THE NOISE EMISSIONS ASSOCIATED WITH WIND FARMING IN AUSTRALIA

This document has been prepared as a part of project made possible by a grant of monies from the Australian Greenhouse Office to the Australian Wind Energy Association under the Renewable Energy Industry Development Programme (Round 5).

Australian Government
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This document is a detailed briefing paper discussing the noise emissions associated with wind farming in Australia. This paper was prepared as background information for the preparation of a fact sheet for dissemination to the general public. As a result this document, any related documents (listed below) and the fact sheet itself attempts to be as non-technical as possible and sometimes goes to great pains to explain what may appear to be quite obvious to someone intimately involved in either wind energy or specific noise issues.

However, as is often the case, such attempts may unintentionally oversimplify the issue or present information in a distorted way. We may also have made errors or omissions in the preparation of this document. Please do not hesitate to forward any suggested changes or additions to this document to Grant Flynn at Sustainable Energy Australia (Grant@SustainableEnergyAustralia.com.au).

Where possible footnotes have been provided within the text to allow the reader to consult the source article directly.

This document should be read in conjunction with the following sub-documents;

- None

This document has also been distilled into a very brief fact sheet of just 2 pages which can also be downloaded from the AusWEA: Australian Wind Energy Association web site at www.auswea.com.au.

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SOURCES OF INFORMATION

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- Danish Wind Energy Association
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SUMMARY

WHAT IS SOUND?

Sound is a pressure disturbance caused by some mechanical means that propagates through an elastic material or medium (in our case air). The initiating mechanical disturbance may be produced in any number of ways but the result is a sudden increase in pressure (i.e. a compression). Since the material is elastic, the compression is not permanent, and once the disturbing influence is removed, the compressed region rebounds and will compress an adjacent region. The result is a repeating cycle of a compression zone, followed by a rarefaction zone.

A great many of the sounds encountered in daily life are periodic waveforms, characterized by a dominant frequency. The frequency of the sound wave determines the pitch and the amplitude determines the intensity of the sound. The intensity of sound can be described in terms of its sound power or sound pressure levels. Sound power level describes compressional power of the wave per unit area while sound pressure level describes the actual pressure change from equilibrium.

Sound waves propagate in spherical wavefronts, so as the wavefront spreads out from the source the power of the sound is spread across a larger area. This leads to a dissipation of the sound power level (called attenuation) according to the inverse square law. This is the main reason why sounds are quieter as the distance from the source increases. Sound wave energy is also absorbed as it propagates, as some of the energy is transferred into the medium itself. Sound waves also reflect off surfaces (allowing for whispering chambers), they can also be diffracted (allowing them to go around corners and through slots), refracted (allowing them to bend) and when different wavefronts meet they can interfere with each other (causing acoustic shadows).

The way sound propagates is relatively well understood and so the behaviour of sound can be well predicted. Complicating matters though is that not all sounds are equal to the human ear. The way we perceive different sounds is a psychophysical process. Human perception of any noise source is influenced by many factors, including the acoustic characteristics of the noise, (whether it has audible tones or other characteristics that may annoy the hearer) and how much louder the noise is than the existing noise environment.

The ear has an enormous range of response, both in frequency and in intensity. The frequency range of human hearing extends from about 20 Hz to about 20kHz and we can perceive a pressure range is from about 10^{-5} Pascal (threshold of hearing) to about 10 Pascals (threshold of pain). The human ear typically serves to distinguish between about 1,500 levels of pitch and 325 separately perceived levels of loudness just in the region of greatest auditory sensitivity (about 1,000 to 4,000 Hertz). The number of discernable tones is in the hundred thousands.

While related to sound intensity, loudness is a subjective phenomenon and can be measured only comparatively, by means of a standard reference sound under specified conditions. The intensity level at which a sound can be heard is also affected by the existence of other stimuli (called masking) which is important in the psychophysical response to sound.

Location of a sound source laterally in space is achieved in the brain which is sensitive to phase change in a sound that is independently detected by each of our ears. However even this ability depends upon the frequency of the sound itself.

Noise is simply any undesirable or unwanted sound. Importantly, the perception of a noise is also influenced by the attitude of the hearer towards the sound source. One person may find the morning chorus of birds delightful, and another may want to reach for a shotgun! It is certainly true that a hearer who for some reason has a negative attitude towards a noise source is much more likely to view the noise itself negatively, however low its level.

HOW DO WE MEASURE SOUND?

Unlike loudness, sound intensity is objective and can be measured by auditory equipment independent of an observer's hearing. This intensity is determined using a sound level meter which is an instrument designed to respond to sound in approximately the same way as the human ear and to give objective, reproducible measurements of sound pressure level.

The pitch of a sound, i.e. its frequency, is measured in Hertz and the intensity of sound is measured in decibel (i.e. tens of bels). The decibel (dB) range is a logarithmic scale based on a ratio of the sound pressure to a reference value (by default the threshold of hearing). This non linear scale helps take account of non-linear intensity response of the ear. However to take account of the frequency response of the ear we apply a weighting network to the intensity levels of different frequencies. By international standard, environmental noise is weighted according to the "A" network and this is denoted by the use of the dBA units.

Sound pressure levels of some typical sounds are shown in the table below.

Decibels	Type Of Sound
130	artillery fire at close proximity (threshold of pain)
120	amplified rock music; near jet engine
110	loud orchestral music, in audience
105	Jet aircraft at 250m
100	electric saw
95	Pneumatic drill at 7m
90	City traffic
85 - 90	bus or truck interior
80	automobile interior
70	average street noise; loud telephone bell
65	Truck at 50km/hr at 100m
60 - 65	normal conversation
60	busy general office
55	Car at 65 km/hr at 100m
50	Quiet restaurant; private office
40	quiet room in home
35 - 45[1]	Busy road 5km away Wind farm 350m away
30	quiet lecture hall; bedroom
20 - 40	Rural night-time background
20	radio, television, or recording studio
10	soundproof room
0	absolute silence (threshold of hearing)

An increase of 10 dBA roughly sounds like a doubling of loudness and an increase of about 3dBA is the smallest change we can detect. Importantly the logarithmic nature of the decibel scale means that we cannot simply add sound pressure levels (i.e. two people speaking at 60dBA are louder than one but do not cause a sound of 120 dBA – more likely 61 dBA).

Somewhat confusingly, sound power levels (i.e. the power of the initial disturbance causing the sound wave) are also measured in dB. However this is NOT a measure of the noise we hear but of the noise power emitted by the source. A Sound Power Level of 95 to 105 dBA will create a sound pressure level of about 50 dBA to 60 dBA at 40m away (i.e. the same level as conversational speech) and at 500 m away the Sound Pressure Level will have dropped to between 30 to 40 dBA.

The level of sound in the environment changes quite dramatically over even short periods of time. There are a variety of ways we can measure sound levels – we could measure the highest sound pressure level, the lowest level, the average level, etc. To describe how we are measuring sound levels, descriptors such as L_{50}, L_{95} and L_{eq} are used. They all relate to the measurement of sound over a discrete time period (typically over a period of 10 minutes).

An L_{50} refers to the level of sound that is exceeded 50% of the time within that sample time period, an L_{95} refers to the level that is exceeded 95% of the time and an L_{eq} refers to the equivalent constant level of sound within that time period. An L_{eq} is closer to an L_{50} than a L_{95}. Overseas studies[1] on wind farm sound have shown that L_{95} is typically 1.5 dB – 2.5 dB lower than L_{eq} measured over the same period.

SOURCES OF WIND FARM NOISE – OPERATION

Noise will be created by traffic on the wind farm's access tracks, from the viewing area, from the switchyard and powerlines and of course from the wind turbine generators themselves.

The noise from traffic on the wind farm access tracks depends upon the vehicle, road surface, the number of vehicle movements and speed of vehicles. Maintenance staff typically drive utes or vans, at speed limits of 40km/hr or less across access tracks formed from compacted dirt or limestone and, once the wind farm is bedded-in, there will be few vehicle movements. This means that access track noise is rarely a problem provided the route of access tracks and where they connect with the public road network are considered carefully so as to minimise the risk of annoyance to the wind farm's host and neighbours.

Viewing areas are constructed at most wind farms so as to provide a safe and controlled environment in which the public can view the wind farm. This too could be a cause of noise due to traffic noise, exuberant children, etc. Again this will rarely be a problem provided the viewing area site is located away from residential dwellings.

Switchyard and power lines can cause noise both through wind whistling through the equipment itself or through the hum of the air ionising around the insulators of high voltage conductors. The level of noise is very low and generally the separation provided by safety fencing or ground clearance to prevent inadvertent electrocution is sufficient to mean that such noise is not a problem.

Virtually everything with moving parts will make some sound, and wind generators are no exception. Wind turbines are not silent, they are audible, and create unwanted sound – i.e. noise – to some degree. The two main sources of wind turbine generator noise are mechanical noise from inside the nacelle and aerodynamic noise from the blades.

Mechanical noise may originate from the gearbox, the drive train and in the generator of a wind turbine and is prone to containing tonal components. The mechanical noise from wind turbine generators can be dramatically reduced (and tonal components eliminated) through specific design of the mechanical components and also by adding resilient couplings in the drive train to isolate vibrations. Dynamic analysis of the machines before they are constructed allows designers to ensure that vibrations are not transmitted to parts of the machine that would allow the radiation of sound to the environment.

The aerodynamic noise of a wind turbine is produced by the flow of the air over the blades. The rotor blades must act as a brake on the flow of wind to transfer its kinetic energy to the rotor. In the process the blades cause some emission of white noise. This is the swishing sound you might hear when standing next to an operating wind turbine.

In modern wind turbines the surfaces of the rotor blades are very smooth (which indeed they must be for aerodynamic reasons) and great care taken in the aerofoil shape, so only a minor part of the energy is lost to noise (less than one ten millionth). Furthermore the noise emitted is broadband in nature not tonal. Indeed, guarantees with severe financial penalties are provided by manufacturers of large wind turbine generators to provide comfort that such tonal noises will not be present in their machines.

[1] The assessment and Rating of Noise from Wind Farms. The Working Group on Noise from Wind Turbines, Final Report 1996, ETSU-R-97.

There are several areas of the blade that may emit noise but most of the noise will originate from the trailing (back) edge and the tips of the blades. Other things being equal, sound pressure will increase with the speed of the blade relative to the surrounding air (i.e. the blade speed ratio). In modern wind turbines with large rotor diameters, very low rotational speeds are used to help reduce the blade speed ratio, especially at the tip of the blades (i.e. to reduce the tip speed ratio).

A variety of specialist design and manufacturing techniques are used with wind turbine blades even down to the use of turbulator strips or vortices suppressors. Research on quieter rotor blades continues, but given that noise is now such a minor problem – especially given the generally large distances between turbines and neighbouring houses – most of the benefits of that research will be turned into increased rotational speed and increased energy output rather than reducing the sound power levels further.

SOURCES OF WIND FARM NOISE – CONSTRUCTION

During wind farm construction there will be some noise, primarily associated with the civil works (i.e. formation of roads and foundations). Other construction noise will be associated with the delivery of the wind turbine generator equipment and during the erection of the individual wind turbine generators. Just like any construction site, the noise will need to comply with the relevant guidelines for construction noise and addressed in the project's Environmental Management Plan.

Fortunately the construction phase of a wind farm is very short, typically 6 to 9 months. Wind farms are spread over large areas and construction is not continuous at any single part of the site so it tends to be a lesser problem compared to a normal industrial or residential construction site.

HOW NOISY IS A WIND FARM

Wind turbines are not silent, they are audible. Well designed, modern wind turbine generators are generally quiet in operation. It is quite possible to carry out a normal conversation at the base of a turbine running at maximum power, without raising one's voice. Members of the public invariably comment on the quietness of wind turbines when they visit a wind farm for the first time.

Indeed the noise from a wind farm 100 m away would be inaudible in most residential areas of Australia, drowned out by road noise and the other background noise of large numbers of people living in a relatively small space. These sounds are not un-healthful and do not interfere with normal activities such as talking quietly to ones neighbour any more than do the sounds common in any suburban setting.

However the sound wind turbine generators produce – the swish of the blades through the air – are typically foreign to the rural settings in which wind farms are most often built. A European study[2] in the mid-1990's found "... the number of people actually indicating annoyance by wind turbine noise was fairly small. It appeared that the degree of annoyance was not related to an objective level of sound."

The addition of new sound which most residents have had little or no part in creating and from which they receive no direct benefit can be disturbing for some people; no matter how insignificant the sound may be in a technical sense. Neighbours to a wind farm must learn to coexist peacefully with their new neighbours (the wind farm) just as wind farm operators must learn to minimise their intrusion onto their neighbours' peaceful rural setting. Of the 3,500 turbines in Denmark, less than 2% have caused noise complaints[3]. Nearly all of these are less than 225m from the complaining neighbour.

[2] Wolsink, M., Sprengers, M., Keuper, A., Pedersen, T. Holm, Westra, C. A.: *Annoyance from Wind Turbine Noise on Sixteen Sites in Three Countries,* 1994.
[3] "Development of Wind Energy in Denmark" Poul Nielsen. DEFU the Association of Danish Utilities, paper presented at the American Wind Energy Association Annual conference, Windpower '93, San Francisco July 19993.

Wind Farm Noise Assessment

Typically the noise from a factory near a residential area will be assessed with the noise source operating at its highest sound power level in conditions most suitable to the propagation of the sound to the potential receiver. The sound pressure level at the receiver is then tested to determine if it complies with the stipulated limit. Typically the "conditions most suitable to propagation" mean no wind and low background noise. For factory noise this is usually reasonable because the factory will be emitting the noise regardless of the wind speed and background noise.

In the case of wind turbine generators the situation is very different. If there is no wind, the wind turbine generator does not operate and makes no noise. As the wind speed increases the sound power level of an operating wind turbine generator increases. However, the background noise also increases with wind speed and at a rate faster than the noise of the wind turbine generator. Consequently there comes a wind speed when the background noise will completely mask the noise from the wind turbine generator. As a result special noise measurement techniques, unique to wind farms, are required since wind farm compliance measurements need to be taken in windy conditions rather than calm conditions.

In Australia we generally use the New Zealand Standard[4] (soon to be a joint Australian Standard) to assess noise. This standard proposes a noise sound pressure level limit of the greater of 40dBA or 5dBA above background at a residence. This limit will vary according to wind speed. This is comparable international guidelines, though is significantly quieter than limits used in many parts of the world.

The reason for having a variable noise compliance limit is that both the existing background noise level and the wind generator source noise level increase with increasing wind speed. Having a fixed noise limit may result in the wind farm complying with the prescribed limits at a certain wind speed but could mean non-compliance at some other wind speed where even the background noise level itself may not comply with the limit.

Designing Wind Farms to Eliminate Noise

Quiet operation has become an important design criterion for successful wind turbine manufacture. Noise is also an important design criteria used in the development of the wind turbine generator layout of a wind farm. Assessment of a wind farm's noise emissions prior to construction is therefore an important process. The advisable distance between a wind farm development and neighbouring residences to avoid disturbance of neighbours will depend upon a variety of factors including the local topography, the character and level of background noise, the size of development, etc and so needs to be determined on a case-by-case basis.

Wind farm layouts are assessed using complex computer models in which iso-noise contours are plotted and sound pressure levels are assessed at particular locations – generally at each of the nearby residences – to ensure the limits are not exceeded. Using this approach ensures that there is sufficient separation distance between the wind generators and the nearby residences such that noise levels will be attenuated to an acceptable level at the nearby residences.

Best practice for wind farm design means identifying neighbouring house locations at an early stage to ensure that all iterations of the wind farm layout consider the noise impact of all the generators within the development at all houses adjacent to the proposed wind farm project.

Many of the noise problems with early wind farms were as a result of tonal noise from the wind turbine generator's gearbox or generator. These problems have been designed out of modern machines which also use sound insulation and isolation techniques to reduce

[4] NZS6808:1988, Acoustics - The Assessment and Measurement of Sound from Wind Turbine Generators

the overall noise emission. Wind turbine noise warranties guarantee that the machines will be free of tonal noise.

In well designed modern wind farms the wind generator noise is at a similar level to that of the background and rarely gives rise to any noise problems. A well designed wind farm with measurable and appropriate limits will not result in noise disturbance to the community. This is generally borne out after a visit is made to an operational wind farm.

The way sound propagates through air is well understood and this allows us to predict the sound pressure levels that will be experienced around a source. Provided we know the sound power level of the source and the conditions in which it will be placed, we can ensure that noise will not be a cause of nuisance to neighbours (regardless of the source).

The sound power levels of wind turbines are determined using detailed computer modelling even before the first machine is built. Once the machine has been manufactured it is tested by independent verifications agencies according to rigorous standards and certificates of noise emission levels issued. The manufacturer is then in a position to provide the guarantees of noise levels that the wind farm developers demand of them. This means that we understand very well the source of the noise.

The environment in which the machine will be placed will generally be much less well understood. The topography, wind speed and wind direction can be determined relatively easily but the effects of vegetation, buildings, etc is exceedingly difficult to determine over such a large area. However we can make some conservative assumptions of how the sound will travel through the local environment of the proposed wind farm. For wind farm proposals these noise predictions are undertaken using a very conservative noise propagation model, i.e. one which is known to generally over-predict the noise levels.

The model that is generally used is that proposed by the International Energy Agency (IEA) and this forms the basis of the New Zealand Standard[5]. The IEA model is based on hemispherical noise propagation over a flat, reflective surface and includes sound attenuation by air. Less well understood effects such as topographical shielding and wind speed effects are not modelled and their exclusion generally makes the predictions more conservative. In effect the IEA model can be considered to represent the down wind noise level predictions for all wind directions. Therefore it produces the 'worst-case' predictions for all neighbouring locations, with the assumption that all wind generators are visible with no attenuation from obstacles or screening.

The IEA noise propagation model has a predictive accuracy of ± 2 dBA, however, given the conservative (high) nature of the predictions, an uncertainty of 0 to +2 dBA is more likely.

The results of the noise level predictions can then be represented as iso-noise contours around the wind farm. These may be completed for various wind speeds and indeed will be different for each wind speed because the noise increases with wind speed. However two important wind speeds that are often used are 5 m/s and 10 m/s. The 5 m/s case represents the wind generators in a continuously operational condition in low wind speeds where background noise levels will be low. The 10 m/s case represents the wind generator close to full power before the background level completely dominates over the wind turbine generator noise.

The plots of iso-noise contours produced by the modelling can then be used to determine if a dwelling is located in an area where sound pressure levels would be above the prescribed limit. If this is the case the wind farm layout can be altered so as to reduce the noise.

Sometimes the manufacturer or model of wind turbine generator is not yet known during the planning stage. In such cases sound power levels from a representative wind turbine generator are used for the purposes of undertaking the noise level predictions for the proposed wind farm. The sound power levels used in this way, although representative of

[5] NZS6808 Acoustics – The measurement and assessment of sound from wind turbine generators.

the wind generators proposed, are not guaranteed by the ultimate manufacturer. At the final specification and wind generator selection stage of the proposal, measured and warranted levels will be obtained and the noise propagation plots repeated to ensure compliance.

BACKGROUND NOISE MEASUREMENT

Noise compliance levels are generally set in relation to the existing background level, so it is necessary to undertake some noise measurements to characterise the existing background levels and how it varies with changes in wind speed. Measurement of the existing background noise levels prior to construction of a wind farm is undertaken on "noise sensitive" properties in the vicinity of the proposed wind farm.

The measurements are 10 minutes averages conducted over a 2 week period to give approximately 2,000 background noise level measurements at each location. They are then plotted against the wind speed measured on the site for the concurrent 10 minute period. The wind speed measurements are those recorded at the closest anemometry mast.

Noise loggers are placed in a location close to the residence but in a position such that it is clear of screening or noise sources that might inappropriately affect the noise level. For example the logger should not be placed close to dense hedges or fences or water pumps etc. Such things may inappropriately raise or lower the background noise level. These measurements are used to set the baseline background noise level prior to the construction of the project and can also be used to determine the noise level with which the wind farm shall comply once completed.

It should be noted that while measurements may only be taken at several residences adjacent to a proposed wind farm, the wind farm layout is designed such that it complies with the lowest of the background level measurements. Furthermore, if the project is approved, it may be necessary to undertake a few more background noise level surveys at noise sensitive locations.

WHO DETERMINES WHEN A SOUND IS NOISE?

A sound becomes noise when it is unwanted, undesirable or when it causes annoyance or nuisance. The noise emissions from any activity can cause nuisance to neighbours or the wider community. Wind farms are no different. In order to be economically viable, wind farms must be built in windy areas and in relatively close proximity to electrical infrastructure so that they can supply the electricity they produce to the end user. In practice this means that are usually built in areas where people live. The design of wind farm projects must take this into consideration so as to ensure that their noise emissions do not cause nuisance.

The level of noise emissions from any noise source - including wind turbines – permitted at neighbouring residences is very strictly regulated in most countries, including Australia. The actual level permitted usually depends on the existing noise environment before the noise source is created.

Noise limits are usually set by local government (i.e. the Shire or District Council) although in some cases the State (or even the Commonwealth) Government may impose a limit on noise for a particular place or activity. Generally the state's Environment Protection Authority (EPA) or its equivalent will issue guidelines for noise limits and recommend standard methods to use in predicting and measuring noise. Typically the local government will simply adopt some or all of the EPA guidelines as their limits; however this is not always the case.

The guidelines (if any) issued by the EPA or its equivalent will vary from state to state. The adoption (if any) either in full or in part of these guidelines may also vary from one local government district to another. Consequently it is not a simple task in a document like this one to stipulate noise limits across all of Australia.

MISCONCEPTIONS ABOUT WIND FARM NOISE

The introduction of any new development such as a wind farm which many residents have had little or no part in creating and from which they receive no direct benefit, can be disturbing for some people. No matter how insignificant the impact may seem in a technical sense, these new developments may signify an outsider's intrusion. An "intrusion" rather than a personal choice may produce a different opinion about any aspect of the proposed development including noise.

Quite reasonably, people near a proposed development will seek information about the development itself and others like it in other areas. It is possible that in the search for "independent" information that someone not familiar with the development or its technology will come across out-of-date, inappropriate or incorrect information. As a result misconceptions may arise which are not useful either for supporters or detractors of a proposal as it distracts one from the actual issues of concern and makes it increasingly difficult to work toward a consensus outcome, with the best overall outcome for the community.

Low frequency sound and vibrations will affect foundations. The only instance where low frequency sound (infrasound) has been known to be caused by a wind generator was more than 25 years ago with a prototype downwind wind turbine generator. Each time a blade passed the lee of the tower, the blade radiated an acoustic pulse. Since the wind generators being used in modern Australian wind farms are upwind in design there is no possibility that there will be any infrasound associated with the blade passing frequency, i.e. there will be no throbbing or vibration of nearby buildings.

Wind turbine generators sound like passing traffic. The loudness and character of road traffic noise is significantly different to wind turbine generator noise. Road traffic noise is significantly louder than the level audible from a wind generator. A truck doing 45 km/h, 100m away would generate 65 dBA while a wind turbine at the same distance would produce only 51 dBA. At larger separation distances the tonal nature of road traffic noise predominates and it is mainly the engine noise that is heard. Wind turbine generator noise has no tonal component and will not be heard.

A Wind Turbine Generator is like a tractor on a pole. This misconception usually arises when people confuse sound power level with sound pressure level – both measured in decibels. The sound *power* level of a wind generator will typically be in the order of 95 to 105 dBA (a measure of the noise power emitted by the machine NOT of the noise we hear). This will create a sound pressure level of about 50 to 60 dBA at 40m away from the base of the generator, i.e. the same level as conversational speech. At a house 500 m downwind of the turbine the sound *pressure* level would be 30 to 40 dBA.

Wind farms become noisier as they age. The noise limit that will apply to a wind farm will apply regardless of the age of the machines within the wind farm. The primary source of noise from a wind turbine generator is the aerodynamic noise created by the blades and there is no reason why this noise should change significantly with time. If there is a problem with a particular rotor blade which gives rise to a significant increase in noise, it is very likely to affect the performance of the machine too and will be quickly repaired.

MAIN DOCUMENT

Introduction

Wind turbines are rotating machinery, and thus necessarily make some noise. But is this noise a major annoyance factor? Steady design improvements since the 1980s mean that today's turbines elicit very few noise complaints. A modern turbine at 350 metres is about as audible as the background noise of a quiet bedroom.

"thanks to improvements in technology .... noise is no longer the issue it was."

- House of Lords Select Committee on the European Communities, 12th Report, Session 1998-99, Electricity from Renewables HL Paper 78

Are wind turbines noisy? Thanks to steady design improvements, a modern wind turbine just 350 metres away is less noisy than a quiet conversation[6] (about 35 dBA).

"Noisy" was an apt description of early wind turbines in the 1980s. At that time, they were designed for maximum generation and emission savings, rather than reduction of noise. By comparison, today's turbines make less noise for up to 50 times more electrical power.

As wind farms have become more plentiful they have attracted greater regulatory scrutiny, and quiet operation is now an important design criterion for success. It is quite possible to carry out a normal conversation at the base of a wind turbine generator running at maximum power, without raising one's voice.

For an "industrial" noise, wind also has some unique characteristics. The sound turbines produce is predominantly aerodynamic, and is generally perceived as more "natural" than most sources of industrial noise. In addition, the noise tends to be at a lower level when wind speed is low, and rises as the wind speed increases. As wind speed increases, so does wind-generated background noise from trees and bushes at neighbouring houses, which also masks the sound of the wind turbine generator.

Members of the public invariably comment on wind turbine generators' quietness when visiting a wind farm. More than 30,000 wind turbine generators have been installed around the world, often in close proximity to homes. Many countries have less rigorous noise regulation than Australia, yet there have been very few noise complaints.

This background paper endeavours to explain some of the basic technical issues associated with noise emissions from wind turbine generators so that you might be able to make an informed decision about the issue.

[6] http://www.greenhouse.gov.au/yourhome/technical/fs53.htm

What is Sound?

Sound is defined as a mechanical disturbance from a state of equilibrium that propagates through an elastic material medium. While we often think about sound travelling through the elastic medium of air, we need to remember that most solids, liquids, and gases of ordinary experience can serve as a media for sound.

A mechanical disturbance may be produced in any number of ways but will consist of a sudden increase in pressure at some point. Since the material is elastic, the compression is not permanent; once the disturbing influence is removed, the compressed region will rebound, but in doing so it will compress an adjacent region. The result of this cycle repeating itself is the generation of a compression wave, followed by a rarefaction wave as each region of elastic material rebounds.

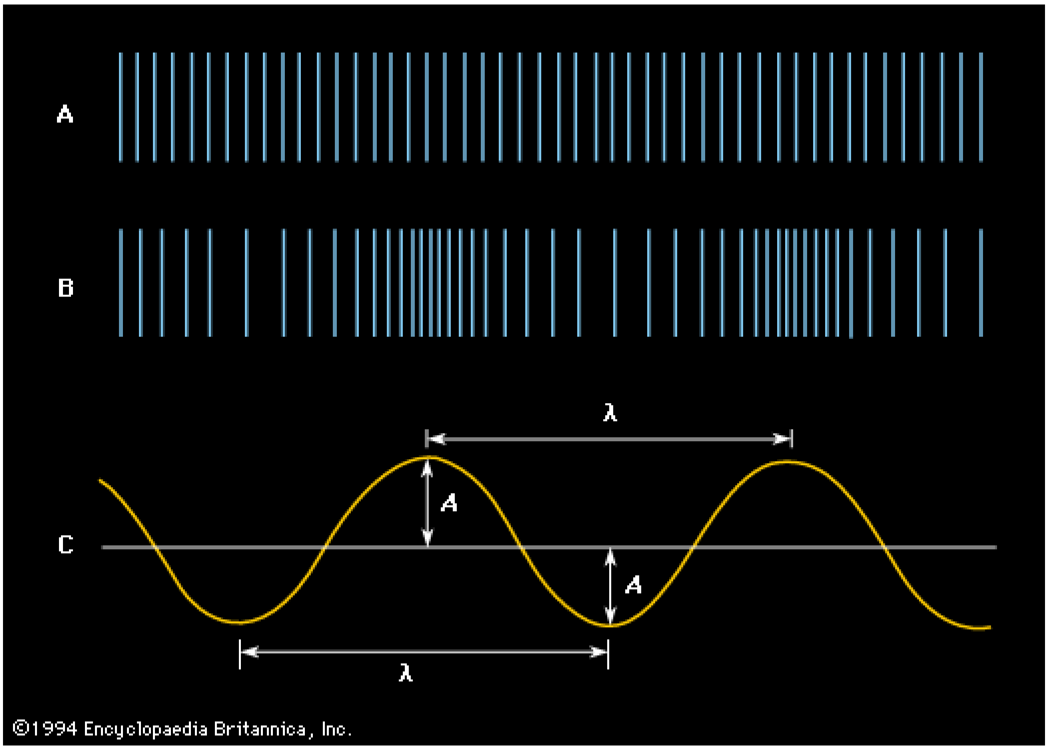


Figure 1 Graphic representations of a sound wave[7].
(A) Air at equilibrium, in the absence of a sound wave;
(B) compressions and rarefactions that constitute a sound wave;
(C) transverse representation of the wave, showing amplitude (A) and wavelength (λ).

These waves are longitudinal, i.e., the displacement of a particle of the medium is in the direction of wave motion. However, there is no net transport of material. The waves thus generated travel through the medium at a speed that is a function of the equilibrium pressure and density of the material and, to various extents, of the specific heat (for a gas), the elasticity (for liquids and solids), and the temperature of the medium and of the frequency of the wave.

In dry air at 0°C and a sea-level pressure of 1013.25 hecta-Pascals the speed of sound is 331.29 metres per second (1,192 km/hr). The speed of sound in seawater is 1,490 metres per second (5,364km/hr) and in steel 5,000 metres per second (18,000 km/hr).

[7] Encyclopaedia Britannica 2003

A great many of the sounds encountered in daily life are periodic, that is, the sound waves associated with them occur in patterns that repeat with regularity over time. Such sounds are characterized by a dominant frequency, or pitch, which may be defined as the number of waves that pass a fixed point per unit time.

Another parameter of sound, in addition to velocity and frequency, is intensity, which is defined as the average flow of energy per unit time through a unit area of the medium. Intensity is usually measured in watts per square centimetre. The standard usually used for the quietest sound audible to the human ear has an intensity of 10^{-16} watt per square centimetre.

Closely related to the intensity of a sound is the sound pressure or pressure excess over equilibrium caused by a sound wave. Sound pressure is measured in Pascals. The sound pressure of the human voice at ordinary conversational level, measured directly in front of the mouth, is about 0.1 Pascal, which may be compared with the standard pressure of the atmosphere of about 10^5 Pascals.

Also related to sound intensity, although not simply, is loudness. Loudness is a subjective phenomenon and can be measured only comparatively, by means of a standard reference sound under specified conditions.

Sound waves behave in many ways as light waves do, and optical analogies are frequently useful in describing acoustical phenomena. Thus, sound waves can be reflected, refracted, diffracted, and scattered, and many of the differences in behaviour between sound and light waves simply reflect the very great difference in wavelength of the two.

Sound Wave Propagation

The above discussion of the propagation of sound waves begins with a simplifying assumption that the wave exists as a plane wave. In most real cases, however, a wave originating at some source does not move in a straight line but expands in a series of spherical wavefronts. The fundamental mechanism for this propagation is known as Huygens' principle, according to which every point on a wave is a source of spherical waves in its own right.

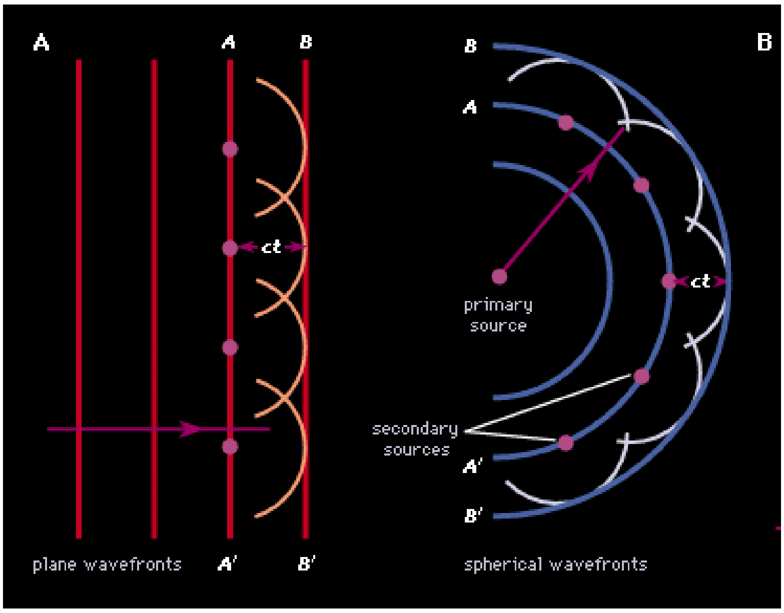


Figure 2 Sound Wave Viewed as a (A) Plane Wave and as a (B) Spherical Wave. Each point on the wave front AA´ can be thought of as a radiator of a spherical wave that expands out with velocity *c*, traveling a distance *ct* after time *t*. A secondary wave front BB´ is formed from the addition of all the wave amplitudes from the wave front AA´.

The result is a Huygens' wavelet construction for a two-dimensional plane wave and circular wave. The insightful point suggested by the Dutch physicist Christiaan Huygens is that all the wavelets form a new coherent wave that moves along at the speed of sound to form the next wave in the sequence. In addition, just as the wavelets add up in the forward direction to create a new wavefront, they also cancel one another, or interfere destructively, in the backward direction, so that the waves continue to propagate only in the forward direction.

The principle behind the adding up of Huygens' wavelets, involving a fundamental difference between matter and waves, is known as the principle of superposition. The old saying that no two things can occupy the same space at the same time is correct when applied to matter, but it does not apply to waves. Indeed, an infinite number of waves can occupy the same space at the same time; furthermore, they do this without affecting one another, so that each wave retains its own character independent of how many other waves are present at the same point and time.

A radio or television antenna can receive the signal of any single frequency to which it is tuned, unaffected by the existence of any others. Likewise, the sound waves of two people talking may cross each other, but the sound of each voice is unaffected by the waves' having been simultaneously at the same point.

Superposition plays a key role in many of the wave properties of sound discussed in this section. It is also fundamental to the addition of Fourier components of a wave in order to obtain a complex wave shape (see below Steady-state waves).

Attenuation of Sound

A plane wave of a single frequency in theory will propagate forever with no change or loss. This however, is not the case with a circular or spherical wave such as a sound wave. One of the most important properties of this type of wave is a decrease in intensity as the wave propagates out from its source. The mathematical explanation of this principle is known as ***the inverse square law***.

As a circular wave front (such as that created by dropping a stone onto a water surface) expands, its energy is distributed over an increasingly larger circumference. The intensity, or energy per unit of length along the circumference of the circle, will therefore decrease in an inverse relationship with the growing radius of the circle, or distance from the source of the wave.

In the same way, as a spherical wave front expands, its energy is distributed over a larger and larger surface area. Because the cross sectional surface area of a sphere is proportional to the square of its radius, the intensity of the wave is inversely proportional to the square of the radius. This geometric relation between the growing radius of a wave and its decreasing intensity gives rise to the inverse square law.

The decrease in intensity of a spherical wave as it propagates outward can also be expressed in decibels (described later). A spherical wave attenuates at a rate of six decibels for each factor of two increase in distance from the source. If a wave is propagating as a hemispherical wave above an absorbing surface, the intensity will be further reduced by a factor of two near the surface because of the lack of contributions of Huygens' wavelets from the missing hemisphere. Thus, the intensity of a wave propagating along a level, perfectly absorbent floor falls off at the rate of 12 decibels for each factor of two in distance from the source.

This additional attenuation leads to the necessity of the sloping seats of an auditorium in order to retain a good sound level in the rear of the auditorium.

Sound Absorption

In addition to the geometric decrease in intensity caused by the inverse square law, a small part of a sound wave is lost to the air or other medium through various physical processes. One important process is the direct conduction of the vibration into the medium as heat, caused by the conversion of the coherent molecular motion of the sound wave into incoherent molecular motion in the air or other absorptive material.

Another cause is the viscosity of a fluid medium (i.e., a gas or liquid). These two physical causes combine to produce the classical attenuation of a sound wave. This type of attenuation is proportional to the square of the sound wave's frequency, as expressed in the formula

$$\frac{\alpha}{f^2},$$

where;

α .... is the attenuation coefficient of the medium, and

f .... is the wave frequency.

So, sound absorption is the transfer of the energy of an acoustic wave to matter as the wave passes through it. The energy of an acoustic wave is proportional to the square of its amplitude - i.e. the maximum displacement, or movement of a point on the wave; and as the wave passes through a substance, its amplitude steadily decreases.

If there is only a small fractional absorption of energy, the medium is said to be transparent to that particular radiation, but if all the energy is lost then the medium is said to be opaque. All known transparent substances show absorption to some extent, even if it is only to a very small extent.

Substances are selectively absorbing - that is, they absorb radiation of specific wavelengths. Thus, radiation of an unwanted wavelength may be removed from a mixture of waves by letting them pass through an appropriate medium. Those substances that are designed to absorb a particular wavelength or band of wavelengths are called filters (see below).

As radiation passes through matter, it is absorbed to an extent depending on the nature of the substance and its thickness. A homogeneous substance of a given thickness may be thought of as consisting of a number of equally thin layers. Each layer will absorb the same fraction of the energy that reaches it. The change in energy as the wave passes through a layer is a constant of the material for a given wavelength and is called its absorption coefficient.

The table below gives sound-absorption coefficients for several gases. The magnitudes of the coefficients indicate that, although attenuation is rather small for audible frequencies, it can become extremely large for high-frequency ultrasonic waves. Attenuation of sound in air also varies with temperature and humidity.

Fluid	attenuation coefficient
Helium	52.5
Hydrogen	16.9
Nitrogen	133.0
Oxygen	165.0
Air	137.0
Carbon dioxide	140.0
Water at 0 ^oC	0.569
Water at 20 ^oC	0.253
Water 80 ^oC	0.079
Mercury 25 ^oC	0.057
Methyl alcohol at 30 ^oC	0.302

Because less sound is absorbed in solids and liquids than in gases, sounds can propagate over much greater distances in these mediums. For instance, the great range over which certain sea mammals (e.g. humpback whales) can communicate is made possible partially by the low attenuation of sound in water. In addition, because absorption increases with frequency, it becomes very difficult for ultrasonic waves to penetrate a dense medium. This is a persistent limitation on the development of high-frequency ultrasonic applications.

ACOUSTIC FILTRATION

Filtration of sound plays an important part in the design of air-handling systems. In order to attenuate the level of sound from blower motors and other sources of vibration, regions of larger or smaller cross-sectional area are inserted into air ducts. The impedance mismatch introduced into a duct by a change in the area of the duct or by the addition of a side branch reflects undesirable frequencies, as determined by the size and shape of the variation. A region of either larger or smaller area will function as a low-pass filter, reflecting high frequencies; an opening or series of openings will function as a high-pass filter, removing low frequencies. Some automobile mufflers make use of this type of filter.

A connected spherical cavity, forming what is called a band-pass filter, actually functions as a type of band absorber or notch filter, removing a band of frequencies around the resonant frequency of the cavity.

Diffraction

Diffraction is the capacity of sound waves to bend around corners and to spread out after passing through a small hole or slit. If a barrier is placed in the path of a wave, the part of the wave passing just by the barrier will propagate in a series of Huygens' wavelets, causing the wave to spread into the shadow region behind the barrier.

This diffraction also occurs in light waves but the wavelengths are very small compared with the size of everyday objects so very little diffraction occurs and a relatively clear shadow can be formed. The wavelengths of sound waves, on the other hand, are more nearly equal to the size of everyday objects, so that they readily diffract.

Diffraction of sound is helpful in the case of audio systems, in which sound emanating from loudspeakers spreads out and reflects off of walls to fill a room. It is also the reason why “sound beams” cannot generally be produced like light beams.

On the other hand, the ability of a sound wave to diffract decreases as frequency rises (or wavelength shrinks). This means that the lower frequencies of a voice bend around a corner more readily than the higher frequencies. This means that a diffracted voice has a “muffled” sound because of the differing effect of diffraction on its component sound frequencies. Also, because the wavelengths of ultrasonic waves become extremely small at high frequencies, it is possible to create a relatively narrow beam of ultrasound which has become very useful in modern medicine.

Scattering

The scattering of a sound wave is a reflection of some part of the wave off an obstacle around which the rest of the wave propagates and diffracts. The way in which the scattering occurs depends upon the relative size of the obstacle and the wavelength of the scattering wave.

If the wavelength is large in relation to the obstacle, then the wave will pass by the obstacle virtually unaffected. In this case, the only part of the wave to be scattered will be the tiny part that strikes the obstacle; the rest of the wave, owing to its large wavelength, will diffract around the obstacle in a series of Huygens' wavelets and remain unaffected.

If the wavelength is small in relation to the obstacle, the wave will not diffract strongly, and a shadow will be formed similar to the optical shadow produced by a small light source.

If the size of the obstacle is the same order of magnitude as the wavelength, diffraction may occur, and this may result in interference among the diffracted waves. This would create regions of greater and lesser sound intensity, called acoustic shadows, after the wave has propagated past the obstacle. Control of such acoustic shadows becomes important in the acoustics of auditoriums.

Refraction

Diffraction involves the bending or spreading out of a sound wave in a single medium, in which the speed of sound is constant. Another important case in which sound waves bend or spread out is called refraction. This phenomenon involves the bending of a sound wave owing to changes in the wave's speed. Refraction is the reason why ocean waves approach a shore parallel to the beach and why glass lenses can be used to focus light waves.

An important refraction of sound is caused by the natural temperature gradient of the atmosphere. Under normal conditions the Sun heats the Earth and the Earth heats the adjacent air. The heated air then cools as it rises, creating a gradient in which atmospheric temperature decreases with elevation by an amount known as the adiabatic lapse rate. Because sound waves propagate faster in warm air, they travel faster closer to the Earth. This greater speed of sound in warmed air near the ground creates Huygens' wavelets that also spread faster near the ground.

Because a sound wave propagates in a direction perpendicular to the wave front formed by all the Huygens' wavelets, sound under these conditions tends to refract upward and become “lost.” The sound of thunder created by lightning may be refracted upward so strongly that a shadow region is created in which the lightning can be seen but the thunder cannot be heard. This typically occurs at a horizontal distance of about 22.5 kilometres from a lightning bolt about 4 kilometres high.

At night or during periods of dense cloud cover, a temperature inversion may occur; the temperature of the air increases with elevation (i.e. cold air pools near the surface). In these circumstances sound waves are refracted back down to the ground. Temperature inversion is the reason why sounds can be heard much more clearly over longer distances at night than during the day - an effect often incorrectly attributed to the psychological result of night time quiet. The effect is enhanced if the sound is propagated over water, allowing sound to be heard remarkably clearly over great distances.

Refraction is also observable on windy days. Wind, moving faster at greater heights, causes a change in the effective speed of sound with distance above ground. When one speaks with the wind, the sound wave is refracted back down to the ground, and one's voice is able to “carry” farther than on a still day. When one speaks into the wind, however, the sound wave is refracted upward, away from the ground, and the voice is “lost.”

Another example of sound refraction occurs in the ocean. Under normal circumstances the temperature of the ocean decreases with depth, resulting in the downward refraction of a sound wave originating under water - just the opposite of the effect in air described above. However there is a layer of water that has a different temperature and salinity that acts as a conduit for sound propagation. Many marine biologists believe that this refraction enhances the propagation of the sounds of marine mammals such as dolphins and whales, allowing them to communicate with one another over enormous distances. For ships such as submarines located near the surface of the water, this refraction creates shadow regions, limiting their ability to locate distant vessels.

Reflection

A property of waves and sound, quite familiar in the phenomenon of echoes, is reflection. This plays a critical role in room and auditorium acoustics, in large part determining the adequacy of a concert hall for musical performance or other functions. In the case of light waves passing from air through a glass plate, close inspection shows that some of the light is reflected at each of the air-glass interfaces while the rest passes through the glass (this allows for the “nigh” setting of rear-view mirrors). This same phenomenon occurs whenever a sound wave passes from one medium into another – i.e. whenever the speed of sound changes or the way in which the sound propagates is substantially modified.

The direction of propagation of a wave is perpendicular to the front formed by all the Huygens' wavelets. As a plane wave reflects off some reflector, the reflector directs the wave fronts formed by the Huygens' wavelets just as a light reflector directs light “rays.” The same law of reflection is followed for both sound and light, so that focusing a sound wave is equivalent to focusing a light ray.

Reflectors of appropriate shape are used for a variety of purposes or effects. For example, a parabolic reflector will focus a parallel wave of sound onto a specific point, allowing a very weak sound to be more easily heard. Such reflectors are used in parabolic microphones to collect sound from a distant source or to choose a location from which sound is to be observed and then focus it onto a microphone. An elliptical shape, on the other hand, can be used to focus sound from one point onto another – an arrangement called a whispering chamber. Domes in cathedrals and capitols closely approximate the shape of an ellipse, so that such buildings often possess focal points and function as a type of whispering chamber. Concert halls on the other hand must avoid the smooth, curved shape of ellipses and parabolas, because strong echoes or focusing of sound from one point to another are undesirable in an auditorium.

Acoustic Impedance

One of the important physical characteristics relating to the propagation of sound is the acoustic impedance of the medium in which the sound wave travels. Acoustic impedance is given by the ratio:

$$Z = \frac{p}{U}$$

where;

Z .... is acoustic impedance

P .... is acoustic pressure of the wave

U .... is the volume velocity of the wave

Like its analogue, electrical impedance (or electrical resistance), acoustic impedance is a measure of the ease with which a sound wave propagates through a particular medium. Also like electrical impedance, acoustic impedance involves several different effects applying to different situations.

For example, specific acoustic impedance (z), the ratio of acoustic pressure to particle speed, is an inherent property of the medium and of the nature of the wave. Acoustic impedance, the ratio of pressure to volume velocity, is equal to the specific acoustic impedance per unit area.

Specific acoustic impedance is useful in discussing waves in confined mediums, such as tubes and horns. For the simplest case of a plane wave, specific acoustic impedance is given by:

$$Z=\rho S$$

Where;

ρ .... is the density of the medium at equilibrium

S .... is the wave speed

The unit of specific acoustic impedance is the Pascal second per metre ($Pasm^{-1}$), often called the rayl, after Lord Rayleigh.

The unit of acoustic impedance is the Pascal second per cubic metre ($Pasm^{-3}$), called an acoustic ohm, by analogy to electrical impedance.

IMPEDANCE MISMATCH

Media, in which the speed of sound is different, generally have differing acoustic impedances. So when a sound wave strikes an interface between the two, it encounters an impedance mismatch. As a result, some of the wave reflects while some is transmitted into the second medium. This situation is similar to that of a light wave entering glass, where a close inspection will show that in general some light is reflected while most of the light is transmitted into the glass.

The efficiency with which a sound source radiates sound is enhanced by reducing the impedance mismatch between the source and the outside air. For example, if a tuning fork is struck and held in the air, it will be nearly inaudible because of the inability of the vibrations of the tuning fork to radiate efficiently to the air. Touching the tuning fork to a wooden plate such as a tabletop will enhance the sound by providing better coupling between the vibrating tuning fork and the air. This principle is used in the violin and the piano, in which the vibrations of the strings are transferred first to the back and belly of the violin or to the piano's sounding board, and then to the air.

Interference

Interference occurs when two waves are combined and the disturbances overlap. If the waves arrive at a point in step, enhancement occurs and the disturbance is large. Where the waves are out of step, their opposing motions cancel and the disturbance is small or nonexistent. The net effect is therefore a distinctive interference pattern of large and small disturbances.

The particular manner in which sound waves can combine is known as interference. Two identical waves in the same place at the same time can interfere constructively if they are in phase, or destructively if they are out of phase. “Phase” is a term that refers to the time relationship between two periodic signals. “In phase” means that they are vibrating together, while “out of phase” means that their vibrations are opposite. Opposite vibrations added together cancel each other.

Constructive interference leads to an increase in the amplitude of the sum wave, while destructive interference can lead to the total cancellation of the contributing waves. An interesting example of both interference and diffraction of sound, called the “speaker and baffle” experiment, involves a small loudspeaker and a large, square wooden sheet with a circular hole in it the size of the speaker. When music is played on the loudspeaker, sound waves from the front and back of the speaker, which are out of phase, diffract into the entire region around the speaker. The two waves interfere destructively and cancel each other, particularly at very low frequencies, where the wavelength is longest and the diffraction is thus greatest.

When the speaker is held up behind the baffle though, the sounds can no longer diffract and mix while they are out of phase, and as a consequence the intensity increases enormously. This experiment illustrates why loudspeakers are often mounted in boxes, so that the sound from the back cannot interfere with the sound from the front. In a home stereo system, when two speakers are wired properly, their sound waves are in phase along an anti-nodal line between the two speakers and in the area of best listening. If the two speakers are wired incorrectly - the wires being reversed on one of the speakers - their waves will be out of phase in the area of best listening and will interfere destructively - especially at low frequencies, so that the bass frequencies will be strongly attenuated.

One possible application of destructive interference is in industrial noise control. This would involve sensing the ambient sound in a workplace, electronically reproducing a sound with the opposite phase, and then introducing that sound into the environment so that it would interfere destructively with the ambient sound and reduce the overall sound level.

BEATS

An important occurrence of the interference of waves is in the phenomenon of beats. In the simplest case, beats result when two sinusoidal sound waves of equal amplitude and very nearly equal frequencies mix. The frequency of the resulting sound (F) would be the average of the two original frequencies (f_1 and f_2):

$$F = \frac{(f_1 + f_2)}{2}$$

The amplitude or intensity of the combined signal would rise and fall at a rate (f_b) equal to the difference between the two original frequencies,

$$F_b = f_1 - f_2$$

where..............f_1 is greater than f_2.

Beats are useful in tuning musical instruments to each other: the farther the instruments are out of tune, the faster the beats. Other types of beats are also of interest. Second-order beats occur between the two notes of a mistuned octave, and binaural beats involve beating between tones presented separately to the two ears, so that they do not mix physically.

Moving sources and observers

THE DOPPLER EFFECT

The Doppler Effect is a change in the frequency of a tone that occurs by virtue of relative motion between the source of the sound and the observer of the sound.

When the source and the observer are moving toward each other, the perceived frequency is higher than the normal frequency, or the frequency heard when the observer is at rest with respect to the source.

When the source and the observer are moving away from each other, the perceived frequency is lower than the normal frequency.

For the case of a moving source, one example is the falling frequency of a train whistle as the train passes a crossing. In the case of a moving observer, a passenger on the train would hear the warning bells at the crossing drop in frequency as the train sped by.

For the case of motion along a line, where the source moves with speed v_s and the observer moves with speed v_o through still air in which the speed of sound is S, the general equation describing the change in frequency heard by the observer (F_o) is;

$$F_0 = f_s \left(\frac{S + v_0}{S - v_s} \right)$$

In this equation the speeds of the source and the observer will be negative if the relative motion between the source and observer is moving them apart, and they will be positive if the source and observer are moving together.

From this equation, it can be deduced that a Doppler Effect will always be heard as long as the relative speed between the source and observer is less than the speed of sound. The speed of sound is constant with respect to the air in which it is propagating, so that, if the observer moves away from the source at a speed greater than the speed of sound, nothing will be heard. If the source and the observer are moving with the same speed in the same direction, v_o and v_s will be equal in magnitude but with the opposite sign; the frequency of the sound will therefore remain unchanged, like the sound of a train whistle as heard by a passenger on the moving train.

SHOCK WAVES

If the speed of the source is greater than the speed of sound, another type of wave phenomenon will occur: the sonic boom. A sonic boom is a type of shock wave that occurs when waves generated by a source over a period of time add together coherently, creating an unusually strong sum wave.

An analogue to a sonic boom is the V-shaped bow wave created in water by a motorboat when its speed is greater than the speed of the waves. In the case of an aircraft flying faster than the speed of sound (about 1,230 kilometres per hour, or 342 ms^{-1}), the shock wave takes the form of a cone in three-dimensional space called the Mach cone. The Mach number is defined as the ratio of the speed of the aircraft to the speed of sound. The higher the Mach number - that is, the faster the aircraft - the smaller the angle of the Mach cone.

Fundamental Frequencies and Harmonics

When two identical waves move in opposite directions along a line, they form a standing wave - that is, a wave form that does not travel through space or along a string even though (or because) it is made up of two oppositely travelling waves.

The resulting standing wave is sinusoidal, like its two component waves, and it oscillates at the same frequency. An easily visualized standing wave can be created by stretching a rubber band between two fixed points, displacing its centre slightly, and releasing it so that it vibrates back and forth between two extremes. In musical instruments, a standing wave can be generated by driving the oscillating medium (such as the reeds of a woodwind instrument) at one end; the standing waves are then created not by two separate component waves but by the original wave and its reflections off the ends of the vibrating system.

When a string of a given length is plucked gently in the middle, a vibration is produced with a wavelength that is twice the length of the string. As the vibration that has the lowest frequency for that particular type and length of string under a specific tension, this frequency is known as the fundamental or first harmonic.

Additional standing waves can be created in a stretched string; the three simplest are represented graphically in the figure below. At the top is a representation of the fundamental, which is labelled n = 1.

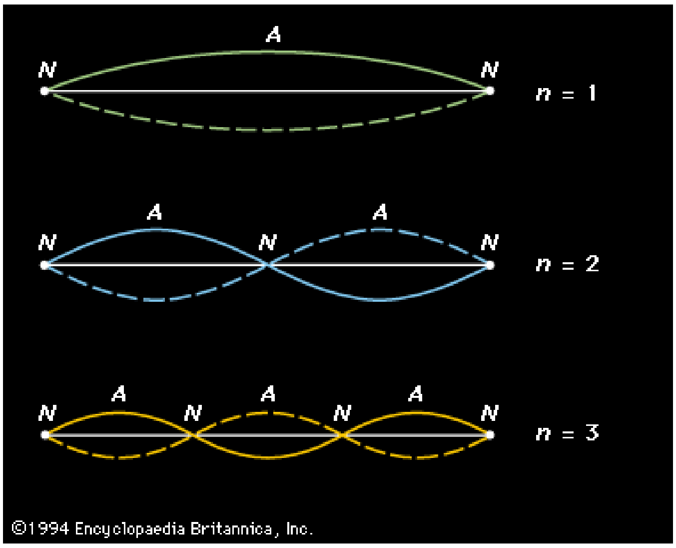


Figure 3 Fundamental Frequency and harmonics in a taut string

Each end is fixed so there can be no motion of the string at these points. The ends are called nodal points, or nodes, and labelled N. In the centre of the string is the point at which the string vibrates with its greatest amplitude; this is called an anti-nodal point, or anti-node, and labelled A.

In the next two vibrational modes of the string the string is divided into equal segments called loops. Each loop is one-half wavelength long, and the wavelength is related to the length of the string. Here n is called the harmonic number, because the sequence of frequencies existing as standing waves in the string are integral multiples, or harmonics, of the fundamental frequency.

In the second harmonic, the string vibrates in two sections, so that the string is one full wavelength long. Because the wavelength of the second harmonic is one-half that of the fundamental, its frequency is twice that of the fundamental. Similarly, the frequency of the third harmonic (labelled n = 3) is three times that of the fundamental.

Acoustic Design Problems

Certain acoustic problems often result from improper design or from construction limitations. If large echoes are to be avoided, focusing of the sound wave must be avoided. Smooth, curved reflecting surfaces such as domes and curved walls act as focusing elements, creating large echoes and leading to bad texture. Improper blend results if sound from one part of the musical ensemble is focused to one section of the audience. In addition, parallel walls in an auditorium reflect sound back and forth, creating a rapid, repetitive pulsing of sound known as flutter echo and even leading to destructive interference of the sound wave. Resonances at certain frequencies should also be avoided by use of oblique walls.

Acoustic shadows, regions in which some frequency regions of sound are attenuated, can be caused by diffraction effects as the sound wave passes around large pillars and corners or underneath a low balcony. Large reflectors called clouds, suspended over the performers, can be of such a size as to reflect certain frequency regions while allowing others to pass, thus affecting the mixture of the sound.

External noise can be a serious problem for halls in urban areas or near airports or highways. One technique often used for avoiding external noise is to construct the auditorium as a smaller room within a larger room. Noise from air blowers or other mechanical vibrations can be reduced using techniques involving impedance and by isolating air handlers.

Good acoustic design must take account of all these possible problems while emphasizing the desired acoustic features. One of the problems in a large auditorium involves simply delivering an adequate amount of sound to the rear of the hall. The intensity of a spherical sound wave decreases in intensity at a rate of six decibels for each doubling in distance from the source. If the auditorium is flat, a hemispherical wave will result. Absorption of the diffracted wave by the floor or audience near the bottom of the hemisphere will result in even greater absorption, so that the resulting intensity level will fall off at twice the theoretical rate, at about 12 decibels for each factor of two in distance. Because of this absorption, the floors of an auditorium are generally sloped upward toward the rear.

Types of Sound and Noise

In acoustics, any undesired sound, either one that is intrinsically objectionable or one that interferes with other sounds that are being listened to is called noise.

There are two main types of noise – tonal noise and broad band noise.

Tonal Noise

The simplest form of sound wave, called a pure tone, can be represented by a sine wave of a given frequency. More complex, but still relatively simple forms of sound - such as notes played on various musical instruments - can be represented by more complex harmonic curves. In this case a number of harmonic tones or overtones are superimposed on the fundamental tone.

Tones posses controlled pitch, loudness, timbre, and duration. Each of these attributes is revealed in the wave form of the tone. Most tones consist of more than a single wave form. Any material undergoing vibratory motion imposes its own characteristic oscillations on the fundamental vibration, thus creating partial wave forms in addition to the fundamental wave form. These partials are not fortuitous. They bear harmonic relationships to the fundamental motion that are expressible as frequency ratios of 1:2, 3:4, etc.

Listen to 30 seconds of Tonal Noise
by double clicking on this icon

Wave Sound

Broad Band Noise

Just as white light is the combination of all the colours of the rainbow, so white noise can be defined as a combination of equally intense sound waves at all frequencies of the audio spectrum. A characteristic of noise is that it has no periodicity, and so it creates no recognizable musical pitch or tone quality, sounding rather like the static that is heard between stations of an FM radio.

Another type of noise, called pink noise, is a spectrum of frequencies that decrease in intensity at a rate of three decibels per octave. Pink noise is useful for applications of sound and audio systems because many musical and natural sounds have spectra that decrease in intensity at high frequencies by about three decibels per octave.

Other forms of coloured noise occur when there is a wide noise spectrum but with an emphasis on some narrow band of frequencies - as in the case of wind whistling through trees or over wires. This broad band noise is the type of noise which is made by wind turbine generators.

Listen to 30 seconds of Broad Band Noise
by double clicking on this icon

Wave Sound

How Do We Perceive Noise

Not all sounds are equal to the human ear. The way we perceive different sounds is a psychophysical process. Human perception of any noise source is influenced by many factors, including the acoustic characteristics of the noise, (whether it has audible tones or other characteristics that may annoy the hearer) and how much louder the noise is than the existing noise environment.

Importantly, the perception of a noise is also often influenced by the hearer's attitude towards the noise source. One person may find the morning chorus delightful, and another may want to reach for a shotgun! It is certainly true that a hearer who, for whatever reason has a negative attitude towards a noise source, is much more likely to view the noise itself negatively, however low its level.

Dynamic Range of the Human Ear

The ear has an enormous range of response, both in frequency and in intensity. The frequency range of human hearing extends over three orders of magnitude, from about 20 Hertz to about 20,000 Hertz. The minimum audible pressure amplitude, at the threshold of hearing, is about 10^{-5} Pascal, or about 10^{-10} standard atmosphere, corresponding to a minimum intensity of about 10^{-12} Watts per square metre. The pressure fluctuation associated with the threshold of pain, meanwhile, is over 10 Pascals - one million times the pressure or one trillion times the intensity of the threshold of hearing. In both cases, the enormous dynamic range of the ear dictates that its response to changes in frequency and intensity must be nonlinear.

The human ear typically serves to distinguish between about 1,500 levels of pitch. For loudness, differential-threshold studies reveal about 325 separately perceived levels in the region of greatest auditory sensitivity (about 1,000 to 4,000 Hertz). The number of discernable tones is in the hundred thousands.

When two sounds are heard in close succession the intensity or loudness of the second is judged by comparing it with the first. Thus, a murmur may sound loud when compared to a whisper, or a "deafening" noise may make all other sounds inaudible. The hum of an electric fan may help to diffuse the street noises of traffic and thus improve the discrimination of sounds in the room.

Shown in the figure below is a set of equal-loudness curves (or Fletcher-Munson curves).

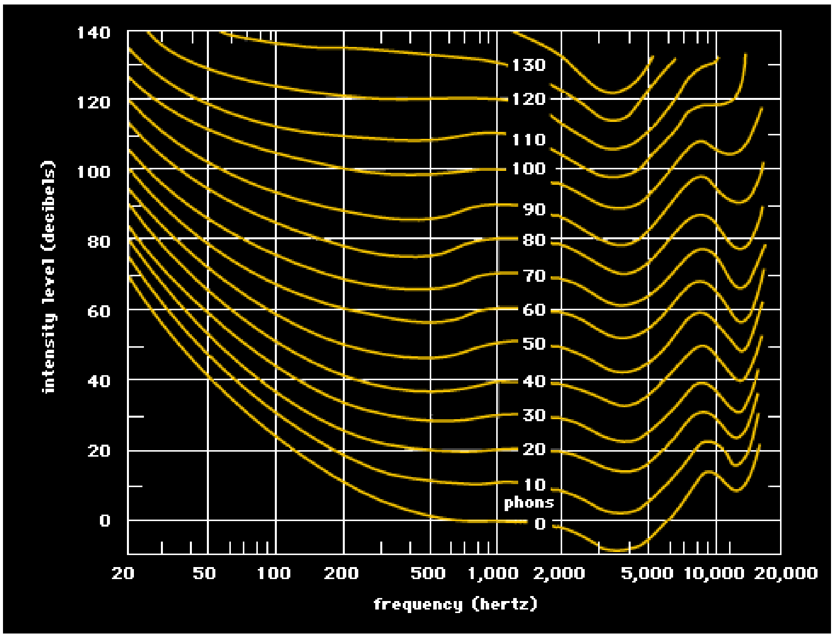


Figure 4 Equal-loudness, or Fletcher-Munson, curves.

The curves show the varying absolute intensities of a pure tone that has the same loudness to the ear at various frequencies.

The determination of each curve, labelled by its loudness level in phons, involves the subjective judgment of a large number of people and is therefore an average statistical result.

Several interesting observations can be made regarding Figure 4. The minimum intensity in the threshold of hearing occurs at about 4,000 hertz. This corresponds to the fundamental frequency at which the ear canal, acting as a closed tube about two centimetres long, has a specific resonance. The pressure variation corresponding to the threshold of hearing, roughly equivalent to placing the wing of a fly on the eardrum, causes a vibration of the eardrum of less than the radius of an atom. If the threshold of hearing did not rise for low frequencies, body sounds, such as heartbeat and blood pulsing, would be continually audible.

Music is normally played at intensity levels between about 30 and 100 decibels. When it is played more softly, decreasing the sound level of all frequencies by the same amount, bass frequencies fall below the threshold of hearing. This is why the loudness control on an audio system raises the intensity of low frequencies - so that the music will have the same proportion of treble and bass to the ear as when it is played at a higher level.

The ear is responsive to the periodicity of a wave, so that it will hear the frequency of a complex wave as that of the fundamental - whether or not the fundamental is actually present as a component in the wave - although the wave will have a different timbre than it would were the fundamental actually present. This effect, known as the missing fundamental, subjective fundamental, or periodicity pitch, is used by the ear to create the fundamental in sound radiating from a small loudspeaker that is not capable of providing low frequencies.

INTENSITY RESPONSE

As stated above, the ear has an enormous dynamic range, the threshold of pain corresponding to an intensity 12 orders of magnitude (10^{12} times) greater than the threshold of hearing. This leads to the necessity of a nonlinear intensity response. In order to be sensitive to intense waves and yet remain sensitive to very low intensities, the ear must respond proportionally less to higher intensity than to lower intensity. This response is logarithmic, because the ear responds to ratios rather than absolute pressure or intensity changes.

At almost any region of the Fletcher-Munson diagram, the smallest change in intensity of a sinusoidal sound wave that can be observed, called the intensity just noticeable difference, is about one decibel (further reinforcing the value of the decibel intensity scale). One decibel corresponds to an absolute energy variation of a factor of about 1.25. Thus, the minimum observable change in the intensity of a sound wave is greater by a factor of nearly 10^{12} at high intensities than it is at low intensities.

FREQUENCY RESPONSE

The frequency response of the ear is likewise nonlinear. Relating frequency to pitch as perceived by the musician, two notes will “sound” similar if they are spaced apart in frequency by a factor of two, or octave. This means that the frequency interval between 100 and 200 hertz sounds the same as that between 1,000 and 2,000 hertz or between 5,000 and 10,000 hertz. In other words, the tuning of musical scales and musical intervals is associated with frequency ratios rather than absolute frequency differences in Hertz. As a result of this empirical observation that all octaves sound the same to the ear, each frequency interval equivalent to an octave on the horizontal axis of the Fletcher-Munson scale is equal in length.

The audio frequency range encompasses nearly nine octaves. Over most of this range, the minimum change in the frequency of a sinusoidal tone that can be detected by the ear, called the frequency just noticeable difference, is about 0.5 percent of the frequency of the tone, or about one-tenth of a musical half-step. The ear is less sensitive near the upper and lower ends of the audible spectrum, so that the just noticeable difference becomes somewhat larger.

Masking

The intensity level at which a sound can be heard is affected by the existence of other stimuli. This effect, called masking, plays an important role in the psychophysical response to sound. Low frequencies mask higher frequencies much more strongly than high frequencies mask lower ones; this is one reason why a complex wave is perceived as having a different tone quality or timbre from a pure wave of the same frequency, even though they have the same pitch. Noise of low frequencies can be used to mask unwanted distracting sounds, such as nearby conversation in an office, and to create greater privacy.

Binaural perception

The paths from the ears to the brain are separate; that is, each ear converts the sound reaching it into electrical impulses, so that sounds from the two ears mix in the brain not as physical vibrations but as electrical signals. This separation of pathways has the direct result that, if two pure tones are presented to each ear separately (i.e., binaurally) at low levels, it will be very difficult for the ears to compare the frequencies because with no direct mixing of the mechanical waves there will be no regular beats. This difference in pitch perception between the two ears, called diplacusis, is generally not a problem. A type of beating known as binaural beats can sometimes be observed when the two tones are presented binaurally.

Also, two tones very close to an octave apart produce another type of monaural beating as they change in phase. This effect, known as second-order beats or quality beats, is observed as a slight periodic change in the quality of the combined tone. It serves as a counterexample to Ohm's law of hearing, which suggests that the quality of a sound depends only on the amplitudes of the harmonics and not on their phases.

Although the two ears are not connected by mechanical means, the brain is sensitive to phase and is able to determine the phase relationship between stimuli presented to the two ears. Locating a sound source laterally in space makes use of fundamental properties of sound waves as well as the ability of the brain to identify the phase difference between signals from the two ears.

At low frequencies, where the wavelength is large and the waves diffract strongly, the brain is able to perceive the phase difference between the same sound reaching both ears, and it can thus locate the direction from which the sound is coming. On the other hand, at high frequencies the wavelength may be so short that there may be more than one period of time delay between the signals arriving at the two ears, creating an ambiguity in the phase difference. Fortunately, at these high frequencies there is so much less diffraction of sound waves that the head actually shields one ear more than the other. In such cases the difference in intensity of the sound waves reaching the two ears, rather than their phase difference, is used by the ears in spatial localization.

Spatial localization in the vertical direction is poor for most people.

Measuring Sound

Sound Intensity and Pressure

The amplitude of a sound wave determines its intensity, which in turn is perceived by the ear as loudness. Loudness is a subjective phenomenon and can be measured only comparatively, by means of a standard reference sound under specified conditions. Unlike loudness, sound intensity is objective and can be measured by auditory equipment independent of an observer's hearing. Acoustic intensity is the amount of energy flowing per unit time through a unit area that is perpendicular to the direction in which the sound waves are travelling. Sound intensity may be measured in units of energy or work - e.g., micro-Joules (10^{-6} Joule) per second per square centimetre - or in units of power, as micro-Watts (10^{-6} Watt) per square centimetre.

Intensity is usually measured in Watts per square centimetre or Watts per square metre. The standard usually used for the quietest sound audible to the human ear has an intensity of 10^{-12} watt per square metre (or 10^{-16} watt per square centimetre).

Closely related to the power intensity of a sound is the sound pressure, or pressure excess over equilibrium, caused by a sound wave. Sound pressure is measured in Pascals. The sound pressure of the human voice at ordinary conversational level, measured directly in front of the mouth, is about 0.1 Pascal, which may be compared with a standard pressure. The value of atmospheric pressure under "standard atmospheric conditions" is generally given as about 10^5 Pascals, or 10^5 Newtons per square metre. This pressure can be used as a reference pressure.

The minimum amplitude of pressure variation that can be sensed by the human ear is about 10^{-5} Pascal, and the pressure amplitude at the threshold of pain is about 10 Pascals, so the pressure variation in sound waves is very small compared with the pressure of the atmosphere.

Consequently it is possible to measure both the ratio of sound pressure levels against a reference or alternatively a sound power level against a reference. However it needs to be kept in mind that the two are very different values.

THE DECIBEL SCALE

The ear mechanism is able to respond to both very small and very large pressure waves by virtue of being nonlinear; that is, it responds much more efficiently to sounds of very small amplitude than to sounds of very large amplitude. Because of the enormous nonlinearity of the ear in sensing pressure waves, a nonlinear scale is convenient in describing the intensity of sound waves.

Consequently the intensity of sound is measured in logarithmic units known as decibels. A change from a level of 10 decibels to one of 20 decibels actually represents a 100-fold increase in the sound level. Although the decibel scale is nonlinear, it is directly measurable, and sound-level meters are available for that purpose. Sound levels for audio systems, architectural acoustics, and other industrial applications are therefore most often quoted in decibels.

The intensity of one sound can be compared to that of another of the same frequency by taking the ratio of their powers or pressures. When this ratio is 10, the difference in intensity of the sounds is said to be one "Bel" (named in honour of Alexander Graham Bell). Accordingly, the relative intensities of two sounds in Bel are equal to the logarithm of the ratio of intensities;

$$B = \log_{10} (I/I_0).$$

Where

B .... is the intensity ratio in Bels,

I .... is the intensity of one sound, and

I_0 .... is the intensity of another sound.

The unit in general use is the decibel (abbreviated dB), equal to 0.1 Bel. Thus the equation for relative intensities may be written as

$$L_W = 10 \log_{10} (I/I_0)$$

Where

L_W .... is the sound power level in decibels

.... Note the use of "W" to indicate Watts or power

I .... is the intensity of one sound, and

I_0 .... is the intensity of another (reference) sound.

From this equation it can be shown by calculation that one decibel corresponds to a 26 percent change in intensity.

The value for L_W will obviously change according to the value used for I_o. To ensure that values for L_W can be readily compared, a standard reference is used. The standard reference power intensity used is that equal to the power intensity of the faintest sound that can be heard at 1 kHz – i.e. 1 x 10^{-12} watt per square metre or one pico-Watt per square metre (pWm^{-2}). Using this standard reference the power intensity, or sound power level, of any sound can be measured in decibels using the formula;

$$L_W = 10 \log_{10} (I)$$

Where[8]

L_W .... is the sound power level in decibels, and

I .... is the intensity of one sound in pWm^{-2}

Thus speech with a power intensity 10^{-8} watt per square metre has a sound power level of $L_W = 10 \log_{10} (10^{-8}/10^{-12}) = 10 \log_{10}(10,000) = 40$ decibels.

The threshold of hearing is about zero decibels (10^{-12} watt per square metre) for the average young listener for a sound wave with a frequency of 1,000 Hertz. The threshold of feeling - extremely loud sounds - is 130 decibels (10 watts per square metre). This represents a power 10,000,000,000,000 (or 10^{13}) times greater than zero decibels[9].

Because the decibel scale mirrors the function of the ear more accurately than a linear scale, it has several advantages in practical use. A fundamental feature of this type of logarithmic scale is that each unit of increase in the decibel scale corresponds to an increase in absolute intensity by a constant multiplicative factor. Thus, an increase in absolute intensity from 10^{-12} to 10^{-11} watt per square metre corresponds to an increase of 10 decibels, as does an increase from 10^{-1} to 1 watt per square metre.

Likewise sound pressure levels can be measured in the same way using a ratio of sound pressure levels. Sound pressure levels are what are the human ear responds to and so “sound level” is usually a sound pressure level. It is calculated as follows;

$$L_P = 10 \log_{10} (P/P_0)$$

Where

L_P .... is the sound pressure level in decibels

.... Note the use of “P” to indicate pressure

P .... is the pressure of one sound in, and

P_0 .... is the pressure of another (reference) sound.

In the same way as with sound power levels, the reference pressure used is that of the faintest sound that can be heard at 1 kHz – 2 x 10^{-5} Pascal. The fact that the reference pressure is actually 20 micro-Pascal means that the formula becomes;

$$L_P = 20 \log_{10} (P)$$

Where

L_P .... is the sound pressure level in decibels, and

P .... is the pressure of the sound in µPa (so P_0=1)

Thus a sound at about the threshold of pain which has an actual pressure of 10 Pascal will have a sound pressure level of $L_P = 20 \log_{10} (10/10^{-5}) = 20\mathrm{Log}_{10}(1,000,000) = 120$ dB.

[8] Note that the value of Io in pWm-2 is equal to one and so is not shown in the formula.

[9] Sometimes the threshold of pain is given as 120 decibels, or 1 watt per square metre rather than 130 dB. In both cases, pain will be experienced and irreparable damage done to the human ear so the difference is essentially semantic.

ADDITION AND SUBTRACTION OF SOUND PRESSURE LEVELS

From the discussion of sound propagation and interference it is clear that two equal sources of noise are likely to be louder to an observer than a single source of noise. If the sound levels from two or more machines have been measured separately and you want to know the total Sound Pressure Level made by the machines when operating together, the sound levels must be added.

However, because sound levels are measured using a logarithmic scale (i.e. the decibel) it is not possible to simply add two sound levels directly. So a sound with a sound pressure level of 50dBA cannot simply be added to one of 55 dBA to give a sound with a sound pressure level of 105 dBA!

The Sound Pressure Level of various sounds are added and subtracted according to a somewhat complex procedure. In brief it involves measuring the sound pressure levels of each source, calculating the mathematical difference in sound pressure levels in dBA and then looking up a nomograph that provides a relevant change in dBA to give the resultant combined sound pressure level.

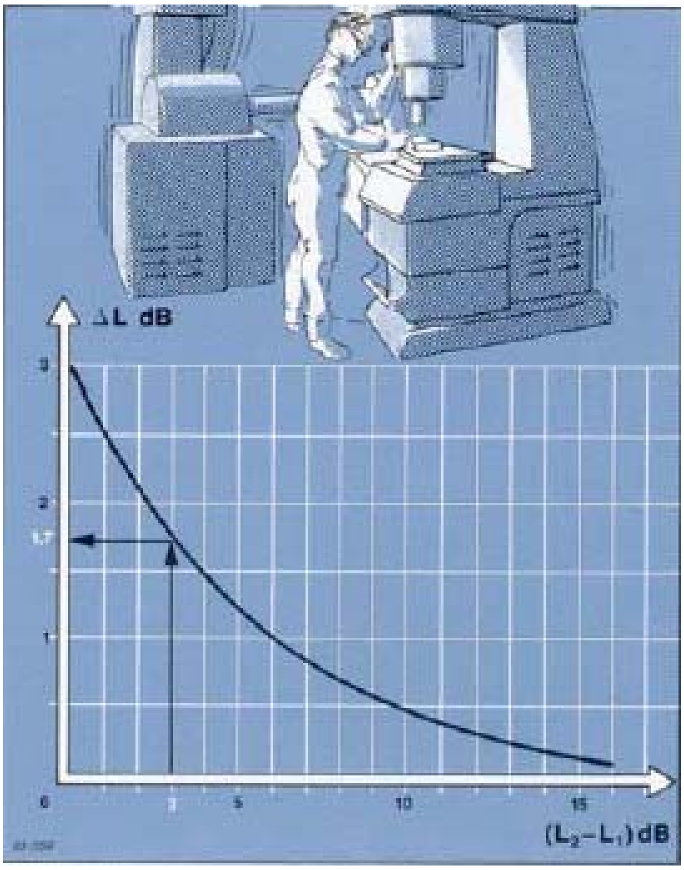


Figure 5 Nomograph for Adding Sound Pressure Levels

For example one sources of noise leads to a sound pressure level of 82 dBA and a second one leads to a sound pressure level of 85 dBA. The mathematical difference is 3 dBA but the nomograph indicates a change in level of 1.7 dBA so that if both operate at the same time the resulting sound pressure level will be 86.7dBA. For more than two machines the process is simply repeated as often as necessary until all the levels have been added.

What is clear from Figure 5 is that if the difference in sound pressure levels is large the effect of addition is quite small. This makes sense because the louder noise will simply mask the quieter sound. The classic example of this is a whispered comment that is inaudible in a noisy room full of conversation becomes quite noticeable if the conversation ceases abruptly – often to the whisperers embarrassment!

Distinguishing Sound Power Levels From Sound Pressure Levels

Any two parameters can be compared using this logarithmic scale and expressed in decibel. Clearly in acoustics there is the possibility for those of us that are unfamiliar with the terms being used to become confused between the decibel values of a Sound Power Level and the decibel value of a Sound Pressure Level.

For clarification, a sound source radiates power and this results in a sound pressure. Sound power is the cause. Sound pressure is the effect. Consider the following analogy. An electric heater radiates heat into a room and temperature is the effect. Temperature is also the physical quantity that makes us feel hot or cold. The temperature in the room is obviously dependent on the room itself, the insulation, and whether other sources of heat are present. But for the same electrical power input, the heater radiates the same power, practically independent of the environment. The relationship between sound power and sound pressure is similar. What we hear is sound pressure but it is caused by the sound power emitted from the source.

Too high a sound pressure may cause hearing damage. So when trying to quantify human response to sound, such as noise annoyance or the risk of hearing loss, pressure is the obvious quantity to measure. It is also relatively easy to measure: The pressure variations on the eardrum we perceive as sound are the same pressure variations which are detected on the diaphragm of a condenser microphone.

The sound pressure that we hear, or measure with a microphone, is dependent on the distance from the source and the acoustic environment (or sound field) in which sound waves are present. This in turn depends on the size of the room and the sound absorption of the surfaces. So by measuring sound pressure we cannot necessarily quantify how much noise a machine makes. We have to find the sound power because this quantity is more or less independent of the environment and is the unique descriptor of the noisiness of a sound source.

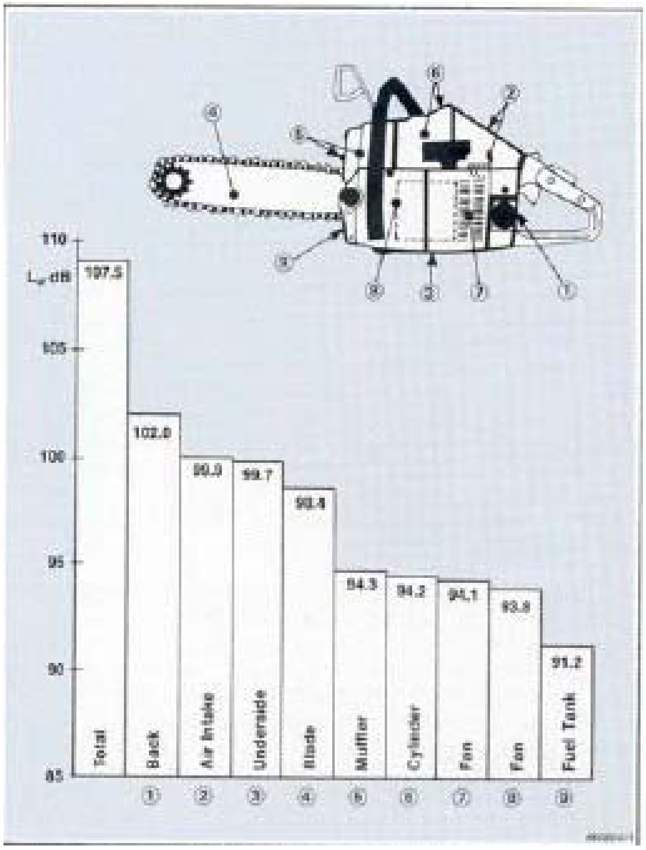
Environmental noise in decibels is a measure of the Sound *Pressure* Level, i.e. the magnitude of the pressure variations in the air. Although an increase of 6 dB represents a doubling of the sound pressure, an increase of about 10 dB is required before the sound subjectively appears to be twice as loud. The smallest change we can hear is about 3 dB. So an increase of 10 dB roughly sounds like a doubling of loudness.

The noise a wind generator makes at source is usually expressed in term of its Sound *Power* Level. Although this is also given in dB, it is NOT a measure of the noise we hear but of the noise power emitted by the machine. The Sound Power Level of a wind generator will typically be in the order of 95 to 105 dBA (see below for an explanation of the A weighting network and use of dBA rather than dB). This will create a sound pressure level of about 50 dBA to 60 dBA at 40m away from the base of the generator, i.e. the same level as conversational speech. At a house 500 m away, the equivalent Sound Pressure Level would be 30 to 40 dBA when the wind is blowing from the generator to the house.

Noise Source Ranking

A complicated structure may radiate sound from several sources and absorb sound in other places. To evaluate the effectiveness of noise reduction methods we need to know how much noise is being radiated by the individual components of machines. This means finding the sound power from the components of a machine.

This is simple with sound intensity measurements because we can define a measurement surface which can enclose single components. All the other noise radiating components can be treated as background noise - provided the noise is stationary. Furthermore the total sound power can be found simply by adding the partial sound powers from all the noise radiating components. In the chain saw study shown below it was not possible to enclose all the individual sources. But the study still revealed that several surfaces were responsible for the noise. In order for there to be a significant reduction in the overall level, several components would have to be treated.



The intensity technique is straightforward. An investigation can be performed in situ, which is a great improvement on existing techniques. Previously, individual parts of a complex structure, a diesel engine for example, had to be isolated with soundproof enclosures. The pressure level from this component could be measured only if the machine were placed in an anechoic or reverberant room. This procedure often took several weeks.

SOUND LEVEL METER

A sound level meter is an instrument designed to respond to sound in approximately the same way as the human ear and to give objective, reproducible measurements of sound pressure level. There are many different sound measuring systems available. Although different in detail, each system consists of a microphone, a processing section and a read-out unit.

The microphone converts the sound signal to an equivalent electrical signal. The most suitable type of microphone for sound level meters is the condenser microphone, which combines precision with stability and reliability. The electrical signal produced by the microphone is quite small and so it is amplified by a preamplifier before being processed.

Several different types of processing may be performed on the signal. The electronic circuitry can be adjusted, usually by an external switch, to register the integrated level of all frequencies in the sound being measured or the intensity of selected bands of frequencies. When the intensity of a selected band is desired the signal is passed through a weighting network. It is relatively simple to build an electronic circuit whose sensitivity varies with frequency in the same way as the human ear, thus simulating the equal loudness contours. This has resulted in three different internationally standardized characteristics termed the "A", "B","C" and “D” weightings (see below).

The indicating device is usually a meter calibrated to read the sound level in decibels (dB).

In the early 1970s, as concern about noise pollution increased, accurate, versatile, portable noise-measuring instruments were developed.

Sound level is a measure of loudness. However the actual loudness is a subjective factor and depends on the characteristics of the ear of the listener. In an attempt to overcome this problem, scales have been developed to correlate loudness with objective measurements of sound. The Fletcher–Munson curve in Figure 4 for example, shows the relationship between loudness in decibels and subjectively judged loudness measured in phon or sone (see below).

Sound Level Descriptors

The level of sound in the environment changes quite dramatically over even short periods of time. This is obvious even in conversational speech as the sound level varies dramatically as each syllable is enunciated and separated by brief periods of relative quiet. There are a variety of ways we can measure sound levels – even something as "simple" as conversational speech. We could measure the highest sound pressure level, the lowest level, the average level, etc.

To describe how we are measuring sound levels descriptors, such as L_{50}, L_{95} and L_{eq}, are often used when describing sound levels. They all relate to the measurement of sound over a discrete time period (typically over a period of 10 minutes).

An L_{50} refers to the level of sound that is exceeded 50% of the time within that sample time period, while an L_{95} refers to the level of sound that is exceeded 95% of the time within that time period, and so on. An L_{eq} refers to the constant level of sound that is equivalent to the fluctuating sound within the time period.

An L_{eq} is closer to an L_{50} than a L_{95}. Overseas studies[10] on wind farm sound have shown that L_{95} is typically 1.5 dB – 2.5 dB lower than L_{eq} measured over the same period.

If descriptors of sound level using different time periods are used together then the syntax used is

$$L_{xx,t}$$

Where
xx .... is the descriptor
t .... is the time period in minutes

Weighting

As previously discussed, the response of the human ear to sound pressure levels is non-linear and the logarithmic decibel scale can account for this response. However the response of the human ear over its frequency range is also non-linear. This creates a problem if sound level meters do not respond in a similar way to the human ear.

For example a sound level meter that is able to detect and respond to very high frequencies or very low frequencies that the human ear is unable to detect, will provide an integrated sound level higher than it should - if its measurement is to be used as an estimate of what the human ear will detect.

In effect a sound level meter is making a statistical measurement of a variety of frequencies at a variety of sound pressure levels. Without any adjustment it would be possible to detect a very large sound level of very high frequency sound even though a person exposed to this "sound" would not hear anything! Such an instrument is of very little use for assessing environment noise levels.

To avoid this problem a filtering circuit can be used to weight the measurements made by the sound level meter according to the frequency response of the healthy human ear. In this way frequencies outside of the human range of frequencies are discounted (or eliminated) while those within the human range are counted.

[10] The assessment and Rating of Noise from Wind Farms. The Working Group on Noise from Wind Turbines, Final Report 1996, ETSU-R-97.

This is called a weighting network. To make things even more complicated the frequency response of the human ear varies at different sound pressure levels. As a consequence there is not just one but four main weighting networks set out in international references – “A”, ”B”, ”C” and “D”. In addition to one or more of these weighting networks, sound level meters usually also have a Linear or "Lin." network. This does not weight the signal but enables the signal to pass through unmodified.

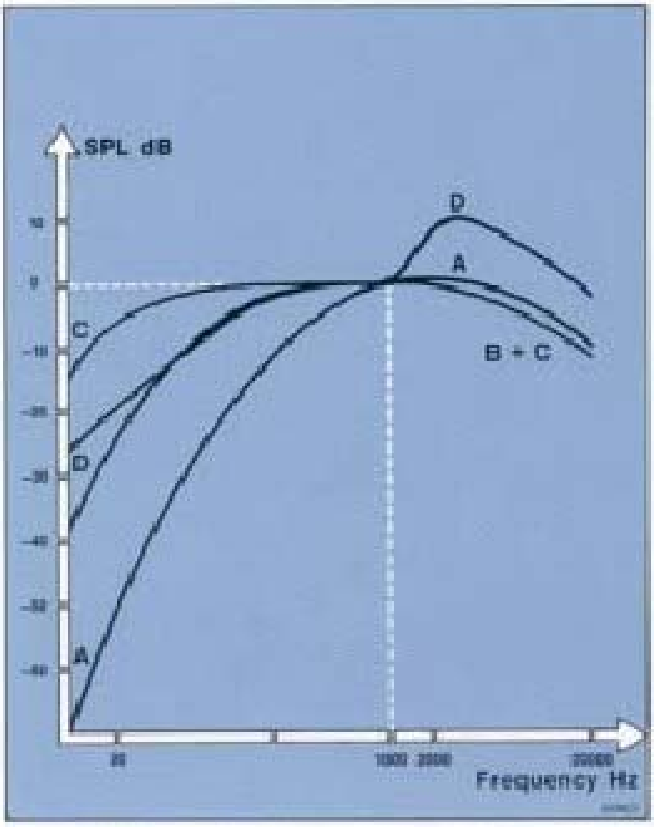


Figure 6 Standard Weighting Networks

The "A" weighting network weights a signal in a manner which approximates to an inverted equal loudness contour at low sound pressure levels, the "B" network corresponds to a contour at medium low sound pressure levels and the "C" network to an equal loudness contour at high low sound pressure levels. A specialized characteristic, the "D" weighting, has also been standardized for aircraft noise measurements at very high sound pressure levels.

Nowadays the "A" weighting network is the most widely used since the "B" and "C" weightings do not correlate well with subjective tests. One reason for this lack of correlation between subjective tests and "B" and "C" weighted measurements is because the equal loudness contours were based on experiments which used pure tones - and most common sounds are not pure tones, but very complex signals made up of many different tones.

As an example, a sound pressure level measured at 20 Hz will be discounted by 50 dB while one at 200 Hz will only be discounted by 10 dB and one at 1kHz will not be discounted at all. At higher frequencies the sound pressure level is also decreased and at frequencies above about 200 kHz – above the human frequency range - the values are again heavily discounted (by 50 dB or more).

Calibration of Sound Level Meters

Sound level meters should be calibrated in order to provide precise and accurate results. This is best done by placing a portable acoustic calibrator, such as a sound level calibrator or a piston-phone, directly over the microphone. These calibrators provide a precisely defined sound pressure level to which the sound level meter can be adjusted. It is good measurement practice to calibrate sound level meters immediately before and after each measurement session. If recordings are to be made of noise measurements, then the calibration signal should also be recorded to provide a reference level on playback.

Microphones and The Influence of the Environment

The type of microphone and its orientation in the sound field also influence the accuracy of measurements. A measurement microphone should have a uniform frequency response – i.e. the microphone must be equally sensitive throughout the frequency range.

A microphone is normally characterized by one of three types of frequency response characteristics - free-field (usually at 0° incidence), pressure, and random-incidence, and is named after the response that is the most linear.

It is important to note that any microphone will disturb a sound field, but the free-field microphone compensates for the disturbance it causes in the sound field. The pressure microphone however, responds uniformly to the actual sound pressure level, including the pressure disturbance caused by the microphone itself. The random incidence microphone is designed to respond uniformly to sounds arriving simultaneously from all angles, as is the case in highly reverberant or diffuse sound fields. (For most microphones the pressure and random incidence responses are very similar so a pressure microphone may also be used for random incidence measurements).

In general, when making free-field measurements (most outdoor measurements are essentially free-field), a free-field microphone is the most appropriate to use. In a diffuse-field, the microphone should be as omnidirectional as possible.

Wind

Wind blowing across the microphone produces a lot of extraneous noise, similar to the noise you can hear with the wind blowing in your ear. To reduce this noise, a special windscreen consisting of a ball of porous sponge should always be used over the microphone. It also shields the microphone from dust, dirt and precipitation, and helps to protect it from mechanical damage.

The condition and type of windscreen used can also affect measurements.

Humidity

In most cases relative humidity levels up to 90 % will have a negligible effect on the sound level meter and microphone. However, care should be taken to shield the instrument from rain, snow, etc. A windscreen should always be fitted over the microphone during precipitation. Even if the windscreen becomes very wet, measurements will still be accurate. However, for continuous use in extremely humid environments, special outdoor microphones, rain covers and dehumidifiers are recommended.

Temperature

All good sound level meters are designed to operate accurately over the -10 to +50 °C range. However, care should be taken to avoid sudden temperature changes which may lead to condensation in the microphone.

Ambient Pressure

Variations in atmospheric pressure of ±10% will have a negligible influence (less than ±0.2 dB) on microphone sensitivity. However, at high altitudes the sensitivity may be affected by more than this, especially at high frequencies. Also, when calibrating the instrument with a Pistonphone, a correction must be made for atmospheric pressure.

Vibration

Although the microphone and sound level meter are relatively insensitive to vibration, it is always a good practice to isolate them from strong vibrations and shock. Foam rubber pads or similar isolating material may be used if the sound level meter must be used in a high vibration environment.

Magnetic Fields

The influence of electrostatic and magnetic fields on sound level meters is negligible.

Sone

A sone is a unit of loudness. Loudness is a subjective characteristic of a sound (as opposed to the sound-pressure level in decibels, which is objective and directly measurable). Consequently, the sone scale of loudness is based on data obtained from subjects who were asked to judge the loudness of pure tones and noise. One sone is arbitrarily set equal to the loudness of a 1,000-hertz tone at a sound level of 40 decibels above the standard reference level (i.e., the minimum audible threshold). A sound with a loudness of four sones is one that listeners perceive to be four times as loud as the reference sound.

Phon

A phon is another unit of loudness level. The loudness level of a sound is a subjective, rather than an objective, measure. To measure loudness, the volume of a 1,000-hertz reference tone is adjusted until it is perceived by listeners to be equally as loud as the sound being measured. The loudness level, in phons, of the measured sound is then equal to the sound-pressure level, in decibels, of the adjusted reference sound above the standard reference level, which is the minimum audible threshold. A variation of one phon in the loudness level of a sound is approximately the smallest change in sound-pressure level detectable by the human ear under normal listening conditions.

How loud is that noise

For those of us who are not constantly involved in the acoustic industry it is often very difficult to relate and sound pressure level in decibels to common activities.

Firstly we need to understand how changes in sound pressure levels on the decibel scale relate to changes in perceived loudness. Although an increase of 6 dB represents a doubling of the sound pressure, an increase of about 10 dBA is required before the sound subjectively appears to be twice as loud. The smallest change in sound pressure level we can hear is about 3 dBA. So an increase of 10 dBA roughly sounds like a doubling of loudness.

Table 1[11] contains various noise sources with their typical sound pressure levels in dBA for comparison with wind turbines. Measurements of environmental noise are usually made in dBA, which includes a correction for the sensitivity of the human ear.

Decibels	Type Of Sound
130	artillery fire at close proximity (threshold of pain)
120	amplified rock music; near jet engine
110	loud orchestral music, in audience
105	Jet aircraft at 250m
100	electric saw
95	Pneumatic drill at 7m
90	City traffic
85 - 90	bus or truck interior
80	automobile interior
70	average street noise; loud telephone bell
65	Truck at 50km/hr at 100m
60 - 65	normal conversation
60	busy general office
55	Car at 65 km/hr at 100m
50	restaurant; private office
40	quiet room in home
35 - 45[1]	Busy road at 5km Wind farm at 350m
30	quiet lecture hall; bedroom
20 - 40	Rural night-time background
20	radio, television, or recording studio
10	soundproof room
0	absolute silence (threshold of hearing)

Table 1 Sound Levels for different types of sound

[11] Information other than road noise level taken from The Scottish Office, Environment Department, Planning Advice Note, PAN 45, Annes A:Wind Power, A.27. Renewable Energy Technologies, August 1994 and Victorian Environment Protection Authority.

Problems Caused By Exposure to Noise

At a level of 80 decibels, sound is annoying; but steady exposure to noise in excess of 90 decibels - a level that is frequently exceeded by many common urban sounds, such as jackhammers, jet planes, and excessively loud music - can cause permanent loss of hearing. In addition to causing loss of hearing, there is some evidence that noise can produce other deleterious effects on human health and on work performance.

The effects of noise exposure on hearing, depends on the intensity and duration of the noise. The effects may be temporary or permanent. A single exposure to an extremely intense sound, such as an explosion, may produce a severe and permanent loss of hearing. Repeated exposures to sounds in excess of 80 to 90 decibels may cause gradual deterioration of hearing by destroying the hair cells of the inner ear, with possible subsequent degeneration of nerve fibres.

The levels of noise produced by rock music bands frequently exceed 110 decibels. The noise generated by farm tractors, power mowers, and snowmobiles may reach 100 decibels.

Individuals differ in their susceptibility to hearing loss from noise exposure. Because hearing loss typically begins at the higher frequencies of 4,000 to 6,000 Hertz, the effects of noise exposure may go unnoticed until the hearing loss spreads to the lower frequencies of 1,000 to 2,000 Hertz.

Non-auditory effects of acoustic energy can also occur; most of these can be prevented by use of ear protection devices. The body's equilibrium is partially controlled by the vestibular system in the ears; high-level noise may cause disorientation, motion sickness, and dizziness.

Noise does not usually affect the speed at which work is performed; it may increase the number of errors, however. More constant noises of moderate to high levels cause stress, fatigue, and irritability.

Inhalation of carbogen, a mixture of 5 percent carbon dioxide and 95 percent oxygen, for 20 minutes will accelerate recovery of hearing if administered within a few hours after excessive noise exposure.

Where does noise come from in an operating wind farm

The most important source of noise in an operating wind farm is that of the wind turbine generators and this source of noise is discussed in detail below. However other parts of the wind farm may create noise. For example there will be noise from the traffic of maintenance vehicles along wind farm access tracks, from the viewing area and from the wind farm's switchyard and the power line connecting the wind farm to the existing grid.

Access Track Traffic Noise

The noise from traffic depends upon the vehicle, road surface, the number of vehicle movements and speed of vehicles.

Once a wind farm is operational the vehicles used by maintenance staff will typically be either a passenger car or commercial van so noise levels are relatively low. On the rare occasions when large vehicles (e.g. cranes) are used the vehicle movement will be during normal business hours. The surface of access tracks at most wind farms will be compacted dirt or limestone which is a relatively quiet compared with an all weather bitumen surface. Speed limits within the wind farm area are usually 40km/hr or less. This means that each vehicle movement is likely to be relatively quiet compared to typical rural road noise.

Generally there will be very few vehicle movements each day, especially once the wind farm is about 1 year old and fully "bedded in" (i.e. all the minor glitches requiring attendance of maintenance staff have been resolved).

However the route of access tracks and where they connect with the public road network needs to be considered carefully so as to minimise the risk of annoyance to the wind farm's host and neighbours. This usually can be achieved by ensuring access tracks are kept away from residences and where possible that the connection with the public road network is also located away from residences (road safety also needs to be considered).

Viewing Area Noise

Wind farms have proven to be a significant tourist attraction in Australia (e.g. Codrington has received over 50,000 visitors in its first 2 years). While viewing areas are often required by the Responsible Planning Authority so as to ensure that members of the public can learn about and understand the project, it is possible that they can create a noise problem.

Most visitors are considerate of others and will not purposely cause a nuisance. However the movement of vehicles (especially large touring coaches) in and out of the viewing area, opening and closing of car doors and the excited vocalisations of exuberant children, have the potential to cause a nuisance on the wind farm's host and neighbours.

Again the problem can be ameliorated or eliminated simply through sensitive siting of the viewing area so that it, and its road access, is away from residential dwellings.

Switchyard Noise

Like any switchyard, the switchyard of a wind farm has the potential to generate noise. This is generally in the form of a high frequency crackling or hum emanating from insulators. This hum comes from a partial ionisation of the air around insulators and more noticeable at higher voltages and at high relative humidity.

To prevent inadvertent electrocution, the public are protected from switchyards by surrounding fences. Typically the distance of the fence from electrical equipment will mean that it is often difficult to hear this noise at the fence let alone at nearby residences. Regardless of this, switchyards are typically sited away from residences.

Power Line Noise

Power lines also have the potential to create some noise, both around the insulators as described above but also from the wind vibrating the taut wire. Again, both sounds are relatively quiet. More often than not the interconnecting power line will be at normal distribution voltages and will follow an existing power line easement. Regardless of whether an existing power line easement is followed or a new one needs to be established, the level of noise from the power line is so low that the separation from residential dwellings will mean that it should not cause a nuisance.

Wind Turbine Noise

The two main sources of wind turbine generator noise are mechanical noise and aerodynamic noise from the blades. Standing next to the turbine, it is usually possible to hear a swishing sound as the blades rotate; the whirr of the gearbox and generator may also be audible. However, as distance from the turbine increases, these effects are reduced.

Quiet operation has become an important design criterion for successful wind turbine manufacture. Great attention is given to ensuring that both mechanical and aerodynamic noises are as low as possible. Noise from the blades is minimised by careful attention to their design and manufacture. Mechanical components such as the gearbox and generator are also carefully designed and acoustically isolated from the tower and blades using anti-vibration mounts, and the nacelle is insulated to minimise airborne noise radiation.

Compared to early wind turbines, a modern turbine makes less noise for up to 50 times more electrical power. Today only about one ten-millionth of the power of a wind turbine is lost to noise.

Mechanical Noise

Mechanical noise (i.e. metal components moving or knocking against each other) may originate in the gearbox, in the drive train (the shafts), and in the generator of a wind turbine. Mechanical noise is prone to containing tonal components, which add a severe penalty on the total noise emission level.

Machines from the early 1980's or before do emit some mechanical noise, which may be heard in the immediate surroundings of the turbine, in the worst cases even up to a distance of 200 m. This problem was identified and tackled by engineering research at the end of the 1980's and within three years noise emissions had dropped to half their previous level due to better engineering practices.

The mechanical noise from wind turbine generators can be dramatically reduced (and tonal components eliminated) by redesigning the drive-train and especially the gearbox, and also by adding resilient couplings in the drive train to isolate vibrations. The drive-train's high speed drive shaft is the most critical part of the drive-train in terms of noise emissions because of the high rate of rotation. The measures taken to reduce noise emission include specialised grinding and hardening of the gear teeth (to reduce meshing noise) and suspension of the gearbox and generator on rubber dampeners and the installation of noise insulation on the gearbox cover.

Gearboxes for modern wind turbine generators are no longer the standard industrial gearboxes that they once were. They have been adapted specifically for quiet operation of wind turbine generators. One way of doing this is to ensure that the steel wheels of the gearbox have a semi-soft, flexible core, but a hard surface to ensure strength and long time wear. The way this is done is basically to heat the gear wheels after their teeth have been ground, and then let them cool off slowly while they are packed in a special high carbon-content powder. The carbon will then migrate into the surface of the metal. This ensures a high carbon content and high durability in the surface of the metal, while the steel alloy in the interior remains softer and more flexible.

The nacelle is further insulated to reduce the radiation of the noise to the outside of the machine. Even cooling system and ventilation louvers need to be carefully designed so that they act as sound baffles. While sound insulation plays a minor role in most wind modern turbines on the market today, it can be useful to minimise some medium and high-frequency noise. In general, however, the approach adopted is to attack noise problems at the source, in the structure of the machine itself.

An important consideration in the turbine design process is the fact that the rotor blades may act as membranes that retransmit noise vibrations from the nacelle and tower. Turbine manufacturers make computer models and perform dynamic structural analyses of their machines before building them to ensure that the vibrations of different components do not interact to amplify noise.

The installation of dampeners at the top of the tower can help to reduce the transmission of any vibrations from the nacelle into the tower which may otherwise act to radiate the sound into the environment (e.g. NEG-Micon use large, partially filled, water containers with the appropriate anti-freeze additives at the top of the tower to dampen vibrations).

Furthermore the chassis frame of the nacelle on many of the large wind turbines on the market today have odd holes which were drilled into the chassis frame for no apparent reason. These holes are in fact precisely made to ensure that the frame will not vibrate in step with the other components in the turbine.

AERODYNAMIC NOISE

The aerodynamic noise of a wind turbine is produced by the flow of the air over the blades. When the wind hits different objects at a certain speed, it will generally start making a sound. If it hits the leaves of trees and bushes or a water surface, it will create a random mixture of high frequencies, often called "broad band" or "white noise".

The wind may also cause vibration in surfaces, as sometimes happens with parts of a building, a car, a glider, etc. These surfaces in turn emit their own sound. If the wind hits a sharp edge, it may produce a pure tone, as is the case with musical wind instruments.

If you are close to a wind turbine generator at relatively low wind speeds you may hear a slight swishing sound which is made by the rotor blades. The rotor blades must act as a brake on the flow of the wind to transfer the kinetic energy of the wind to the rotor. In the process they cause some emission of white noise. This is the swishing sound you might hear.

Slots or holes in the blades will produce a whistling noise (i.e. tonal sound). However slots and holes in blades are not a desirable feature, in fact the surfaces of the rotor blades are very smooth (which indeed they must be for aerodynamic reasons) and so the surfaces will emit a minor part of the noise and this noise is broadband in nature not tonal. Indeed, guarantees with severe financial penalties are provided by manufacturers of large wind turbine generators to provide comfort that such tonal noises will not be present in their machines.

There are several areas of the blade that may emit noise, as described below, but most of the noise will originate from the trailing (back) edge and the tips of the blades. Careful design of trailing edges and very careful handling of rotor blades to protect them from even seemingly very minor damage while they are mounted, have become routine practice in the industry.

Other things being equal, sound pressure will increase with the fifth power of the speed of the blade relative to the surrounding air (i.e. the blade speed ratio). In modern wind turbines with large rotor diameters, very low rotational speeds are used to help reduce the blade speed ratio, especially at the tip of the blades (i.e. to reduce the tip speed ratio).

Since the tip of the blade moves substantially faster than the root of the blade, great care needs to be taken in the design of the rotor blade tips. Research in this area is also done for performance reasons, since most of the torque (rotational moment) of the rotor comes from the outer part of the blades. In addition, the airflows around the tip of rotor blades are extremely complex, compared to the airflow over the rest of the rotor blade.

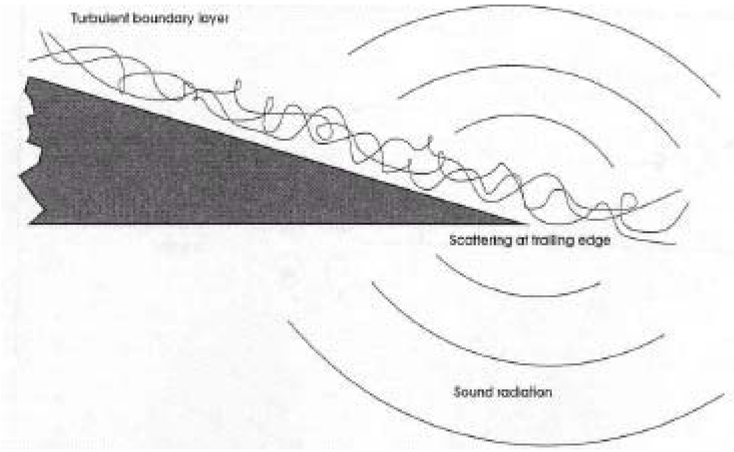
Aerodynamic noise is principally a function of the tip speed ratio and the blade tip shape but is also influenced by trailing edge thickness and blade surface finish. The type of rotor power control employed (i.e. passive stall, active stall or pitch control) also affects aerodynamic noise. Stall controlled machines have higher noise when the blades enter stall during high winds (though the background noise will often mask this). Active stall machines are able to reduce this to an extent and pitch control machines do not put their blades into a state of stall.

The primary determinant of aerodynamic noise is the tip speed ratio, because high tip speeds create greater tip vortices which are generally the dominant emission source of sound. For variable-speed machines the tip speed increases with increasing wind speeds and so the noise emissions increase with increasing wind speed. Of course these machines rotate more slowly at low wind speeds than their constant-speed or two-speed cousins, where there is typically less background noise to mask the noise of the machine.

Research on quieter rotor blades continues, but given that noise is now such a minor problem - especially given the generally large distances between turbines and neighbouring houses - most of the benefits of that research will be turned into increased rotational speed and increased energy output rather than reducing the sound power levels.

Turbulent Boundary Layer Trailing Edge Noise

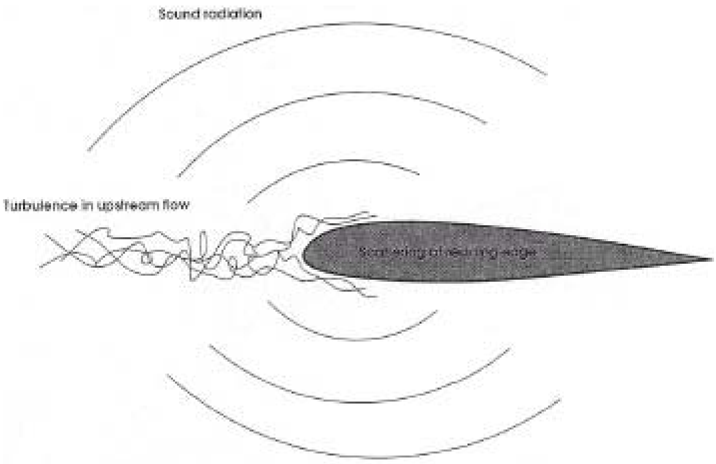
The diagram below indicates the source of noise from the interaction of the boundary layer and the trailing edge. At the trailing edge there is scattering of the boundary layer and noise is generated.



Leading Edge Inflow Turbulence Noise

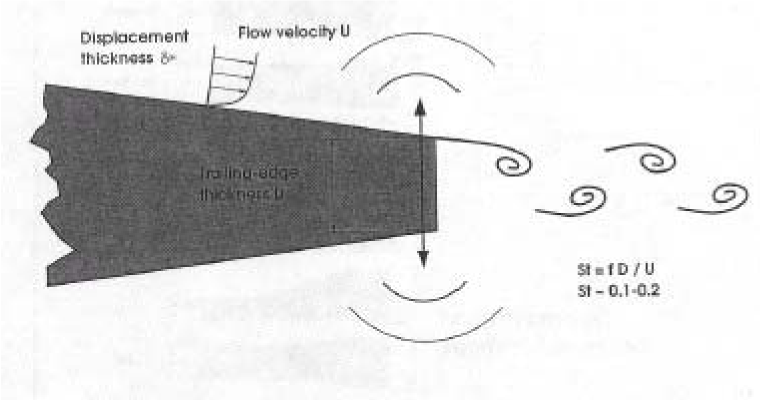
The diagram below indicates the source of noise from the interaction of the leading edge of the blade with turbulence in upstream air flow. This can lead to a thumping noise as the blades pass through these turbulent eddies.

Because it is not related to the wind turbine generator itself it is more difficult to control through the actual blade design. Unlike the whirling eddies created downwind of the tower that historically caused so many problems with early downwind turbines, turbulence eddies in the wind stream itself will affect upwind turbines at exposed sites. Here siting of wind turbines and proper wind regime analysis will be important to ensure the turbulence index is at or below the level for which the wind turbine generator has been design. At a sheltered position at the bottom of a valley in hilly terrain this thumping may even become the dominant noise – another good reason to ensure wind turbines are located in exposed sites with non-turbulent winds.



BLUNT TRAILING EDGE NOISE

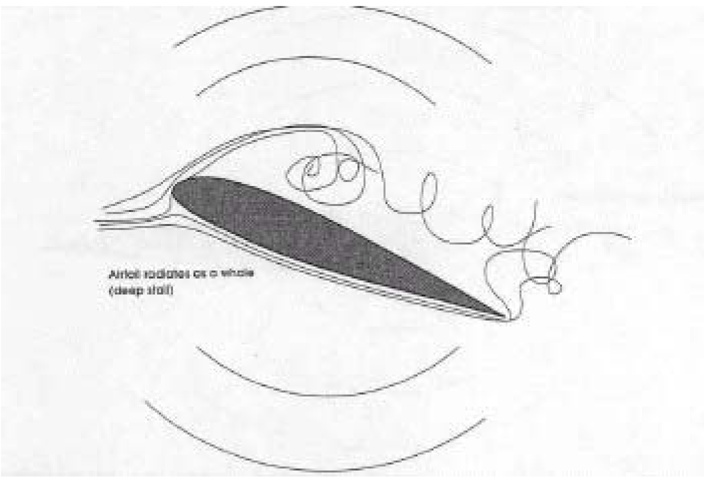
The diagram below indicates the source of noise from the trailing edge of the wind turbine generator blades. If the trailing edge is "blunt" then vortices are generated at the edge and noise is generated. This type of noise is significantly reduced by manufacturing blades with "knife-edge" trailing edges – something that has been aided by the use of modern composite materials.



SEPARATION NOISE

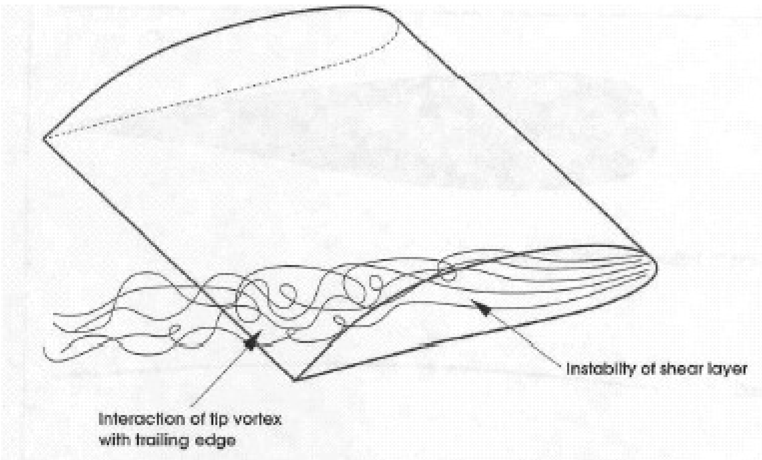
The diagram below indicates the source of noise when the air flow separates from the low pressure surface of the blade. This occurs when the blade goes into stall and so is of particular concern in stall controlled rotors as it can be a significant source of noise at high wind speeds.

Bonus (one of the worlds top tier manufacturers) combat this problem by adding a "turbulator strip" on the leading edge of the blade near the tip (essentially the same as the anti-slip strips used in bathtubs.



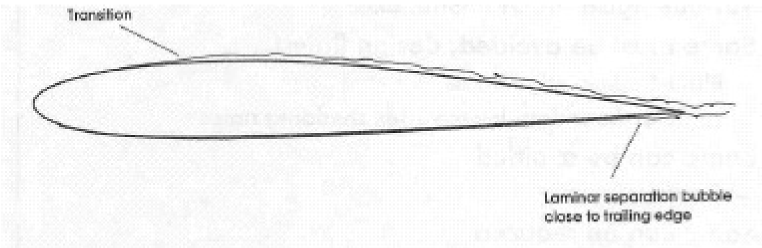
BLADE TIP NOISE

The diagram below indicates the source of noise from the tip of the blade caused by the instability of the shear layer at the tip and the subsequent interaction of tip vortices on the trailing edge. Modern turbine blade tips have a swept back shape (or "torpedo" shape) which dramatically reduces the formation of these vortices.



LAMINAR BOUNDARY LAYER VORTEX-SHEDDING NOISE

The diagram below indicates the source of noise from the separation of the boundary layer from the blade close to the trailing edge. This is often caused by imperfections or minor damage caused during the installation of the blades if the appropriate care is not taken. Modern blade manufacturing techniques and installation practices have essentially eliminated this source of noise.



COMPARISON OF WIND TURBINE GENERATOR NOISE

Virtually everything with moving parts will make some sound, and wind generators are no exception. Wind turbines are not silent, they are audible. All wind turbines create unwanted sound – i.e. noise - some do so to a greater degree than others.

Well designed, modern wind turbine generators are generally quiet in operation, and compared to the noise of road traffic, trains, aircraft and construction activities, to name but a few, the noise from wind generators is very low.

Outside the nearest houses, which are at least 300 metres away, and often much further, the sound of an operating wind turbine generator is likely to be about the same level as noise from a flowing stream about 50 to 100 metres away or the noise of leaves rustling in a gentle breeze. This is similar to the sound level inside a typical living room with a gas fire switched on or the reading room of a library or in an unoccupied, quiet, air-conditioned office (see Table 1 in previous section above).

It is quite possible to carry out a normal conversation at the base of a turbine running at maximum power, without raising one's voice. Members of the public invariably comment on the quietness of wind turbines when they visit a wind farm for the first time.

Even when wind speed increases, it is difficult to detect any increase in wind generator sound above the increase in normal background sound, such as the noise the wind itself makes and the rustling of grass and trees.

The level of noise permitted from wind farms at neighbours' houses is similar to the level of noise that would be audible from a busy road[12] five kilometres away. Indeed the noise from a wind farm 100 m away would be inaudible in most residential areas of Australia, drowned out by road noise and the other background noise of large numbers of people living in a relatively small space.

However the sound wind turbine generators produce – the swish of the blades through the air – are typically foreign to the rural settings in which wind turbine generators are most often installed. These sounds are not physiologically un-healthful; they do not damage hearing for example. Nor do they interfere with normal activities such as talking quietly to ones neighbour any more than do the sounds common in any suburban setting. But the sounds are new and different.

A mid-90's European study[13] on the annoyance factor of wind turbine noise at sixteen sites in three countries (Denmark, The Netherlands and Germany) involved interviews with nearby residents. The main finding was that "... the number of people actually indicating annoyance by wind turbine noise was fairly small. It appeared that the degree of annoyance was not related to an objective level of sound."

Those that live in a rural setting may do so because they prefer the peaceful lifestyle of the country to that of the city. Such people may become accustomed to the relative quiet of rural life and become familiar with the noises that exist in that setting. They have learned to live with them or even to find them desirable: the wind in the trees, the chirping of the birds, the creaking of a nearby farm "windmill", the hum of the neighbour's tractor. Rather than being nuisances these sounds reinforce the bucolic sensation of living in the country.

The addition of new sound which most residents have had little or no part in creating, and from which they receive no direct benefit, can be disturbing for some people. No matter how insignificant they may be in a technical sense, these new sounds signify an outsider's intrusion. An "intrusion", rather than a personal choice, may produce a different opinion about noise. The perception and reaction to noise is related to level of acceptance and personal preference. For example people often prefer to camp or live near running water or crashing waves even though the noise level may be quite high.

Neighbours to a wind farm must learn to coexist peacefully with their new neighbours (the wind farm) just as wind farm operators must learn to minimise their intrusion onto their neighbours' peaceful rural setting. Of the 3500 turbines in Denmark, less than 2% have caused noise complaints[14]. Nearly all of these are less than 225m from the complaining neighbour. Only one wind farm and Kyndby has encountered serious noise problems that required extensive mitigation.

Where does noise come from during wind farm construction

During the period of wind farm construction there will be some construction noise, primarily associated with the civil construction phases, i.e. formation of roads and foundations. Other construction noise will be associated with the delivery of the wind turbine generator equipment and during the erection of the individual wind turbine generators. All construction noise will need to comply with the relevant guidelines for

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[12] Calculated using the road traffic noise calculator at the National Physics Laboratory UK website (http://www.npl.co.uk/npl/acoustics/techguides/crtn/ defining a busy road as one with 10 vehicles (1 of which is a heavy vehicle), passing along it every minute at a speed of 80kmh. The level of noise audible from the road varies with a number of factors such as ground cover and height differences between the road and the listener but broadly speaking could be expected to be between 35-45 dBA

[13] Wolsink, M., Sprengers, M., Keuper, A., Pedersen, T. Holm, Westra, C. A.: *Annoyance from Wind Turbine Noise on Sixteen Sites in Three Countries,* 1994.

[14] "Development of Wind Energy in Denmark" Poul Nielsen. DEFU the Association of Danish Utilities, paper presented at the American Wind Energy Association Annual conference, Windpower '93, San Francisco July 19993.

construction noise and will typically be addressed in detail in the development and implementation of the projects Environmental Management Plan.

Fortunately the construction phase of a wind farm is very short, typically six to nine months for a wind farm with thirty or more wind turbine generators and sometimes even shorter than this. Furthermore, because wind farms are spread over large areas and because construction is not continuous at any single part of the site, it tends to be a lesser problem to a normal industrial or residential construction site. For example a wind turbine generator can be erected in a single day with the erection crew then moving on to the next wind turbine generator location; foundations are poured in a single day and then left to cure for several weeks. So while the total construction period may spread over a period of six to nine months the impact is not as great as might normally be expected.

Who Determines When a Sound is Noisy?

A sound becomes noise when it is unwanted, undesirable or when it causes annoyance or nuisance. It is perhaps timely to examine what is meant by nuisance in law compared to the common interpretation of the word, as it is different to annoyance and has very different implications in law.

NUISANCE

In law, a nuisance is a human activity or a physical condition that is harmful or offensive to others and gives rise to a cause of action. A public nuisance created in a public place or on public land, or affecting the morals, safety, or health of the community, is considered an offence against the state. Such activities as obstructing a public road, polluting air and water and keeping explosives are public nuisances.

A private nuisance is an activity or condition that interferes with the use and enjoyment of neighbouring privately owned lands, without, however, constituting an actual invasion of the property. Thus, excessive noise, noxious vapours, disagreeable odours and vibrations may constitute a private nuisance to the neighbouring landowners, even though there has been no physical trespass on their lands.

While a public nuisance, as such, is actionable only by the state, through criminal proceedings, injunction, or physical abatement, the same activity or conduct may also create a private nuisance to neighbouring landowners and thus result in a civil suit. The conduct of a business in violation of a zoning ordinance creates a public nuisance, but it may also be actionable as a private nuisance by neighbours who can prove a decrease in the market value of their homes as a result.

Because a private nuisance is based upon interference with the use and enjoyment of land, it is actionable only by persons who have a property interest in such land. If the interference merely makes the use and enjoyment less comfortable, without inflicting physical damage to the land, the courts consider the character of the neighbourhood to determine whether the activity or condition is an unreasonable interference. An activity that causes physical damage to neighbouring land, however, will be held to be an actionable nuisance irrespective of the character of the neighbourhood. Such cases usually involve vibrations that cause walls to crack or noxious vapours that destroy vegetation.

The legal remedies available in the case of a private nuisance are actions to enjoin the operation or continuance of the activity or condition or to collect money damages. If the abatement of a nuisance by injunction would impose an excessive hardship on the community (the closing of factories that would deprive community workers of their livelihood), the usual practice of the courts is to deny an injunction and award money damages for the injury suffered.

The noise emissions from any activity can cause nuisance to neighbours or the wider community. Wind farms are no different. In order to be economically viable, wind farms must be built in relatively close proximity to electrical infrastructure so that they can supply the electricity they produce to the end user. In practice this means that they are usually built in areas where people live. The design of wind farm projects must take this into consideration so as to ensure that their noise emissions do not cause nuisance.

The level of noise emissions from any noise source - including wind turbines – permitted at neighbouring residences is very strictly regulated in most countries, including Australia. The actual level permitted usually depends on the existing noise environment before the noise source is created.

For the measurement of environmental noise level in residential areas the noise level is usually assessed outside, rather than inside houses. This ensures that the amenity of outdoor recreation areas such as gardens is also protected. Noise levels inside the house from any external source can be expected to be much lower even with all the windows open.

Noise limits are usually set by local government (i.e. the Shire or District Council) although in some cases the State (or even the Commonwealth) Government may impose a limit on noise for a particular place or activity. Generally the state Environment Protection Authority (EPA) or its equivalent will issue guidelines for noise limits and recommend standard methods to use in predicting and measuring noise. Typically the local government will simply adopt some or all of the EPA guidelines as their limits; however this is not always the case.

The guidelines (if any) issued by the EPA or its equivalent will vary from state to state. The adoption (if any) either in full or in part of these guidelines may vary from one local government district to another. Consequently it is not a simple task in a document like this one to stipulate noise limits across all of Australia.

Regardless of the actual limit stipulated, the overall process is essentially the same. As an example, to protect the amenity of nearby residents a limit will be imposed on the noise emissions from a factory (or some other noise source) such that the sound pressure level in the residential area does not exceed a given limit (whatever that might be). From our preceding discussion it is clear that the circumstances in which the noise measurement is made and the equipment and method that is used to make the measurements will alter the result. Without standards for the equipment to be used and the methodologies to be followed for measurement, the noise limits become arbitrary and predictive noise assessments become meaningless. Such a situation clearly needs to be avoided both for the protection of the community from nuisance and for the certainty of developers.

Typically the noise from a source such as a factory near a residential area will be assessed with the noise source operating at its highest sound power level in conditions most suitable to the propagation of the sound to the potential receiver. If the sound pressure level at the receiver is over the limit stipulated some amelioration will be required so that it does comply with the limit. Typically the “conditions most suitable to propagation” used are no wind and low background noise. For a typical industrial noise this is reasonable as the noise emission is not related to wind conditions. The factory emitting the noise is just as likely to operate in no wind as it would if there is a lot of wind.

In the case of wind turbine generators the situation is very different. If there is no wind, the wind turbine generator makes no noise. As the wind speed increases the sound power level of an operating wind turbine generator increases, as does the sound power level of background noise sources (eg trees, grass, etc) though the sound power level of the wind turbine generator will increase more slowly than the background noise. Consequently there comes a wind speed when the background noise will completely mask the noise from the wind turbine generator.

Consequently there is a need to use a special noise measurement technique, unique to wind farms, since wind farm compliance measurements need to be taken in windy conditions – unlike other environmental noise levels.

In response to this, a great deal of work has been undertaken around the world to develop suitable standards for noise measurement methods to be used for the assessment of noise from wind farms and limits have been proposed.

In New Zealand a standard (***NZS6808:1988, Acoustics - The Assessment and Measurement of Sound from Wind Turbine Generators***) was developed. Originally this standard was being developed as a joint Australian / New Zealand Standard. However the interest from Australia waned because there was essentially very little interest in wind farming at the time. Because of the resurgence of interest in Australian wind farming, the work required to make this a joint standard has been recommenced. Consequently this standard is often adopted as a de facto Australian Standard.

The New Zealand Standard is very similar in approach to the recommended guidelines for wind farm noise developed in the UK – ***The assessment and Rating of Noise from Wind Farms, (The Working Group on Noise from Wind Turbines, Final Report 1996, ETSU-R-97)***. Those guidelines were compiled by a number of interested parties to wind farm noise including Acoustic Consultants, District and County Councils, Wind Farm Developers and a Legal representative.

Both the New Zealand Standard and the UK guidelines propose a level based on the existing background level at a particular residence. This approach ensures that the wind generators have a compliance level over the whole range of operational wind speeds.

Some countries use a far more simplistic approach where a noise limit is set for a single given wind speed, however this approach has the potential of allowing a development to comply at that wind speed but to create a nuisance at some other wind condition. The methodology for measuring compliance under the New Zealand Standard prevents this from occurring and so is the most robust technique.

The New Zealand Standard proposes that a noise limit of 40 dBA, or 5 dBA above the background be placed on the wind farms, when measured at any existing neighbouring dwellings. This is comparable with the limits proposed by the UK guidelines, though is significantly quieter than that used in other parts of the world.

Wind turbines are usually placed in rural environments, where the ambient noise is very low; indeed peace and quiet are often an important part of the amenity of the area. Consequently the very low limit of 40dBA is appropriate.

The reason for having a variable noise compliance limit is that both the existing background noise level and the wind generator source noise level increase with increasing wind speed. Having a fixed noise limit may result in the wind farm complying with the prescribed limits at a certain wind speed but could mean non-compliance at some other wind speed where even the background level itself may not comply.

Such problems with the noise limit are of no benefit to either the community or the wind farm developer. Compliance needs to be determined over the range of operational wind speeds to ensure acceptable limits at all wind speeds. As the existing background noise level itself is a function of the wind speed, compliance levels for wind farms are generally set as a function of the prevailing wind speed on the site.

Walking Trails and Noise Limits

In submissions to public enquiries the potential noise impact of wind farms on walking trails has been raised. While the levels predicted along parts of walking trails are higher than those that will be experienced at nearby homes, it may be the case that they will be at levels similar to those of the existing background levels at these locations.

Some further background measurements may be required at representative location(s) along the walking trail. The noise levels at sections of walking trail close to wind turbine clusters may reasonably be expected to be limited to a range of 40 to 50 dBA, i.e. below the level of conversational speech.

Misconceptions about Wind Farm Noise

The introduction of any new development such as a wind farm which many residents have had little or no part in creating, and from which they receive no direct benefit, can be disturbing for some people. No matter how insignificant the impact may seem in a technical sense, these new developments may signify an outsider's intrusion. An "intrusion" rather than a personal choice may produce a different opinion about any aspect of the proposed development.

It is quite reasonable for people nearby a new development to seek information about the development itself and others like it in other areas. This may be undertaken by supporters and detractors. Regardless, it is possible that in the search for "independent" information that someone not familiar with the development or its technology will come across out-of-date, inappropriate or incorrect information or worse yet disinformation spread by mischievous people. As a result misconceptions may arise in the public debate about a development.

Such misconceptions are not useful either for supporters or detractors of a proposal as it distracts the debate from the actual issues of concern and makes it increasingly difficult to work toward a consensus outcome with the best overall outcome for the community.

This section aims to dispel some of the more severe misconceptions people may have about the noise emissions from wind turbine generators.

Many of the machines operating in the 1970's and 1980s were large experimental turbines built as a part of government sponsored programmes, especially in the USA. Many of these machines operated at much higher tip speeds than are commonly found today in modern wind turbine generators and worse yet, ignored much of the research work already done in Europe to overcome many of the problems they were to unnecessarily replicate.

Even by the beginning of the 1990's, serial production wind turbine generators were causing significantly less noise than those early machines (reductions of 7dB or more). By the 1990's machines were operating at slightly higher tip speeds and yet produced less noise while capturing more than four times the wind energy.

Advances in airfoils and reductions in tip speeds have essentially decoupled noise emission from the size of the wind turbine. Reduction of the rotor's rotational speed from the aerodynamic optimum reduces noise. By feathering the trailing edge and attention to detail to remove imperfections and using a swept tip reduces noise.

Well designed, modern wind turbine generators are generally very quiet. It is quite possible to carry out a normal conversation at the base of a turbine running at maximum power, without raising one's voice. Members of the public invariably comment on the quietness of wind turbines when they visit a wind farm for the first time.

Outside neighbouring houses, which are at least 300 metres away, the sound of an operating wind turbine generator is likely to be about the same level as noise from a flowing stream about 50 to 100 metres away or the noise of leaves rustling in a gentle breeze.

Even when wind speed increases, it is difficult to detect any increase in wind generator sound above the increase in normal background sound, such as the noise the wind itself makes and the rustling of trees.

INFRASOUND AND SUBTERRANEAN VIBRATIONAL EFFECTS

An issue of concern raised some times by objectors to wind farm is that of sub-sonic noise or very low frequency noise which induces vibrations that may affect caves or the turbine foundations[15].

This low frequency noise is known as infrasound (below 20Hz) and was a know problem with some very early, large wind generators in the United States (e.g. prototype 2MW machine built in 1973). However all of these wind generators had downwind rotors, i.e. the blades were positioned downwind of the tower. Each time a blade passed the lee of the tower, the blade experiences a short duration load fluctuation which led to the radiation of acoustic pulses.

These acoustic pulses were of short duration and while their emission level was very low in comparison to other sources of acoustic energy in this frequency range (e.g. shock waves from explosions) they were understandably the cause of significant noise complaints. These wind generators also had only two blades and were built at a time when the aerodynamics of wind generator rotors was not fully understood.

It is important to understand that the infrasound noise problem from these early large wind generators, is a direct consequence of the wind turbine generators' rotor (i.e. blades) being downwind of the tower. Nearly all of today's wind generators (and certainly all those in Australia) have their rotors positioned upwind of the tower and this same issue does not occur on these wind generators as the wind flow incident on the rotor blades is not affected by the tower.

The only instance where infrasound has been known to be caused by a wind generator was more than 25 years ago with a prototype downwind wind turbine generator. Since the wind generators being used in modern Australian wind farms are upwind in design there is no possibility that there will be any infrasound associated with the blade passing frequency, i.e. there will be no throbbing or vibration of nearby buildings.

Regardless of the turbine technology used, the wind generator foundations themselves are of sufficient strength and size that there is negligible, if any, vibration transmitted into the surrounding ground and this has been demonstrated through operational measurements. Ground vibrations are however not a source of infrasound.

SIMILAR TO ROAD NOISE

Some have suggested that the noise from wind turbine generators was similar to road traffic noise[16]. At similar distances from a wind generator and a road, the character of the noise would be significantly different and it would be difficult to equate the aerodynamic noise from a wind farm to passing traffic.

The primary source of noise from a wind generator is an aerodynamic noise and its character is broadband in nature (i.e. much the same range of frequencies as wave breaking on the beach or wind through trees). This broadband, aerodynamic noise attenuates rapidly with distance and the ability of an observer to hear it is influenced by the location of the observer with respect to the wind generator, the wind speed and other background noise levels. There is some noise from the machinery located in the nacelle; however this is barely audible even at very close distances to the wind generator.

Road traffic noise is significantly louder than the level audible from a wind generator, even when standing directly below the wind generator, adjacent to the tower. A truck at 100 m at 45 km/h would generate 65 dBA while a wind turbine at the same distance would produce only 51 dBA.

[15] Public Submission #114 and #152 to Portland Wind Energy Project Environment Effect Statement and Planning Report. Department of Infrastructure Victoria 2001

[16] Public Submission #121 to Portland Wind Energy Project Environment Effect Statement and Planning Report. Department of Infrastructure Vic2001

In terms of the technical difference between road traffic noise and wind generator noise, the character of road traffic noise is dictated by the proximity of the observer to the road, the volume of traffic on the road and the speed of the traffic. For high volume traffic flows where the observer is relatively close to a road, the traffic noise will appear broadband, however it will be significantly louder than the noise from a wind farm.

To an observer situated some distance from a highway, for example, the noise of the traffic will appear more tonal as the aerodynamic and road tyre noise will have been attenuated with distance and it is mainly the noise of the engine that will be audible. In that case the audibility of the traffic is likely to be dictated by the number of high noise events (trucks passing) and this will be tonal in character and therefore will be more audible that the noise from a wind turbine generator.

Unable to Escape the Noise for kilometres

There is a misconception that wind turbine generators are clearly audible at a distance of 100m and so there is a huge area where one would be unable to escape the noise[17]. Another source of confusion arises from a lack of understanding of the difference between a sound power level and a sound pressure level. Without this proper understanding a summary inspection of technically data sheets that show wind turbine sound power levels of 100dBA or more sometimes leads to a misconception that wind turbine generator noise can be likened to that of a tractor on a pole, a jet aircraft and other such high noise sources[18]. On this basis, some inappropriately call into question the detailed noise prediction models presented by developers or their expert consultants.

For clarification, it needs to be remembered that noise is measured in decibels (dBA). For environmental noise measurements the decibel is a measure of the sound **pressure** level, i.e. the magnitude of the pressure variations in the air. An increase of 10 dB roughly sounds like a doubling of loudness.

The noise a wind generator makes at its source is usually expressed in term of its sound **power** level. Although this is also given in dBA, it is NOT a measure of the noise we hear but of the noise power emitted by the machine.

The sound *power* level of a wind generator will typically be in the order of 95 to 105 dBA. This will create a sound pressure level of about 50 dBA to 60 dBA at 40m away from the base of the generator, i.e. the same level as conversational speech. At a house 500 m away, the equivalent sound *pressure* level would be 30 to 40 dBA when the wind is blowing from the generator to the house.

It is clear that wind generators, like all rotating machinery, will emit some noise. However a wind farm is designed to comply with levels that are based on the protection of sleep disturbance and have been found to be acceptable in other countries where a large number of wind farms already exist. There will be some resulting increase in noise levels in the vicinity of the wind generators; however the noise from the wind generators themselves will generally be at a similar level to the existing background level. It should also be remembered that on very calm still days - i.e. windless days when the background noise levels are at their lowest - the wind generators will be non-operational and will not emit any noise.

The sound from any source, such as a wind turbine generator, is attenuated as it moves through the air both because of the inverse square law and the absorption of the sound energy by material within the environment (air, trees, etc). The sound will therefore be unlikely to be “heard for kilometres and kilometres” around the wind farm. Depending upon the layout of the wind farm and the background noise of the area it is more likely that there will be significant areas even within the wind farm where no noise will be heard.

[17] Public Submission #64 and #135 to Portland Wind Energy Project Environment Effect Statement and Planning Report. Department of Infrastructure Victoria 2001

[18] Witness Statement to the Review Panel for the Portland Wind Energy Project Environment Effect Statement and Planning Report, made by Paul Botha of Garrad Hassan Pacific Pty Ltd 2002

WIND FARMS GET NOISIER AS THEY AGE

There is sometimes a misconception that a wind farm will only comply with noise limits when it is new and as it ages it will become noisier, therefore noise predictions are a waste of time[19].

A noise limit will be imposed on a wind farm development by the relevant local authority. This noise limit will be in place for the life of the wind farm. Whether the wind farms are one year old or ten years old, they will still need to comply with the limits placed on them. So even if the misconception were true (it is not) then the wind farm operator would have to do something about it and rectify the problem.

As the primary source of noise from a wind turbine generator is the aerodynamic noise created as the blades move through the air, this noise will be approximately constant throughout the wind generators life. There is no reason why the aerodynamic noise should change significantly with time. In the event that there is a problem with the aerodynamics of a particular wind generator blade which gives rise to a significant increase in noise, it is very likely to affect the performance of the wind generator too. This loss of performance would likely encourage the operator to rectify the fault even if noise were not an issue that must be dealt with.

OTHER MISCONCEPTIONS?

Please let me know if you are aware of any other misconceptions relating to noise emissions (Grant@SustainableEnergyAustralia.com.au).

[19] Public Submission to Portland Wind Energy Project Environment Effect Statement and Planning Report. Department of Infrastructure Victoria 2001

Noise Emission Prediction and Assessment

The objective of the noise impact assessment for a wind farm proposal is to ensure that the proposed wind farm layout is designed in such a way as to minimise any potential noise impact on the community, specifically at nearby residences. This is achieved by predicting the combined noise level from the wind turbine generators in the wind farm and ensuring that the predicted level at each of the nearby house locations complies with acceptable wind farm noise limits. The limits will be set according to local standards or negotiated limits where such standards do not exist.

Quiet operation has become an important design criterion for successful wind turbine manufacture. Noise is also an important design criteria used in the development of the wind turbine generator layout of a wind farm. Assessment of a wind farm's noise emissions prior to construction (noise prediction modelling) and after construction is therefore an important process. The advisable distance between a wind farm development and neighbouring residences to avoid and disturbance of neighbours will depend upon a variety of factors including the local topography the character and level of background noise and the size of development. The minimum separation distance should therefore be calculated on a case by case basis.

As described previously, as an "industrial noise source" wind turbine generators have some unusual characteristics. The noise they produce is predominantly aerodynamic, which is generally perceived as more "natural" than typical sources of industrial noise. In addition, it tends to be at a lower level when wind speed is low, and rises as the wind speed increases. Of course, below the "cut-in speed" for the turbines, no noise is generated at all. Fortunately, as wind speed increases, so does wind generated background noise from trees and bushes at neighbouring houses, leading to masking of the noise from the turbines.

Most limits on wind turbines therefore allow the wind turbines to exceed the limit of 35 or 40 dBA as long as they don't exceed the level of background noise at the neighbours by more than a specified amount, often 5 dBA. Extensive monitoring of the pre-existing noise environment over the range of wind conditions likely to be experienced at the site is carried out at neighbouring properties to determine the actual level of wind related background noise.

In practice, this means that the noise limit applied to a wind farm does not mean that the wind turbine generators will necessarily be inaudible to all of its neighbours, at all times, under all conditions. They do, however, protect the amenity of neighbours and ensure that the development can reasonably be expected not to disturb them. If limits were to be applied with inaudibility as an objective it would be very difficult to build an economically viable wind farm (or indeed any other type of development) anywhere, as it would be difficult to find locations which combined the required resource, general environmental acceptability and electrical infrastructure at a viable distance for connection, with no nearby neighbours.

Sound, and the way it propagates through the air, is relatively well understood and so it is possible to make predictions of the sound pressure levels around a single or a number of noise sources. For wind farm proposal these noise predictions are undertaken using a very conservative noise propagation model, i.e. one which is known to generally over-predict the noise levels.

The model that is generally used is that proposed by the International Energy Agency (IEA) and this forms the basis of most other propagation models. This is the model that is used in the New Zealand Standard, ***NZS6808 Acoustics – The measurement and assessment of sound from wind turbine generators***.

The noise propagation model proposed by the IEA is widely used largely because of its conservatism, i.e. generally it over-predicts noise levels. It is based on hemispherical noise propagation over a flat reflective surface and includes sound attenuation by air. Less well understood effects, such as topographical shielding and wind speed effects, are not modelled. Their exclusion generally makes the predictions more conservative. For example, in those instances where the wind turbine generator is not in line of site from the observation point, there may be an additional attenuation of 12 dBA [20]. The degree of attenuation will depend upon a number of factors influencing the direct and indirect sound paths between the wind generator and the receiver.

Hemispherical spreading over a flat reflective surface with no absorption results in the sound level from a source reducing by 6 decibels per doubling of distance. Practical tests[21] have shown that for wind generator applications, this propagation model is only valid at distances of less than approximately 1600 metres from the source and concludes that beyond this limit it is suitable to model noise propagation with an attenuation rate of 3 decibels per doubling of distance. This amendment to the IEA model is routinely used in predictive modelling.

As the IEA model does not attempt to model wind effects, the results derived can be considered to represent the down wind noise level predictions for all wind directions. This produces the 'worst-case' predictions for all neighbouring locations, with the assumption that all wind generators are visible with no attenuation from obstacles or screening. As the terrain, in the vicinity of most proposed wind farms, will contain some undulations and screening, the IEA model is expected to produce conservative (high) predictions. In reality, when a house is upwind or cross-wind of a wind generator, the noise levels will be lower than those represented in the model.

The results of the noise level predictions can then be represented as iso-noise contours around the wind farm. These may be completed for various wind speeds and indeed will be different for each wind speed. However two important wind speeds that are often used are 5 m/s and 10 m/s. The 5 m/s case represents the wind generators in a continuously operational condition in low wind speeds and low background noise levels, while the 10 m/s case represents the wind generator close to full power, before the background level completely dominates over the wind turbine generator noise.

Often the manufacturer or specific model of wind turbine generator is not known during the planning stage. This is because the developer will not have completed the tendering process for what is usually a very valuable contract. In such cases sound power levels from a representative wind turbine generator are used for the purposes of undertaking the noise level predictions for the proposed wind farm. For a typical wind farm using 1.5 MW wind turbine generators a sound power level of 102.1 dBA can be used for the modelling as it is representative of that from a typical commercially available machine.

A typical rate of increase in wind generator sound power level (0.9 dBA per m/s) with wind speed is also used. This value is indicative of dual and fixed speed wind generators which generally increase at a rate of between 0.2 and 1.2 dB per m/s. Variable speed wind generators may increase at a slightly greater rate, however they are generally quieter at lower wind speeds.

[20] New Zealand Standard NZS6808:1988, Acoustics - The Assessment and Measurement of Sound from Wind Turbine Generators.

[21] ISVR Consultancy Service University of Southampton, 'The prediction of propagation of noise from wind turbines with regard to community disturbance'. Contract report for ETSU, 1990.

The sound power levels used in this way, although representative of the wind generators proposed, are not guaranteed by the ultimate manufacturer. At the final specification and wind generator selection stage of the proposal, measured and warranted levels will be obtained by the developer for the wind generators proposed for the development. The developer will then ensure that the selected wind generator supplier, provide wind generators in accordance with a suitable noise warranty which will be based on those warranties used for European wind farm projects.

The IEA noise propagation model is stated as having a predictive accuracy of ± 2 dB. Remembering that in many cases the model is expected to produce conservative (high) predictions, an uncertainty of 0 to +2 dB is more likely.

Wind Turbine Generator Sound Power Level Measurements

Obviously the location of each wind turbine is required for this sort of assessment but it is also important that the sound power level of each wind turbine and its response to wind speed is known. The computer model is then able to make the appropriate calculations at each point to determine the contribution of each of the wind turbines in the array to the sound pressure level at any particular point of interest.

As with any other part of noise measurement it is important that the equipment and method used to determine the sound power level of a wind turbine and its response to wind speed, is standardised so that the values may be compared and limitations and assumptions of the measurement properly understood. This is set out in a Certificate of Compliance – from an independent certification agency and prepared in accordance with a recognized Standard.

The wind generator source noise levels are determined by referencing them to an 8 m/s wind speed measured at 10 metres above ground level (agl). The 1/1 octave band distribution of wind generator sound power level at this wind speed are then presented in a tabulated report. All decibel levels presented in these reports are A frequency weighted (dBA) with sound power levels referenced to 1 pW.

The overall character of the wind generator noise is an important consideration since characteristics such as tones can prove very annoying to the neighbours of wind farms. There are now standard accepted conditions which are imposed on wind generator suppliers which ensure the absence of tonal content in the wind generator noise spectra. These conditions are set out in warranty agreements with wind generator suppliers and tonal character is controlled by the compliance level imposed on the wind farm development.

Tonal quality is generally not considered in any detail in predictive assessment as the acoustic reports, provided for the wind generators generally considered, show them to be free of pure tones. It will still be necessary for the developer to ensure and specify that the wind generators used for their proposal will not exhibit any clearly audible tones.

Where audible tones are present in the source noise, the measured operational noise levels will carry a penalty of 5 dBA under the New Zealand Standard.

Background Noise Measurement

Noise compliance levels are generally set in relation to the existing background level, so it is necessary to undertake some noise measurements to characterise the existing background levels. Measurement of the existing background noise levels is undertaken at selected properties in the vicinity of the proposed wind farm over periods of about 2 weeks with 10 minutes averages to give approximately 2,000 background noise level measurements at each location. These measurements plotted against the wind speed measured on the site for the concurrent 10 minute period. The wind speed measurements are those recorded at the closest wind farm anemometry mast and where the wind data was not measured at hub height, it is converted to equivalent hub height wind speeds.

Noise loggers are placed in a location close to the residence but in a position such that it is clear of screening or noise sources that might inappropriately affect the noise level. For example the logger should not be placed close to dense hedges or fences or water pumps etc. Such noise sources may inappropriately raise the background noise level and screening may inappropriately lower the background noise level.

These measurements are used to set the baseline background noise level prior to the construction of the project and can also be used to determine the noise level with which the wind farm shall comply once completed.

It should be noted that while measurements may be taken at several residences adjacent to a proposed wind farm, the wind farm layout is designed such that it complies with conformance levels based on the lowest background level. This effectively means that the wind farm will comply with a proposed limit based on the lowest overall background level measurements.

Furthermore, if the project is approved, it may be necessary to undertake a few more background noise level surveys at noise sensitive locations. Any additional background surveys undertaken prior to the construction will avoid the possibility of having to stop the operational wind farm to achieve the same purpose.

DESIGNING WIND FARMS TO ELIMINATE NOISE

Wind farm layouts are assessed using complex computer models in which iso-noise contours are plotted and sound pressure levels are assessed at particular locations – generally at each of the nearby residences – to ensure the limits are not exceeded. Using this approach ensures that there is sufficient separation distance between the wind generators and the nearby residences such that noise levels will be attenuated to an acceptable level at the nearby residences.

The siting of wind generators in complex terrain in relatively close proximity to houses raises issues that are not present at sites in generally flat terrain. Much work was done in the UK as a result of development of wind farms in the complex terrain of Wales, to determine the cause of the problem and to agree an acceptable methodology to assess the noise levels from future wind farm projects. This was done to assist both local Councils and wind farm developer in establishing a clear methodology to set and measure the operational wind farm noise levels in an appropriate manner.

Based on the measurement methodology outlined in those guidelines and using best practice wind farm design procedures, noise problems at adjacent dwellings can be eliminated. The more recent wind farm developments in Europe and the US have shown that by using a best practice design and due consideration to the noise impact from a wind farm, these developments can operate without creating a noise nuisance to their neighbours.

Best practice for wind farm design means identifying neighbouring house locations at an early stage to ensure that all iterations of the wind farm layout consider the noise impact of all the generators within the development at all houses adjacent to the proposed wind farm project.

Many of the noise problems with early wind farms were as a result of tonal noise from the wind turbine generator's gearbox or generator. These problems have been designed out of modern machines which also use sound insulation and isolation techniques to reduce the overall noise emission. Wind turbine noise warranties guarantee that the machines will be free of tonal noise.

In well designed modern wind farms the wind generator noise is at a similar level to that of the background and rarely gives rise to any noise problems. A well designed wind farm with measurable and appropriate limits will not result in noise disturbance to the community. This is generally borne out after a visit is made to an operational wind farm.

Noise Limit Compliance Testing

The procedure for compliance testing is essentially the same as background noise testing. A noise logger is placed at the residence making the noise complaint and background noise levels measured. The noise measurements are made both with the wind farm operating and not operating.

Should the wind farm be found to be causing a nuisance, compliance testing will continue until the amelioration works undertaken reduced the noise to a level within the limits or some solution is found.

Definition of Terms

SOUND POWER LEVEL (LW)

A sound power level is a measure of acoustic power in decibels. Although the sound power level is given in dBA, it is NOT a measure of the noise we hear but of the noise power emitted by the machine. Sound power level is used in various noise models to project noise at various distance from a wind turbine.

The sound POWER level of a wind generator will typically be in the order of 95 - 105 dBA. This will typically create a sound pressure level of about 50 dBA to 60 dBA at a distance of 40m away from the base of the generator, i.e. the same level as conversational speech. At a house 500 m away, the equivalent sound pressure level would be 30 to 40 dBA when the wind is blowing from the generator to the house.

The source emission strength of wind turbine noise derived by field measurements of the sound pressure level $L_w = L_p + 10 \text{ Log}(4\pi R^2)$ where L_p is the measure sound pressure level and R is the slant distance from the nacelle. If the sound pressure level was measured on a reflective panel, 6 dB must be deducted from L_p.

SOUND PRESSURE LEVEL (L_P)

A sound pressure level is a measure of the magnitude of the pressure variations in the air. It is measured in decibels, relative to a reference pressure of 20 micro-newtons per square metre.

An increase of 10 dB roughly sounds like a doubling of loudness. Measurements of environmental noise are usually made in dBA, which includes a correction for the sensitivity of the human ear.

Because sound pressure levels decrease with increasing distance from the source, location is always specified or implied. For most discrete sources, such as wind turbines the distance from the listener is just as important as the noise level of the source. For example some wind turbine manufacturers estimate that the noise from a typical medium sized wind turbine will drop to 45 dBA within 150 metres.

This term must not be confused with sound power level, even though both measures use the same units.

NUISANCE NOISE

Used in the USA to describe a sound or noise that interferes with the legal right of others by causing damage, creating an annoyance or causing inconvenience.

OFF-SITE MITIGATION

Actions or measure taken beyond the boundaries of a project site to compensate for a project's real or perceived environmental impacts.

NOISE ISOLATION

Component or device used for reducing noise emissions that prevents the interaction between components or the transmission of vibration between components.

EXCEEDENCE LEVELS

The percentage of the time that noise exceeds the given level. The exceedence level L_{90}, indicates the noise level which will be exceeded 90% of the time while L_{95} indicates the level will be exceeded 95% of the time. L_{eq} indicates the level will be exceeded 50% of the time.

Noise disturbance

Annoyance caused by noise. A lesser impact than where noise interferes with some activity such as sleep or communication.

Decibel

Logarithmic scale used to describe the difference in power or intensity between two levels. Generally used in electronics and acoustics. Defined as ten times the common logarithm of the quotient of the two levels, that is 10 Log (P_1/P_2). In acoustics the faintest audible sound, the threshold of hearing is defined as 0 dB. The threshold of pain is 120 dB.

Audible

Sounds that can be heard by most people with normal hearing.

Noise Attenuation

Noise attenuation is a reduction of the intensity of acoustic energy by use of sound deadening materials, baffling or increase in distance between source and receptor.

A Weighted Scale

A weighted scale is a weighting network for sound level measurements that selectively discriminate against low and high frequencies to roughly mimic the response of human hearing.

Sound Absorption

Interception and attenuation of acoustic energy by used of sound deadening materials such as insulation and cladding inside a wind turbine nacelle.

Acoustic Noise

Unwanted audible and inaudible sounds.

Infrasound

Defined as vibrational or stress waves with a frequency below those of sound waves that can be detected by the human ear - i.e., below 20 hertz. In other words, infrasound is sub-audible frequencies below 20 Hz. The range in frequency of infrasound extends down to geologic vibrations that complete one cycle in 100 seconds or longer.

Such waves occur in nature in earthquakes, waterfalls, ocean waves, volcanoes, and a variety of atmospheric phenomena such as wind, thunder, and weather patterns. Naturally occurring infrasonic vibrations take the form of tidal motion or earth tremors. The monitoring of very small earth tremors using a seismograph has value as a means of providing early warning of volcanic activity or of serious earthquake shocks.

Severe earthquakes often cause infrasonic disturbances of the atmosphere that may extend to 50 km above the Earth's surface and can travel considerable distances around the globe.

The reflection of man-made seismic shocks has helped to identify possible locations of oil and natural-gas sources. Distinctive rock formations in which these minerals are likely to be found can be identified by sonic ranging, primarily at infrasonic frequencies.

Human perception of low-frequency sound waves propagating in air does not have a well-defined cut-off point. Above about 18 hertz sound waves appear to have tonality; below this frequency the individual compression waves may be distinguished. Driving an automobile with an open window may generate an infrasonic resonance and the sonic boom of supersonic aircraft contains significant levels of infrasound.

Infrasound has the ability to set up resonances and vibrations within buildings and in certain circumstances occupational exposure to infrasound may be severe: transformer rooms, compressor plants, and engine rooms may all produce levels that are extremely high and cause discomfort.

Studies have shown that many people experience adverse reactions to large intensities of infrasonic frequencies, developing headaches, nausea, blurred vision, and dizziness. The mechanisms by which infrasound may be perceived by humans and their physiological effects are incompletely understood.

On the other hand, a number of animals are sensitive to infrasonic frequencies, as indicated in the Table. It is believed by many zoologists that this sensitivity in animals such as elephants may be helpful in providing them with early warning of earthquakes and weather disturbances. It has been suggested that the sensitivity of birds to infrasound aids their navigation and even affects their migration.

Animal	**frequency (hertz)**	
	low	**high**
Humans	20	20,000
Cats	100	32,000
Dogs	40	46,000
Horses	31	40,000
Elephants	16	12,000
Cattle	16	40,000
Bats	1,000	150,000
Grasshoppers and locusts	100	50,000
Rodents	1,000	100,000
Whales and dolphins	70	150,000
Seals and sea lions	200	55,000

Table 2 Frequency Range of Hearing for Humans and Selected Animals[22]

SOUND BARRIER

The Sound barrier is a sharp rise in aerodynamic drag that occurs as an aircraft approaches the speed of sound and that was formerly an obstacle to supersonic flight. If an aircraft flies at somewhat less than sonic speed, the pressure waves (sound waves) it creates out-speed their sources and spread out ahead of it.

Once the aircraft reaches sonic speed the waves are unable to get out of its way. Strong local shock waves form on the wings and body; airflow around the craft becomes unsteady, and severe buffeting may result, with serious stability difficulties and loss of control over flight characteristics. Generally, aircraft properly designed for supersonic flight have little difficulty in passing through the sound barrier, but the effect upon those designed for efficient operation at subsonic speeds may become extremely dangerous.

[22] Encyclopaedia Britannica 2003

SONIC BOOM

A sonic boom is a shock wave that is produced by an aircraft or other object flying at a speed equal to or exceeding the speed of sound and that is heard on the ground as a sound like a clap of thunder.

When an aircraft travels at subsonic speed, the pressure disturbances, or sounds, that it generates extend in all directions. Because this disturbance is transmitted earthward continuously to every point along the path, there are no sharp disturbances or changes of pressure. At supersonic speeds, however, the pressure field is confined to a region extending mostly to the rear and extending from the craft in a restricted widening cone (called a Mach cone). As the aircraft proceeds, the trailing parabolic edge of that cone of disturbance intercepts the earth, producing on earth a sound of a sharp bang or boom—with silence before and after. When such an aircraft flies at a low altitude, the shock wave may be of sufficient intensity to cause glass breakage and other damage. The intensity of the sonic boom is determined not only by the distance between the craft and the ground but also by the size and shape of the aircraft, the types of manoeuvres that it makes, and the atmospheric pressure, temperature, and winds. If the aircraft is especially long, double sonic booms might be detected, one emanating from the leading edge of the plane and one from the trailing edge.