect the sound power emission level of a wind turbine. Ashtiani and Halstead [54] showed that wind shear did not have a significant effect. However, van der Maal and de Beer [55] found that irregular terrain and meteorological effects could increase the turbine sound power output by 2–3 dBA. It appears that more work is needed on different wind farms to confirm this effect.

Other current research is directed at understanding how meteorological conditions can affect the presence of AM and the AM depth (or degree of modulation) in the noise generated by a turbine. Some researchers have found a strong correlation between time of day/night and the degree of AM [41], while others have found a weak or no correlation between the degree of AM and meteorological conditions [32] and yet others have found a good correlation between the presence of AM and meteorological conditions but a poor correlation between the degree of AM and meteorological conditions (see Figure 12 in [56]). Others [57] suggest that the degree of AM may be related to the extent of unsteady in-flow conditions to the rotor. Clearly, more research is needed to properly understand the causes of both AM and EAM.

3.5. Tonal Emission

Some turbine designs generate more tonal noise than others due to issues with the gearbox and its mounting. Manufacturers have spent considerable effort [35] in reducing the level of these tones in an attempt to ensure that tonal penalties that appear in many regulations do not apply [58]. For existing wind turbine installations with tonal noise issues, retrofitted passive tuned mass dampers have successfully reduced the amplitude of tones such that they were inaudible [59].

When undertaking an analysis of wind turbine noise in the infrasound region, tonal peaks will appear in the spectrum [60]. However, these peaks do not represent continuous tonal noise that we would normally expect. The tonal peaks are produced as a result of the infrasound pulse generated each time a blade passes the tower. As the pulse is a transient, its spectrum contains harmonics of the pulse frequency (number of times per second that the rotor support tower is passed by a rotor blade). Thus, even if the impulse noise were audible (and thus far, there is no evidence that it is), the tones would not be perceived as tones by a listener as the levels between impulses would not be audible, even if the impulses were. Rather, the pulse would be detected as a variation in sound level at the blade passing rate. Although this noise is at a very low level, it does vary in amplitude significantly and researchers do not agree on whether or not it can disturb or affect residents who are exposed to it on a long term basis.

3.6. Rank-Ordering of Noise Source Contributions

The various noise generating mechanisms identified in Section 3 should be rank-ordered in terms of their disturbance properties, which would include noise character and its variation with distance from the source, as well as the overall A-weighted level. This would enable efforts in addressing the problems to be directed towards the most important contributors. However, results of any research in this area have not been published in the open literature.

3.7. Future Directions for Research on Characterisation of Wind Turbine Noise Emission

To properly understand the character of wind farm noise, further work is needed in the following areas.

(a) More accurate computer models to characterise the various noise sources and provide sound power estimates for each source for use in noise propagation models. The provision of uncertainty estimates for all sound power levels is also important.
(b) Development of accurate means for measuring turbine sound power levels when operating as part of a wind farm. This would have to be done by remote sensing.
(c) Determination of directivity in the vertical direction of sound radiation from a turbine.
(d) Characterisation of the effect of upstream turbines and topography on turbine sound power outputs.
(e) Rank ordering of sources contributing to the wind farm noise signature in terms of their contribution to annoyance, sleep disturbance and overall A-weighted sound pressure levels at community locations.

4. Environmental Noise Level Prediction

Whenever a wind farm development is proposed, one of the requirements is a calculation of noise levels at all noise-sensitive locations, which usually means noise levels at all residences located less than 3–5 km from the nearest turbine. The exact distance depends on the turbine layout and number of turbines in the wind farm. However, it is sufficient to terminate calculations at greater distances than the distance at which the sound level is less than 30 dBA. This distance may also be a function of direction from the wind farm (depending on the wind farm layout).

Calculation of the expected noise levels is usually done using a generally accepted noise prediction model such as outlined in the international standard, ISO9613-2 [61], which is supposed to provide results for "meteorological conditions that are favourable for propagation from the sound source to the receiver", i.e. worst case atmospheric conditions. However, instances have been reported for which measured sound pressure levels exceed predicted sound pressure levels by up to 5-6 dBA for single octave bands and 4 dBA for overall A-weighted levels [62–64]. When high sound sources, such as wind turbines, are involved, the direct and ground-reflected sound rays can no longer be considered to be uncorrelated at the receiver, as the ground reflection point is close to the receiver (if the receiver height is much less than the turbine height). This results in the direct and ground reflected rays reinforcing or cancelling one another, depending on the frequency of the noise. At distances from a turbine sound source greater than 2 km, it is possible for more than one ground reflected sound ray (with more than one ground reflection) to arrive at a receiver in the downwind direction. Prediction models, such as in ISO9613-2 [61], in current use in wind farm projects do not account for multiple ground reflections, nor are they capable of predicting time varying phenomena such as amplitude modulation. In addition, currently used models are associated with a considerable level of uncertainty.

The discrepancy between measured and predicted sound pressure levels has resulted in a number of researchers working on more accurate models that include topography and more accurate calculations of ground and meteorological effects (including atmospheric turbulence). One such approach is described as "ray tracing", where ray paths from each turbine source to each receiver are calculated, based on downwind and/or temperature inverted atmospheric conditions [39,40,65–67]. Current research is directed at model validation [66] as well as extending the models to include multiple ground reflections [39] and atmospheric turbulence effects [39].

A more complex theoretical method, referred to as the Parabolic Equation (PE) method has also been developed and applied to wind farm noise propagation predictions [7,41,68]. This method avoids some of the draw-backs suffered by ray-tracing techniques, such as the presence of caustics, as well as inaccuracies at low frequencies and the inability to model scattering into shadow zones in the presence of strong upward refraction [69]. Kelly et al. [70] used the PE method to develop a statistical model to predict the long-term sound pressure level statistics at residential locations up to several kilometres from the turbine noise source. As with ray tracing, the PE method can model arbitrary terrains and atmospheric conditions. Current research is directed at making the computations using the PE method more efficient, especially at longer distances and for frequencies above a few hundred Hertz. Work is also directed at making it applicable to a wider range of atmospheric sound speed profiles, as well as using it together with an aeroacoustic noise source model to predict AM amplitudes [42].

A second but less popular complex method is referred to as the Fast Field Program. Unfortunately, in its current form, it can only be used for the case of a stratified atmosphere and it is unsuitable for propagation over ground with a spatially varying impedance. Some recent work has been reported that used this method for noise level predictions up to 12.8 km from a wind farm [64].

Part of a current French research project is the development of a sound propagation prediction model that includes an estimate of the sound pressure level variability due to meteorological, weather and ground effects [28]. Their work involves a sensitivity analysis as well as uncertainty estimates for the predicted sound pressure levels.

4.1. Outdoor vs. Indoor Levels

Most people are disturbed by indoor noise rather than outdoor noise from wind farms. Thus, it would be useful if a guide existed that provided outdoor to indoor noise reduction estimates that could be used in propagation models to estimate interior noise levels for a range of building constructions and window types (including double glazed and open). Keränen et al. [71] undertook such a study involving 26 different houses. Although the mounting location of the sound sources was a bit low and the −6 dB correction to account for reflection from the façade may not be accurate, the study produced some very useful data for particular façade types. However, more such data are needed, especially data that take into account transmission through the roof of dwellings as well as doors and windows as this is important for estimations of wind farm noise indoors.

4.2. Off-Shore Wind Farms

As off-shore wind farms are located above a flat, reflecting surface, and are usually much further from dwellings than on-shore wind farms, uncertainties in a prediction model can become much more significant [72]. This is because interference from the ground reflected ray is more coherent, resulting in larger fluctuations of sound pressure level with distance, and the increased distance of the wind farm from residences also results in less accurate noise predictions. It seems that there is considerable scope for using ray tracing or PE methods for these cases, but no significant current research on improving sound propagation models for off-shore wind farms has been reported. There is some evidence that, when wind turbine noise is propagating over water, there is a 3 dB decrease in sound level for each doubling of distance (cylindrical propagation) instead of the more usual 6 dB (spherical propagation) used for on-shore calculations [64]. However, more work is needed to properly quantify this effect.

4.3. Uncertainty

One way of accounting for inaccuracies in propagation models currently used for wind farm noise predictions is to undertake uncertainty estimates and report these along with predicted data at sensitive receiver locations [73]. Some researchers have made estimates of uncertainty for standard propagation models (±4 dBA) [74] and turbine sound power measurements (±2 dBA) [50] but more research is needed to validate the results. There are two types of uncertainty used for propagation model predictions that are sometimes confused. One is the uncertainty in the predicted noise level at a specified location, which tells us the maximum amount that a single measurement may deviate from the predicted level at a single location. This is the uncertainty that should be provided in noise level prediction reports and is usually specified as a 95th percentile level, which means that 95% of the measurements will have an error less than this. The other type of uncertainty, which is really model bias, although it is sometimes called uncertainty, is the difference between predictions and measured data averaged over many different locations. This result is also expressed as a 95th percentile, but it is inappropriate for use in a noise level prediction report as it does not indicate the error that could exist at a single location. Rather it tells us that, although in some locations the predictions may be high, in others they will be low, so that the average is usually less than the uncertainty for a single location.

4.4. Future Directions for Research on Environmental Noise Level Prediction

The development of more accurate propagation models to predict likely sound pressure levels at residences prior to construction is of considerable interest to turbine manufacturers and wind farm developers as they wish to maximise the electrical output power of a given development. More accurate propagation models would mean that noise estimates prior to construction would not need to be so conservative to ensure that regulations would be met. Thus, work in the following areas would be of considerable benefit.

(a) Development of a more accurate model that could reduce uncertainty estimates. Such a model may be based on the PE analysis method. Research is needed to properly quantify uncertainty for both existing and new models.
(b) Better quantification of both short-term and long-term wind farm noise variability at residential locations.
(c) Development of a specialised model for noise propagation from off-shore wind farms that involves propagation over large distances above water.

(d) Development of a guide for estimating noise reductions from outdoor to indoor for a range of building constructions, so that propagation models can be extended to estimate indoor sound pressure levels in addition to outdoor levels.

5. Environmental Noise Level Measurement

Work on noise measurement includes those measurements that validate propagation models [28,63,75] as well as those that investigate, by measurement, the effects on noise levels of various terrain, ground or meteorological conditions, such as snow covering the ground [76]. This type of work is likely to continue sporadically as various other meteorological or ground surface conditions are studied [77].

5.1. Long-Term Monitoring

Long-term monitoring, which may extend from a month to a year or longer, has been undertaken for a number of wind farms [78,79] for the purpose of documenting turbine noise levels corresponding to the four seasons as well as documenting the influence of turbine operating conditions and environmental conditions (such as wind direction and speed, atmospheric temperature profiles and foliage). This allows a complete picture to be established concerning noise levels that are experienced at nearby residences, which provides insight into compliance with local regulations [78]. The prevalence and magnitudes of special acoustic characteristics associated with wind farm operation such as amplitude modulation (AM), LFN, tonality and infrasound can also be determined. Substantial short- and long-term variation in turbine sound pressure levels at particular locations exist, and considerable difficulty has been experienced in attempts to classify levels according to local wind speed, direction and distance [79]. Meteorological conditions must also be taken into account to reduce variations within a particular category of wind speed, direction and distance [79]. Note that each category contains a range of values of the included variables. For example, a particular wind speed category may include wind speeds ranging from 5 to 6 m/s.

5.2. Ambient Noise and Its Isolation From Wind Farm Noise

Ambient noise (non-wind-farm noise) varies considerably with location, wind direction and strength, as well as time of day, time of year and also as a result of intermittent noises such as dog barking [80]. However, it is necessary to identify and remove ambient noise from the total (wind farm plus ambient noise) measurement so that any additional noise generated by a wind farm can be properly evaluated and compared to regulations [81–83]. Existing regulations specify methods to minimise the impact of ambient noise; however, they suffer from many drawbacks as discussed in Section 7.3 and they allow wind farm noise to potentially exceed allowable limits for 50% of the time. As a result of these problems, there have been a number of attempts, reported in the literature, to develop methods to automatically separate wind farm noise from ambient noise. At best, the methods reported thus far have only been partially successful, as each is either scientifically flawed or needs more research to be properly validated. Various alternative approaches that have been reported in published papers are listed below.

(a) **Use of manual separation** whereby each 10-min recording is listened to manually (or its time trace shown on a screen) and recordings rejected if they include significant levels of non-wind-farm noise [78]. This is a very time consuming and expensive process and should be avoided if at all possible.

(b) **Use of dual microphone systems** where one microphone is placed such that it is shielded from the wind farm by a large barrier such as a house [84]. It is then assumed that the unshielded microphone measures wind farm noise as well as other environmental noise, whereas the shielded microphone measures all noise except wind farm noise. However, this method has obvious flaws, such as the assumptions that the environmental noise is the same level at both microphones and that wind farm noise does not intrude over or around the barrier.

(c) **Use of an Ai-weighting instead of an A-weighting** [84,85]. This results in A-weighted noise in the frequency bands from 10 to 1250 Hz only being recorded. This makes some sense, as it excludes insect and bird noise as well as wind rustling leaves in trees, while at the same time having a negligible effect on wind farm noise, especially when the distance from the nearest turbine exceeds 700 m or so (although there may be residences closer than this in Europe and the USA). However, use of an Ai-weighting does not exclude environmental noise in the frequency range of 10–1250 Hz and is not considered to be very reliable.

(d) **Use of a proxy site** (or an average of several different proxy sites) in a similar environment but sufficiently far from any wind farm that wind farm noise is not detectable. This suffers from the problem of there being no guarantee that the environmental noise levels will be identical for the proxy site and for the actual site where wind farm noise exists.

(e) **Measurement of the ambient noise prior to construction** of the wind farm. This method is the one most commonly used in compliance measurements and assumes that the environmental noise will be the same prior and post construction, which cannot be guaranteed. Even for a specified wind speed at turbine nacelle height, the existing ambient noise will not necessarily be the same for each total noise measurement; thus, this method does not guarantee that results will be wind farm only noise. This approach also suffers from the problems discussed at the beginning of this section.

(f) **Use of statistical methods** to determine wind farm noise contributions. This approach is described in Chapter 6 of [86] and was first suggested by Ashtiani [87,88]. However, more research is needed to properly validate the suggested procedures, which are quite complex.

(g) **Use of two microphones** to determine the difference in sound pressure level at two locations for each 1/3-octave band and each wind speed segment of interest [89]. Wind speed segments usually span a 1 m/s wind speed range; for example, one segment may include all wind speeds between 3.5 and 4.5 m/s. The difference in sound pressure levels between the two microphones is then used to determine whether the dominant noise in a particular 1/3-octave band and wind speed segment is due to the wind farm or to some other source. This method has not yet been validated and is likely to be problematic in situations in which turbines are located in several different directions from the dwelling of interest.

(h) **Use of a virtual turbine** to represent the entire wind farm [90–92]. In this method, the sound pressure at a receiver is expressed in terms of a single wind farm parameter, N_{eq}, which represents the rotational speed of a virtual turbine and which is a function of the number of turbines in the wind farm and their respective distances to the receiver. An iterative procedure is then used, with wind speed and sound pressure level data measured at the receiver over a three-week period, to determine the contributions of wind farm noise and ambient noise. This procedure is very complex and time consuming, requiring a significant amount of manual intervention and is not amenable to automation. However, the authors of the above-mentioned papers have found it to work effectively.

(i) **Use of iterative machine learning**, which consists of a learning and validating phase to develop a preliminary model and then a testing phase to isolate ambient noise from wind farm noise in new datasets [93]. This work is in a very preliminary stage and considerably more development is needed before it can be applied. Part of the new work would be to use larger datasets with more variables (noise level vs. meteorological effects, distance, number of turbines, and ambient noise vs. wind farm operational noise). This approach would work best if pre-construction ambient data or noise data when the wind farm was shut down for maintenance were available.

(j) **Use of signal analysis on recorded data** to identify transient ambient noise events by their spectral content and rate of change in level, followed by automatic rejection of non-wind-farm noise from the noise sample prior to further analysis. No research in this area has been reported to date and it is expected that only transient ambient noise events would be rejected, and that, after removal of these events, it would still be necessary to subtract the average ambient noise from the wind farm noise. This method may need to be used in conjunction with machine learning to be able to properly isolate wind farm noise.

It appears that the last two methods or a combination of the two offer the best possibility of success but they will need a substantial amount of development work and a large database of wind farm noise and ambient noise.

5.3. Wind Noise

Wind noise consists of two components. The first is the noise generated by the wind interacting with vegetation and solid obstacles. The second is the pseudo noise recorded by a microphone as a result of the turbulent pressure fluctuations caused by wind blowing over the microphone and its wind screens. Considerable work has been done in the past to minimise pseudo wind noise, by developing effective primary and secondary wind screens and placing the microphone on the ground where the wind speed is always lower. Even if primary and secondary wind screens are used together with ground mounted microphones, problems with wind-induced noise still exist when very LFN and infrasound is to be measured [94–96]. An additional problem is determining the frequency-dependent correction that should be added to the ground microphone signal to make it equivalent to a measurement at the 1.5 m height, which is usually specified in regulations [67].

Work is also on-going in the development of a microphone array that is insensitive to wind noise [97].

5.4. Amplitude Modulation (AM)

One of the potentially annoying characteristics of wind farm noise, which has been identified and which has been the subject of considerable past research, is AM [56]. AM is the regular variation of wind farm noise experienced as turbine blades rotate. The frequency of variation is the frequency at which blades pass the tower (blade-pass frequency, usually between 0.5 and 2 Hz). Recent work has shown that, although the highest noise levels are experienced in the downwind direction of a wind turbine, higher levels of AM (albeit with lower overall sound pressure levels) are experienced in a cross-wind direction, approximately 60° from the front of the nacelle [98]. The effect of meteorological conditions on the generation of much higher than expected levels of AM (often referred to as EAM) continues to be the subject of a significant amount of continuing research effort (see [32,34,57,99]).

There is also considerable interest in the development of a metric for quantifying AM, as this is the first step for it to be included as part of a noise regulation. Work in this area has been on-going for almost 10 years, with the first comprehensive review reported by Oerlemans [33], which was part of a general study on wind farm AM by Renewable UK [100]. Schemes currently being researched were summarised in [86] and a comprehensive review of a number of schemes was undertaken by Bass et al. [101]. Based on their review, a final report was produced [102], which outlines a preferred scheme. However, this scheme has several limitations, such as only being applied to swish noise, lack of justification for the various parameter choices and lack of comprehensive validation. Thus, work continues in validating and improving various proposed models [56,103,104].

5.5. Low-Frequency Noise (LFN)

The extent of the LFN problem in the vicinity of a wind farm can be quantified by measuring the dBC level [105], by determining the difference between overall dBC and dBA levels [106,107] and/or by measuring 1/3-octave band levels in the frequency range 10–160 Hz [108]. Alternatively, 1/3-octave band indoor sound pressure levels in the frequency range 10–160 Hz [108,109] or 5–80 Hz [110] can be used to quantify a LFN problem.

5.6. Tonality

It is generally accepted that any noise that contains easily distinguishable tones is more annoying than the same noise at the same level without tones. Many regulations contain a penalty (up to 5 dBA) for wind farm noise with one or more tones. The presence of tones and their audibility is usually assessed using procedures in the standard, IEC61400 [49]. However, this standard is only applicable to measurements taken close to a turbine and not at a typical residential location where the tone would be experienced. In work undertaken a few years ago, Cooper [59] suggested a means to extend the tonal assessment described in IEC61400 [49] to residential locations and also pointed out that the wind conditions at which the tone was most audible were outside the wind speed and direction range required to be assessed by IEC61400 [49]. It is necessary for additional research to be undertaken to confirm the results obtained by Cooper [59] so that IEC61400 [49] can be appropriately updated.

5.7. Infrasound

It is possible to obtain reliable measurements of overall sound pressure level at infrasonic frequencies using either very low-frequency microphones or specialised infrasound sensors. The latter sensors are better at minimising pseudo wind noise as they consist of four long tubes arranged in spokes (at angular separations of 90°) emanating from the microphone enclosure to transmit the sound to the microphone. Such an arrangement minimises pressure fluctuations due to the wind and enhances acoustic pressure fluctuations. This is because the turbulent pressure fluctuations sampled at the outer ends of the four tubes are uncorrelated whereas the acoustic pressure fluctuations from a sound source are correlated. It has been shown that infrasonic noise from wind farms can be at a higher level inside houses than outside, due to the tonal infrasound from wind turbines exciting resonances within the rooms inside the house [111,112]. Such amplification depends on the construction of the house as well as the room sizes. Both of the preceding references contain details of how best to measure indoor infrasound.

Results of some measurements [113] show that infrasound due to wind farms is well below the 50th percentile perception threshold. The 50th percentile perception threshold level (in dB) is a level for which 50% of people have a higher hearing threshold and 50% of people have a lower hearing threshold. Therefore, some sensitive people may be be able to hear infrasound at much lower levels, but perhaps not as low as required to hear wind farm infrasound. Nevertheless, Cooper [114] has found some people who feel sensations such as headache, pressure in the head, ears or chest, ringing in the ears, heart racing, pulsations in the head, fatigue or a feeling of heaviness, when exposed to wind farm noise, even when they cannot hear it. This effect could possibly be a response to infrasound exposure but more research is needed before this can be proven. As discussed in Section 6.2.5, research on the effect of wind farm infrasound on sleep is currently being undertaken in three research projects: one at Flinders University in Australia, funded by the National Health and Medical Research Council (NHMRC) [115]; one at the University of New South Wales in Australia (Prof Guy marks, see [116]), also funded by NHMRC; and one at The University of Minnesota in the USA [117,118].

5.8. Outdoor vs. Indoor Levels

Several researchers [111,119] have measured the difference between outdoor and indoor noise levels for a variety of residences in various countries. Some results [71] are of limited use as they use a loudspeaker adjacent to one of the walls of a residence, which does not simulate the actual situation of wind farm noise, for which the noise is also incident on the roof of a residence as well as other walls. Thorsson et al. [120] suggested that, for practical purposes, it would be better to settle on a standard reduction spectrum for the difference between outdoor and indoor noise and use this for all situations. However, this approach may lead to large errors for some constructions and some sleeping locations.

5.9. Future Directions For Research on Environmental Noise Level Measurement

Research questions that need to be answered by further research on the measurement of wind farm noise are listed below.

(a) What procedures are necessary to improve the efficiency of wind farm noise measurement at residential locations?
(b) What is the amount of noise monitoring necessary to properly characterise wind farm noise immission at residential locations for various meteorological conditions?
(c) What is the best metric to use to characterise AM of the noise and how can this metric be applied in regulations?
(d) How can non-turbine noise be removed from noise measurements in an efficient and semi-automatic way (perhaps using AI and signal processing techniques combined)?
(e) How can wind noise be eliminated from wind farm noise measurements at residential locations?
(f) What are maximum instantaneous (rather than average) levels of infrasound generated at residences in the vicinity of wind farms?

6. Human Response to Wind Farm Noise

Human response to wind farm noise is the subject of considerable past research as well as on-going research [121–126]. There continues to be disagreement among researchers as well as among the general public regarding whether or not wind farms are directly and/or indirectly responsible for adverse health effects [127–130]. However, it seems that wind farm noise is possibly more easily perceived and, compared with noise from other community sources such as traffic noise, railway noise and aircraft noise, wind farm noise is more annoying [122,131–133]. Annoyance levels are also increased as a result of AM of the noise at the blade pass frequency (BPF), the low-frequency bias of the spectrum [126,134], the existence of tones and, possibly, infrasound. The persistent nature of the noise throughout the day and night is also a factor contributing to annoyance, as is the low ambient noise associated with many wind farm sites.

Relatively recently, it has been shown that people living in suburban areas in the UK are less likely to be annoyed by wind farm noise [135] than people living in rural areas. These authors also found that health and well-being were increasingly affected by wind farm noise as the overall A-weighted noise level increased, resulting in increasing incidences of self-reported sleep disturbance, including sleeping less deeply and increasing difficulty in falling asleep. They also found that visibility of the turbines had an adverse effect on self-reported sleep disturbance. However, these results were for a relatively small sample size with very few turbines, thus there is a need to repeat the experiment with larger groups of people near much larger wind farms. The conclusion that visibility of the turbines affects annoyance was supported in a laboratory study by Schäffer et al. [136], who also reported that the order of presentation of stimuli in a laboratory setting was important.

Using a survey of residents near a wind farm, Pawlaczyk-Łuszczyńska et al. [137] showed that wind farm noise at residential locations in the range 33–50 dBA was perceived as annoying or highly annoying by 46% and 28% of respondents living between 204 and 1726 m from the nearest wind turbine, respectively. On the other hand, 34% and 18% were annoyed or highly annoyed indoors, respectively. Annoyance was associated with the A-weighted sound pressure level, distance from the nearest wind turbine, general attitude to wind farms, noise sensitivity and terrain shape (annoyance outdoors) or road-traffic intensity (annoyance indoors). The level of sleep disturbance was also found to be associated with the level of annoyance. Similar levels of annoyance as found by Pawlaczyk-Łuszczyńska et al. [137] were reported in an earlier field study in the Netherlands [122], which also showed that annoyance was inversely correlated with economic benefit from the turbines.

Taylor et al. [138] pointed out that human response to wind farm noise is a complex phenomenon that is linked to many associated factors such as local community attitudes, identity of place, economic participation and perceived industrialisation of local landscapes. Although many studies have convincingly linked wind farm noise level to annoyance level, the follow-on effect that annoyance has an adverse effects on sleep and health is controversial and considerably more work is needed to clarify this (see Section 6.4).

In the following subsections, current research on various aspects of human response to wind farm noise is discussed.

6.1. Sensation, Startle Reflex and Sensitisation

The concept of "sensation" to assess the adverse impact of a wind farm was developed by Cooper [114] in a recent study of a wind farm located at Cape Bridgewater on the Southern Australian coast. The word "sensation" was used in the report to describe both audible and non-audible responses that were experienced by residents living between 650 and 1600 m from the nearest turbine in the wind farm and included headache; pressure in the head, ears or chest; ringing in the ears; heart racing; pulsations in the head; fatigue; or a feeling of heaviness. Diaries from six residents recorded times when the sensations were felt and these were matched to the wind farm noise spectra at corresponding times. The study found that diary responses associated with audible noise were not directly correlated with the wind farm electrical power output but the severity of sensations experienced was directly correlated with times when the wind farm output power changed by 20% or more, when the wind farm began to generate power after a period of no power generation and when the wind increased above the speed corresponding to the maximum power output of the turbines.

In a subsequent conference paper, Laurie et al. [139] discussed the ability of residents living near wind farms to detect when the turbines were off or running, even though the running noise was below the threshold of audibility. They attributed this to the presence of AM and the sensitivity of the residents to AM of the low-frequency part of the spectrum, to which the residents became sensitised after long-term exposure. They also postulated that this was the cause of activation of the startle reflex in these residents, whereby they would often wake up at night feeling a racing heart. They also suggested that regular activation of the startle reflex could lead to a downward spiral in physical and mental health.

6.2. Annoying Aspects of Wind Farm Noise

Annoying aspects of wind farm noise that may be responsible for sleep disturbance and adverse health effects include AM, dominance of the spectrum by LFN at distances greater than 1 or 2 km, tonal noise and, possibly, infrasound. The response of people to various annoying aspects is currently part of the research being undertaken in the on-going studies in Australia at Flinders University [115,140] and funded by the NHMRC and ARC. Infrasound is treated separately in Section 6.2.5

6.2.1. Sudden Changes in Wind Farm Electrical Power Output

Sudden changes in wind farm power output are associated with sudden changes in the wind farm noise output level as well as its character. In particular, changes in the low to very low part of the frequency spectrum can cause annoyance to people who have been sensitised to wind farm noise. As discussed in Section 6.1, the human response to these changes can also manifest as physical symptoms such as headache; pressure in the head, ears or chest; ringing in the ears; heart racing; pulsations in the head; fatigue; or a feeling of heaviness.

6.2.2. Amplitude Modulation (AM)

In 2017, after a review of 69 papers on AM, Perkins et al. [141] concluded that AM can cause annoyance and that such annoyance could in turn result in sleep disruption followed by corresponding adverse health effects. In particular, it seems that EAM, which occurs under certain meteorological conditions and is lower in frequency compared to normal AM [100], is a significant contributor to the annoyance that many be experienced in response to audible wind farm noise.

There have been many previous studies on the assessment of the effect of AM on human response to wind farm noise and quite a few schemes have been suggested for calculating the size of the penalty that should be applied to the allowed noise levels in the presence of various magnitudes of AM. However, research in this area is still continuing (see [56,117,142]).

6.2.3. Low-Frequency Noise (LFN)

Annoyance experienced by people subjected to any noise is a function of the decibel level that the noise exceeds the hearing threshold level. However, for LFN below 100 Hz, the annoyance increases at a more rapid rate with increasing noise level than it does for higher-frequency noise [143]. Thus, when noise contains a high low-frequency content, it is more annoying [144]. Recent research has focussed on low-frequency hearing thresholds [145]. However, we have found no published work on annoyance of LFN since that reported by Leventhall [146].

6.2.4. Tonal Effects

The presence of tones in wind farm noise is well known to increase annoyance by varying amounts, depending on the individual [147]. Oliva et al. [148] derived penalties for tones with frequencies of 50, 110, 290, 850 and 2100 Hz and tonal audibilities ranging from 5 to 25 dB(A). While these researchers covered an impressive number of combinations of tonal frequency and audibility, the penalties were derived based on the group mean, which does not take into account differences between individuals. In addition, the short sample time of 15 s may not have been long enough to capture the extent of annoyance. This may take longer and importantly depend on variable human factors such as attention, concentration, irritability and situational factors at the time. Hence, more work is needed to properly quantify the effects and to determine how best to include them in regulations, even though some existing regulations have a 5 dBA penalty for tonality measured according to IEC61400 [49].

6.2.5. Infrasound

Several studies in the past have attempted to evaluate the effect of wind farm infrasound on people [116,131,133]. Although these studies have not found that people can perceive the existence of infrasound at the levels typically produced by a wind farm, the studies have a few serious drawbacks, which make the results questionable and point to the need for more work to be undertaken before the question of whether wind farm infrasound can lead to adverse health effects can be answered definitively. The problems with the previous studies are as follows.

(a) Use of simulated wind farm infrasound (as done by Tonin [116]), not recorded infrasound in the vicinity of a wind turbine.
(b) Use only of participants who have not lived near a wind farm and so have not been conditioned to the presence of infrasound (as done by Tonin [116]).
(c) Use of short exposure times (as done by Tonin [116]), which means that the studies ignore the effects of long-term exposure. Use of participants from the vicinity of existing wind farms would help ameliorate this problem.

Work undertaken at the UCL Ear Institute in London [149] suggests that amplitude-modulated LFN may underlie complaints about environmental infrasound in cases where measured infrasound levels are well below any sensation threshold. Wind farm noise contains a significant level at low-frequencies, especially at typical distances of dwellings from a wind farm, so the results of this study are very pertinent.

An on-going study in Australia at the University of New South Wales (led by Guy Marks) and funded by the Australian NHMRC consists of a short-term study and a longer-term study to investigate whether exposure to simulated wind farm infrasound causes health problems [116]. The short-term study will be laboratory based, run for three one-week periods and use simulated infrasound, while the longer-term study will be community based and run for six months. Sleep quality, balance, mood and cardiovascular health will be measured.

A second on-going study in Australia at Flinders University [115,140] and funded by the NHMRC is investigating the effect of wind farm noise on sleep and some of the tests will include infrasound (by itself, with no other noise) that has been recorded in the vicinity of a wind farm. A unique part of this project is the testing of people who have been subjected to wind farm noise for an extended period of time as well as people who have not experienced wind farm noise previously. One purpose of the work is to test the hypothesis that people living near wind farms can become sensitised to the noise, causing it to be more annoying and more sleep disruptive.

Another on-going study in the USA at the University of Minnesota [117,118] and funded by the Renewable Energy Fund (USA) is investigating the response of participants when subjected to infrasound that has been recorded in the vicinity of a wind farm, as well as simulated infrasound for which the spectral peaks were enhanced. In the pilot study, participants (who were awake and in a laboratory) were not able to detect the presence of either infrasound type, when played at levels recorded in the vicinity of a wind farm.

In an on-going German study, researchers [150] are currently investigating the effects of wind farm infrasound on ECG, EEG and blood pressure of 30 participants.

6.2.6. Ambient Noise Level Effects

The response to wind farm noise of people living near wind farms is expected to decrease as noise levels from other sources (ambient noise, including traffic noise) increase [151,152]. This effect is yet to be quantified.

6.3. Dose–Response Relationships

The percentage of people annoyed and highly annoyed by wind farm noise increases at a rapid rate, with increasing A-weighted sound pressure level, after 35 dBA is exceeded [132]. The rate of annoyance increase with A-weighted sound pressure level is much greater than it is for other noise sources such as road traffic, railways and aircraft. There is also a difference in response of suburban dwellers compared to rural dwellers [135]. This difference may be partly explained by people living in rural areas being more sensitive to intrusive noise, as they are not as used to it as suburban residents who live with varying levels of road traffic noise. The difference may also be partly explained by there being higher levels of ambient noise in suburban areas, which tends to mask the wind farm noise (see also Section 6.2.6). This latter reason was explored in a study undertaken by Van den Berg and de Boer [153], which involved adding brown noise (spectral energy per Hz proportional to $1/f^2$) and black noise (spectral energy per Hz proportional to $1/f^3$) to the existing soundscape experienced by the study participants. Van den Berg and de Boer [153] found that 50% of their study participants, who were complaining of annoyance caused by LFN were helped by the addition of brown and black noise.

There have been several studies on the dose–response relationship for wind farm noise [121–123,154,155]. These studies are difficult to compare, as they use different methods for predicting the sound levels experienced by those participating in the surveys. However, Old [156] normalised the results using a common metric of 1-hour L_{Aeq} and the ISO9613-2 [61] propagation model, and concluded that levels of annoyance become significant once wind farm noise levels, predicted using the International standard, ISO9613-2 [61], exceed 35 dBA.

6.4. Sleep Disturbance

Due to the difficulty in obtaining statistically significant results from resident surveys, it has been decided by some researchers that insight into possible adverse health effects may be substituted by studies of the effect of wind farm noise on sleep. There is general consensus in the medical community that sleep disruption can have adverse health effects, so the study of the effect of wind farm noise on sleep may be representative of an indirect study of the effect of wind farms on health. Investigations of the effect of wind farm noise on sleep can be undertaken in the houses of people living in the vicinity of one or more wind farms or in a sleep laboratory, in which participants are exposed to varying levels of wind farm noise, with and without various annoying aspects, such as AM, while they are attempting to sleep. During this time, measurement of physiological parameters enables the determination of awakening levels for sleeping participants exposed to varying levels and types of wind farm noise accompanied with varying levels of ambient noise [115,126,157]. All of these studies include the introduction of a number of physiological monitoring tools to continually test for sleep quality in the presence of wind farm noise at various levels. Sleep disturbance was also covered in the study by Michaud et al. [158], but there were limitations associated with the measures used to detect sleep disturbance [115].

In sleep studies, there often exists a dilemma regarding whether the noise presented to participants should be an actual recording of wind farm noise or a simulation of the noise. Simulating the noise allows different noise characteristics, such as different levels of AM, to be tested separately, but many argue that tests of annoyance to wind farm noise should use actual recordings of wind farm noise that include frequencies down to 1 Hz, as we do not know which aspects of the noise are causing problems for some people. For these reasons, it is recommended that future studies involve testing participants with both simulated as well as real recordings of wind farm noise. For those tests for which simulated noise is appropriate, Thorsson et al. [126] provided details on how the simulated noise may be produced.

Some of the questions that still need to be answered by sleep studies include the following.

(a) What is the dose–response relationship between the level of A-weighted wind farm noise and the percentage of people suffering sleep disturbance? Sleep disturbance includes difficulty in going back to sleep once awakened, difficulty in going to sleep once in bed and awakened partially and awakened fully by the noise.
(b) Can wind farm noise cause sleep disturbance via annoyance?
(c) Is sleep disruption worse for people living in quieter rural environments?
(d) What part of the wind farm noise spectrum is most disturbing to sleep? Is it the infrasound spectrum including all frequencies below 20 Hz, is it the low-frequency part of the spectrum between 20 and 200 Hz or is it higher frequency noise?
(e) Are there any other wind farm noise characteristics such as the presence of low-frequency tones or AM that exacerbate sleep disturbance?
(f) What is the effect of simultaneous additional broadband noise such as traffic noise or wind blowing in trees, on the effect of wind farm noise on sleep?
(g) What effect do the sensors attached to participants have on the results? This will be able to be tested once remote sensing procedures are developed so that the sleep status of participants can be monitored without using any attached sensors.

A recent study [159] investigated the use of sleep and antidepressant medication by people living in the vicinity of wind farms. The authors found that the prevalence of prescription sleep medication purchase increased as the level of nighttime wind farm noise exposure increased. The same result was found for the use of antidepressant medication. However, the authors stressed that the results are preliminary and they suggested that the study should be repeated with a larger sample size.

6.5. Adverse Health Effects

In the past, several studies [121–125,160] have been carried out to determine whether or not wind farm noise causes adverse health effects in residents living in their near vicinity. Anecdotal evidence would suggest that people living less than 5 km from the nearest turbine in a wind farm can suffer a number of symptoms, including tachycardia (raised heartbeat rate), raised blood pressure, activation of the startle reflex and a feeling of fullness in their hearing mechanism. However, none of the studies undertaken thus far have directly linked wind farm noise with any adverse health effects [125,133,161]. This is possibly a result of several factors as follows.

(a) The link may be an indirect rather than a direct one (see [127,128]), in which wind farm noise causes annoyance which, in turn causes sleep disruption, eventually leading to adverse health effects. A recent Canadian survey [123,124] did find a correlation between the level of wind farm noise exposure and annoyance.
(b) Use of calculated rather than measured noise levels [122,123,135]. In addition to the uncertainties associated with calculated noise levels, the effects of special characteristics of wind farm noise, such as AM and tonality, are not taken into account. These are serious problems with past surveys.
(c) Use of resident surveys rather than medical examination [122,123].
(d) Use of sample groups containing many more people living between 3 and 5 km (or between 5 and 10 km) from the wind farm than between 0.5 and 3 km (as a result of the much greater area associated with the larger distances). This results in the small percentage of people who are affected appearing as statistically insignificant.
(e) Insufficient sample sizes. In many cases, the size of the groups sampled was insufficient to draw any firm conclusions [125,161].
(f) Not accounting for special characteristics of wind farm noise such as AM, tonality and LFN.

One of the difficulties in undertaking large studies involving large populations is accurately estimating the noise exposure of participants. It is generally not practical to measure exposure directly for so many people so it has to be inferred. As mentioned in part (b) above, this has been done in the past using calculated noise levels with limited success. However, more recently, Barry et al. [162] found good correlation between proximity to wind turbines and annoyance as well as health-related quality of life measures.

The research question that remains to be answered definitively is whether or not wind farm noise can be linked to adverse health effects in any individuals exposed for long periods of time. Currently available scientific evidence would suggest that the levels of infrasound associated with wind farms are insufficient to cause health effects directly [127] and the levels of audible noise are well below those levels that are known to cause adverse health effects. Studies undertaken thus far have not disproved that wind farm noise can cause sleep disruption [127,133]. Nevertheless, the studies have shown that wind farm noise can cause annoyance at levels above 35 dBA [131], which is exacerbated by non-acoustic aspects of wind farms such as shadow flicker [127], and this is likely to lead to sleep disruption. Thus, one feasible way of determining whether or not wind farm noise can lead to adverse health effects is to study the effects of wind farm noise on sleep, as discussed in Section 6.4.

6.6. Future Directions for Human Response Research

Even though a considerable effort has been devoted to determining the effect of wind farm noise on people, a considerable amount of work remains if the following questions are to be properly answered. These questions are in addition to those posed for sleep studies at the end of Section 6.4.

(a) What is the dose–response relationship for annoyance caused by wind farm noise and how does it differ for different types of communities? Is it different for rural communities compared to urban communities? Is it different for developed compared to developing countries?
(b) Can wind farms cause adverse health effects in humans, either directly or indirectly when individuals are exposed for long periods of several months or years?
(c) What is the effect of simultaneous relatively high levels of traffic noise (or other ambient noise) on annoyance and sleep disturbance caused by wind farm noise?
(d) What characteristics of wind farm noise cause most annoyance? Is it the A-weighted overall sound pressure level, AM, low-frequency spectral bias or tones? Is infrasound a contributing factor?

(e) Does the presence of ambient noise mask the perception of or reduce the annoyance of wind farm noise and, if so, what are the optimum levels and spectra of the masking noise for various wind farm noise levels and spectra?
(f) What effect does participant conditioning have on noise sensitivity? That is, do residents become more sensitised to noise after being exposed previously for a substantial amount of time (months or years) and do they generally suffer from the sensations reported in Section 6.1 for residents near the Cape Bridgewater wind farm?
(g) What effect does conditioning by anti and pro wind farm web sites, social media and newspaper reports have on the response of residents? There is some evidence that newspaper language can pre-condition residents to be noise sensitive prior to construction of a wind farm [163], but there is scope for considerably more work in this area.

7. Regulation and Compliance

Guidelines for drafting local wind regulations do exist [164,165] and a brief review of a number of existing regulations was provided by van Treuren [2]. A more detailed review was provided by Davy et al. [166] who reviewed various annoyance studies and concluded that the A-weighted noise level that would result in less than 10% of people being highly annoyed in the absence of noticeable AM would be an $L_{A90(10min)}$ of 35 dBA, which would translate to an allowed L_{Aeq} of 37 dBA. It seems that complaints could be minimised provided that the wind farm noise level at dwellings does not exceed 35 dBA, although many jurisdictions believe that this value is too low. However, Fredianelli and Licitra [132] showed that 40 dBA of road traffic noise is equivalent to 34.3 dBA of wind farm noise in terms of the percentage of people highly annoyed by it, which would suggest that wind farm noise limits should be about 5 dBA lower than traffic noise limits.

As illustrated by Dutilleux [167], developing appropriate regulations is a complex procedure and it would be advantageous for the industry if jurisdictions could work towards some uniformity in assessment procedures (including the assessment of annoying aspects) if not absolute allowed levels. It would also be useful to have some international agreement regarding the acceptable percentage of people who are highly annoyed by wind farm noise. Is 10% appropriate, as suggested by Davy et al. [166], or should it be smaller (or larger)?

7.1. Special Characteristics of Wind Farm Noise

Some special characteristics of wind farm noise can be accounted for by adding a penalty in dBA to the measured A-weighted sound pressure level before comparing the measured A-weighted level to the allowed level. Other characteristics may be accounted for by specifying an allowable limit for a particular measurement that quantifies that particular characteristic. However, research is still needed to determine how regulations can best address all characteristics of wind farm noise at the typical range of distances between the nearest turbine in a wind farm and potentially affected residences. Characteristics of wind farm noise that are potentially annoying to residents are listed and explained below.

(a) **Amplitude modulation (AM)** [142,168], which is the periodic variation in wind farm noise level. Allowed levels should be expressed in terms of a single parameter that is proportional to the annoyance and magnitude of the modulation. A suitable modulation metric as well as its suitable value are both subjects of current research [103,169]. The single parameter could then be used as a basis for an AM penalty (decrease in allowed A-weighted sound pressure level as a function of a suitable modulation metric). It may also be necessary for the magnitude of the AM penalty to be a function of the A-weighted noise level [100,170].
(b) **Low-frequency noise (LFN).** This is currently addressed in some regulations that do consider it, in a number of ways by specifying one or more of the following:

    (i) an allowed maximum C-weighted noise level [171];

(ii) an allowed maximum decibel difference between the C-weighted level and the A-weighted level [106,107,109,172];
(iii) allowed overall maximum indoor noise levels in a specified frequency range (see, for example, [173], which specifies, in Danish regulations, an allowed 20 dBA in the range 10–160 Hz for wind speeds at hub height between 6 and 8 m/s); and
(iv) allowed maximum indoor noise levels for each 1/3-octave band in the frequency range 20–200 Hz (Swedish and Finnish regulations according to Sørensen and Kishore [109] and DEFRA criteria according to Moorhouse *et al.* [108]) or 5–80 Hz [110].

A limitation of the methods presented above is their use in isolation. For instance, considering the overall C-weighted level or dBC minus dBA exclusively will result in false positives in the results. On the other hand, comprehensive spectral analysis can be complex for compliance assessment purposes [172].

After reviewing the approaches to LFN assessment and regulation used in various international jurisdictions, Downey and Parnell [172] proposed a new approach that uses a three-stage assessment of LFN:

(i) simple initial screening so that assessment proceeds only if the C-weighted level minus the A-weighted level (dBC − dBA) exceeds 15 dB;
(ii) comparison of 1/3-octave band levels between 10 and 160 Hz with allowed 1/3-octave band levels; and
(iii) assignment of a penalty to the measured A-weighted level, depending on the extent by which the measured 1/3-octave band levels exceed the allowed levels.

As wind turbines become larger, the likelihood of annoyance from excessive infrasound and LFN becomes greater, due to the shift to lower frequencies of the wind turbine noise spectrum [174]. On the other hand, some would argue that, if turbines become sufficiently high, the noise reaching dwellings would be reduced, but this remains very speculative. Research is needed to determine whether or not existing regulations are applicable to turbines larger than those existing in wind farms at the time that the regulations were drafted, and whether satisfaction of the various different requirements in different regulations adequately protects residents from LFN annoyance [109].

(c) **Tones.** It is well known that tones add to the annoyance of wind farm noise. The international standard, IEC61400 [49], describes how to determine tonal prominence for noise measured close to a wind turbine. As discussed in Section 5.6, the procedure is not appropriate for determining the extent of tonality at a dwelling located some distance from the nearest turbine in a wind farm. In addition, results of round robin tests in various laboratories show inconsistencies in identification of the same tone [109], probably due to inconsistencies in interpretation of the standard by different research groups. These inconsistencies in interpretation of IEC61400, probably as a result of the high complexity of IEC61400 [49], will need further research to resolve. It is important that any new standard for wind farm noise specifies appropriate frequency-dependent and sound pressure level-dependent tonal penalties that can be used in regulations [148,175,176].

(d) **Infrasound.** A single number rating for the level of infrasound is currently the G-weighted level (dBG). The G-weighting network has a maximum response at 20 Hz that rolls off in a similar way to the response of the ear as the frequency is decreased to 2 Hz. Above 20 Hz, the weighting is not zero but rolls off at a rate such that the weighting at 2 Hz is similar to that at 63 Hz. It needs to be established whether this is a suitable descriptor to be used in regulations for wind farm noise and, if so, what would be an appropriate allowed dBG level.

The appropriate level would have to be based on the outcomes of further research on the effects of infrasound on annoyance and sleep disruption, as discussed in Sections 6.2 and 6.2.5.

7.2. Set-Back Distance

Some regulations specify a minimum distance (set-back distance) between a residence and the nearest turbine in the wind farm, with the same distance for all wind farms and all terrain types. However, the corresponding noise levels that are experienced at the specified set-back distance are very wind farm specific and more research is needed to address the variations in noise level as a function of the following aspects, although no research on these topics seems to have been undertaken recently.

(a) Total number of turbines in a wind farm.
(b) Number of turbines with distances to the nearest residence within 110%, 120% and 150% of the set-back distance.
(c) Rated power of the turbines.

7.3. Compliance Testing

Testing for compliance of a wind farm with allowed noise levels at community locations is problematic due to the relatively low noise levels involved and the presence of numerous other sources of noise. In many places, it is often difficult to identify the wind farm noise contribution to the total measured noise level. Some regulations suggest taking measurements with the wind farm running and then immediately afterwards with the wind turbines turned off. There are four problems with this approach:

(a) for large grid-connected wind farms, turning multiple turbines off and back on over relatively short time frames can result in large power variations from the wind farm, which need to be managed within the electricity system [177];
(b) worst-case conditions correspond to periods when the wind power output is relatively high and thus wind farm shutdowns result in lost revenue for wind farm operators;
(c) turbines make noise even when turned off, due to the generator left running and wind blowing past the blades; and
(d) meteorological conditions can change significantly between measurements.

For the reasons mentioned above, compliance testing usually involves continuous long-term unattended measurements [177–180]. The quantity of interest is generally the L_{A90} as this measurement excludes transient events because it is the level that is exceeded 90% of the time. Thus, the result is much more representative of the continuous noise level than an energy averaged L_{Aeq} measurement, which would include transient events, such as the odd car driving by. These measurements are done before and after the wind farm installation so that both ambient and wind farm noise levels are recorded. Some regulations (see, for example, [179]) require 2000 or 3000 10-min samples of ambient noise (with at least 500 from the worst-case wind direction) over a two-week period, prior to construction of the wind farm. A polynomial curve is then fitted to the data and this is defined as the ambient noise for compliance purposes. An alternative procedure [49] suggests dividing the wind speed range into segments, each covering a range of 1 m/s (for example, from 5.5 to 6.5 m/s), with all segments together covering the operating range of the turbine. Ambient noise levels within each segment are then averaged to provide an ambient noise level for each wind speed segment. Regardless of which of the two procedures is used, fitting a polynomial curve to the graph of noise level vs. wind speed at hub height and labelling the fitted curve as the ambient noise level suffers from two main problems:

(a) There are many data points below the fitted curve and many of these data are more than 10 dB below. As each data point represents a 10-min average, we may conclude that the ambient noise will be well below the declared value for a substantial length of time, which means that the wind farm noise will be much more noticeable than expected.

(b) The wind speed at the residence is often uncorrelated with the wind speed at hub height.

Perhaps the specification of ambient noise levels could be approached in a different way that accounts for the actual wind speed at a receiver as well as accounting for the amount of time that the ambient level is above specified levels. It would then be relevant to determine the relationship between ambient noise level, wind farm noise level and the expected percentage of the population that would be annoyed. This is a worthy topic of future research effort and results could feed in to better regulations and better guidance for testing compliance.

To determine the wind farm only level, some standards suggest logarithmically subtracting L_{A90} levels measured prior to the installation of the wind farm from L_{A90} levels measured after wind farm installation for a range of hub height wind speeds, and then plotting the result in the form of wind farm sound pressure level vs. wind speed at the receiver location. This approach has three problems:

(a) It is not scientifically valid to logarithmically subtract the average statistical (that is, L_{A90} or level exceeded 90% of the time) ambient noise level (for a particular wind speed segment) from the average statistical wind farm plus ambient noise level to obtain the noise level due to the wind farm only.

(b) L_{A90} levels measured before installation of the turbines are not necessarily representative of ambient levels after installation of the turbines, especially if measured at different times of the year.

(c) The L_{A90} level is the A-weighted sound level that is exceeded 90% of the time and is usually 2–3 dBA less than the average sound pressure level, L_{Aeq}, which is the quantity specified in most regulations [169,181], as L_{Aeq} is more closely related to human response to noise. Bowdler et al. [169] also showed that the difference between L_{A90} and L_{Aeq} increases as the amount of AM increases. Thus, an addition of at least 2 to 3 dBA to the measured L_{A90} level is necessary to properly characterise the true L_{Aeq} level of wind farm noise.

Different possible means to remove ambient noise from wind farm noise measurements are discussed in detail in Section 5.2 above. However, these methods either have significant problems in application or need more research to be properly validated.

To develop suitable regulations and compliance testing procedures that are suitable for wind farm noise and are scientifically justifiable, research work is needed to answer the following questions.

(a) What is the appropriate allowed maximum A-weighted noise level for wind farm noise in a rural environment and what noise measure (L_{Aeq}, L_{A10}, L_{A50} or L_{A90} or a combination) should be used?

(b) What is the difference in the acceptable overall dBA level for suburban and rural environments? Are the differences used in current regulations for road traffic noise appropriate for wind farm noise [151]?

(c) How can annoyance caused by wind farm noise be quantified and included in regulations [132].

(d) What is an acceptable and scientifically justified procedure for the establishment of ambient noise levels that would exist in the absence of the installed wind farm (see Section 5.2)? Can the specification of ambient noise levels be approached in a different way that accounts for the actual wind speed at a receiver as well as accounting for the amount of time that the ambient level is above specified levels?

(e) What is the relationship among ambient noise level, wind farm noise level and the expected percentage of the population that would be annoyed?

(f) What are suitable microphone locations for measuring compliance? Should they be on a ground-mounted board or at 1.5 m above the ground, given that even light wind blowing on a shielded microphone can affect the measured data at frequencies below 200 Hz? In addition to differences due to different wind strengths at the two locations, different results will be obtained due to different contributions at the two locations from the ground-reflected sound ray. These differences should be taken into account when specifying allowed levels [67]. Minimum distances to any reflecting surfaces or vegetation should also be specified.

(g) What procedures should be used to assess the various annoying characteristics of wind farm noise and what penalties are appropriate?
(h) What is the acceptable percentage of residents, within 3 km of a wind farm, to be suffering adverse health or annoyance effects resulting from wind farm noise?
(i) What is adequate compensation for residents adversely affected by wind farm developments?
(j) What is the effect on people of AM of wind farm noise and can a metric be developed that has a low-level of uncertainty and is a measure of the degree of AM, a measure of the effect of the degree of AM on people and suitable for inclusion in wind farm noise regulations?

8. Community Engagement

One of the mistakes made by early wind farm developers was to ignore residents who were not hosting turbines and to insist that "turbines make no audible noise" when speaking at community forums. This approach contributed to communities at first accepting wind farms but after installation, wishing them gone. As word was spread (with the help of language used in social media, anti-wind farm web sites and newspapers, designed to frighten people [163]) that noise from wind farms could be a serious problem for some people, wind farm developers encountered more and more resistance. More recent developments have included financial compensation to local councils, enabling them to build infrastructure that is of benefit to the entire community. In addition, wind farm developers no longer tell communities that wind farms make no audible noise. There have been some attempts to explain why some people become very annoyed by wind farms, and there are also suggestions made as to how to ameliorate this problem (using therapy) without necessarily reducing turbine noise levels [128,130]. However, there is scope for research to determine the most effective fora for facilitating direct and empathetic community consultation with regulators and wind farm developers.

Some wind farm developers have improved their approach to community engagement in more recent times. However, more developers need to follow their lead. Although Simos et al. [182] made nine recommendations to increase community acceptance of wind farms, there still remains work to be done to determine the optimal approach that will maximise the likelihood of widespread community acceptance. Some of the issues that should be considered (and researched) include the following.

(a) Financial compensation for neighbours who remain in their residence. This could take the form of an upfront lump sum or an annual payment or both. Whatever the compensation, it should be adequate, fair and equitably implemented.
(b) Agreed minimum set-back distances of 3 km.
(c) Offers to purchase residences within 5 km of the nearest turbine in the wind farm for their value prior to submission of the wind farm development application.
(d) Involvement of residents living near existing wind farms in projects to measure the impact of existing wind farms, as outlined by Vågene [183].
(e) Investigation of the effect of negative language in newspaper reports on noise sensitivity experienced by residents.

9. Ground Vibration

It is generally accepted that seismic vibration generated by wind turbines is sufficiently small that it cannot be detected by residents living more than 2 km from the nearest turbine in a wind farm [184]. In fact, it is highly unlikely that vibrations would be detectable by residents living even closer than this. However, vibration levels generated by wind farms are sufficiently high that they can interfere with stations set up to monitor atomic bomb testing, earthquakes and volcanoes [185]. For this reason, wind farms are generally excluded within 30–50 km of military establishments or seismic monitoring stations.

Recently, questions have arisen concerning the ability of seismic waves generated by wind farms to generate significant levels of acoustic infrasound [186], but work by Nguyen et al. [184] would suggest that this is unlikely to be the case. Although they found that vibration levels on the floor in dwellings were unlikely to be due to infrasound, they did find that vibration levels on the windows were well correlated with the wind farm acoustic signature (not the ground vibration). However, more extensive studies of wind farm vibration levels in dwellings closer than 1 km to the nearest turbine in a wind farm are warranted.

Although it is generally accepted that ground vibrations due to turbines do not have a detectable effect on humans, more research effort is needed to quantify the effect of wind farms on ground vibration and the distance they should be from sensitive seismic measurement stations used for detection of volcanoes, earthquakes and atomic testing.

10. Local Native Wildlife and Agriculture

Quite a few studies have been undertaken to evaluate whether or not wind farms cause wildlife to leave their vicinity (see for example, [187]). In cases where this is true, it is difficult to determine whether the reason was turbine noise, construction activity, or the visual presence of a huge tower with rotating blades.

Studies have also been undertaken on the effect of wind turbines on livestock (see, for example, [188,189]) and on wildlife (see, for example, [190]). These studies have shown that wind turbine noise may affect communication between animals [189], which may affect breeding, and/or contribute to increased cortisol, indicating a stress response [188,190] that could make the animals more susceptible to infection and disease.

Although it is relatively easy to show that wildlife tend to leave wind farm areas, it is not clear whether this is due to the noise emission or other effects such as the turbine presence or shadow flicker. More work is needed to determine the reasons wildlife leave and if there is anything that can be done to ameliorate this issue.

11. Conclusions

Most of the current research effort on wind farm noise is focussed on turbine noise emission, propagation and its control; the effects of wind farm noise on people, birds and animals; and procedures for developing appropriate noise regulations, testing for compliance and maximising community acceptance. Future research effort is likely to continue to be concentrated in these areas.

In the area of turbine noise emission, propagation and control, future work is likely to concentrate on the development of more accurate computer noise emission models to provide input for use in more accurate propagation models. Uncertainty analyses can be further refined so that residents, developers and regulators have a clearer picture of the wind farm noise environment and its variability. Better means are needed for measuring turbine sound power levels in the presence of varying topography, varying meteorological conditions and wakes from upstream turbines as well as predicting the effects of these phenomena on emission levels. The development of a deeper understanding of the mechanisms responsible for producing wind turbine noise and its special characteristics will allow rank ordering of the relative importance of the various noise sources, which is important in terms of establishing optimal noise control strategies.

In the area of the effects of noise on people, birds and animals, most of the current research effort is directed towards the effects on people, including effects such as annoyance, sleep deprivation and physical health impacts. It is highly likely that future research efforts will continue along these lines, as currently there is no consensus in the scientific community on whether wind farm noise causes sleep deprivation or adverse health effects, although most researchers agree that noise generated by wind farms can be annoying to people who live in their near vicinity.

In the areas of noise regulation and community engagement, current research is directed at establishing appropriate, allowed maximum A-weighted noise levels. Noise levels at sensitive community locations are calculated prior to construction of a wind farm and compared to the maximum allowed levels to determine the likelihood of compliance following construction. Predicted noise levels are dependent on which noise model is used to obtain them and many jurisdictions do not specify which model is to be used. Future work is likely to involve better procedures for testing compliance with regulations, which includes isolating the wind farm noise contribution to the total noise level measured at a residence. Additional pertinent research includes establishing suitable penalties to the allowed A-weighted level to account for special wind farm noise characteristics such as amplitude modulation, tonality and low frequency bias in the spectrum. Research is also needed in establishing suitable set back distance algorithms that take into account the topography, turbine layout and total number of turbines in a wind farm. Finally, future research is needed on the optimal way for wind farm developers to engage with local communities prior to and after construction of a development to maximise community acceptance, and whether such engagement should be facilitated by regulatory bodies.

The various research topics discussed in this paper have by no means been studied exhaustively. As can be seen by the "Future Directions" subsection at the end of each section, there remains a considerable body of work to be done if we are to understand the mechanisms of wind farm noise generation and propagation, how wind farm noise may be minimised, how its character can be less annoying, how the effects of wind farm noise on people, birds and animals can be minimised and how wind farms can be made more acceptable to surrounding communities.

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Abbreviations

The following abbreviations are used in this manuscript:

AM	amplitude modulation
BPF	Blade pass frequency
dBA	A-weighted sound pressure level
EAM	Enhanced amplitude modulation
LA10	A-weighted sound pressure level exceeded 10% of the time
LA90	A-weighted sound pressure level exceeded 90% of the time
L10	Sound pressure level exceeded 10% of the time
L90	Sound pressure level exceeded 90% of the time
LFN	Low-frequency noise
TE	Trailing edge

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