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The Variability Factor in Wind Turbine Noise

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Summary

Public policy decisions about wind turbine noise face several challenges caused by the "variability factor." Most sound ordinances are based on an average sound level, while neighbor responses are generally based on shorter-term peak noise levels, along with the additional variability in the sound quality of wind turbine noise; increasingly, complaints arise around projects that meet average sound level criteria. At the community scale, different types of communities may be more or less tolerant of moderately audible wind turbine noise in their rural environments; working farmers and ranchers often consider such noise trivial, while people in towns where more of the population is seeking peace and quiet may find the same noise intrusive. On the landscape scale, of course, atmospheric conditions can have dramatic effects on sound propagation, absorption, and audibility. Perhaps most importantly, real-world source levels of individual turbines can also vary greatly from idealized sound power levels used in sound modeling—minor wear, wind shear (especially directional), and inflow turbulence from nearby turbine wakes or atmospheric turbulence, can all increase the sound output of individual turbines. Both the transient peak sound levels caused by increased source levels and the variability in the sound quality, especially in turbulent conditions, are likely key drivers in community responses to wind turbine noise. This paper reviews publications that quantify aspects of wind turbine sound variability.

1.0 Introduction

Much of the public debate and the scientific back-and-forth among acousticians is centered on technical questions—dBA/dBC/dBG; perceptibility of infrasound; degree that expectations contribute to health effects reports; veracity of sound models; the best statistical technique to use in assessing property value effects, etc. And, much time and effort is being spent monitoring sound levels around troubled wind projects (most often resulting in simple "noise numbers" very close to the regulatory limit, plus or minus a few decibels). These technical arguments, impassioned testimonies, and health effects studies that typically result in subtle trend lines (and thus ambiguous interpretation) are distracting us from considering what may be the central feature of wind turbine sound and the driving factor in community responses: the many kinds of variability that are inherent in this particular community noise source.

Wind advocates often stress that wind turbine sound is not fundamentally different than other more familiar sources of community noise, and thus should not need to be assessed or regulated with different metrics or standards. This assertion is largely based on the absolute sound levels of wind turbines (both at the source and at typical receptor distances) and the generally broadband nature of audible turbine sound. However, in its variability—especially its variable source sound levels and sound qualities—wind turbine sounds are quite unlike nearly any other industrial or transportation noise source. In particular, the sound level of turbines is strongly affected by wind speed, a factor that does not tend to contribute to the source levels of other noise sources; this introduces an inherent variability that affects neighbor responses. Further, many of the more troublesome sound qualities reported by wind farm neighbors (knocking, banging, sneakers in a drier) are poorly understood. It is possible, or likely, that pockets of inflow turbulence drive many of these sounds, and could likewise trigger some of the peak source levels.

This paper reviews literature that addresses several types of variability that contribute to community responses to wind farm noise. As suggested by the above paragraph, it includes some plausible yet speculative hypotheses, especially about the role of inflow turbulence (including wake effects and atmospheric turbulence, particularly horizontal/directional wind shear) in some of this variability. The intent of the author is to stimulate constructive questions and research that may contribute to both our understanding of wind turbine noise and mitigation/management of community responses.

2.0 Variability of turbine sound

2.1 Averages and peaks

Two recent papers discuss a consequence of turbine sound variability that deserves more widespread appreciation: actual on-the-ground sound levels vary greatly, and in particular, will peak at up to 20dB above the average project sound level. This helps to explain some situations in which projects are operating at (or very close to) compliance criteria, which are usually based on average sound levels, while neighbors report significant annoyance and night time waking, and may even record peak sound levels well above the regulatory threshold.

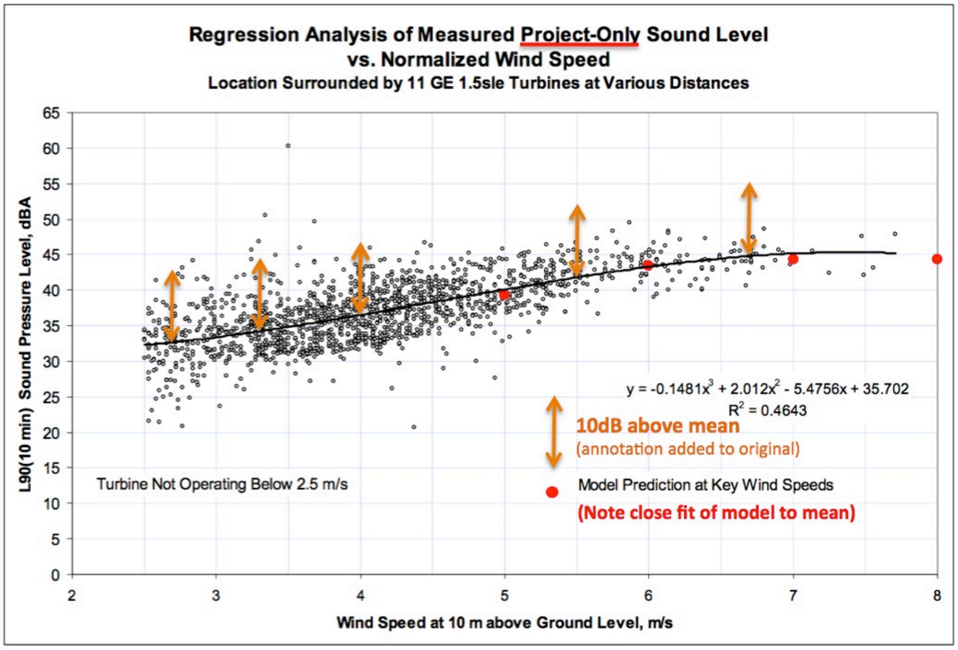
This peak-and-averages factor is expressed most clearly by David Hessler (Hessler, 2011), in a Best Practices Guidelines paper written under the auspices of the National Association of Regulatory Utility Commissioners, with similar language being included in his recent project noise assessments:

> It is important to note that the...suggested sound level targets discussed (below) are mean, long-term values and not instantaneous maxima. Wind turbine sound levels naturally vary above and below their mean or average value due to wind and atmospheric conditions and can significantly exceed the mean value at times. Extensive field experience measuring operational projects indicates that sound levels commonly fluctuate by roughly +/- 5 dBA about the mean trend line

> and that short-lived (10 to 20 minute) spikes on the order of 15 to 20 dBA above the mean are occasionally observed when atmospheric conditions strongly favor the generation and propagation of noise.

The point is seconded by Robert Thorne (Thorne, 2011), whose work often focuses on human responses to moderate noise. Thorne suggests that standard prediction error ranges, which increase over distance, combined with adverse weather effects that can increase turbine source levels and/or enhance sound propagation, will create peaks of up to 20dB over the predicted levels. He has monitored sound levels at many homes around a mile from wind farms, and notes significant short-term variation as well: "in 60 seconds the sound character varies regularly by more than 20dB."

This graph illustrates the variability that Hessler has found on the ground. Note that the greatest variability, most periods with sound 5-10dB (or more) above the mean, and even some of the absolute peak sound levels (above 45dB) occur when wind speeds are moderate (Hessler, 2011, Figure 4.0.4, p15; colored annotations added):



The likelihood of peak sound levels being higher than regulatory criteria based on averages is a fact that needs to be communicated more clearly, both to help create realistic expectations, and because this may be relevant to the choice of what average sound level to aim for. Hessler recommends an “ideal” (but often not possible) design goal of 40dBA (two-week average), and sees 45dBA as a reasonable balance “as long as the number of homes within the 40 to 45dB range is relatively small” (Hessler, 2011). More recently (Hessler, 2012) he has suggested that a two-week mean of 45dB is usually acceptible, even with larger numbers of homes in the 40-45dB zone.

These transient peak sound levels are the cumulative result of turbine source levels and of sound propagation conditions, as discussed in the following two subsections.

2.1.1 Source level differences of individual turbines

Two simple variations in turbine source levels are widely recognized: increasing sound output as wind speeds increase (leveling off at higher wind speeds as seen in Hessler's graph, above), and amplitude modulation, which results in brief pulses of louder sound about once per second (the peak levels of which are not captured in time-averaged measurements). While both of these variations have an effect on community responses, a more fundamental variation has largely been ignored, and is described in this section.

Sound models generally begin with the rated Sound Power level of the turbines in question. Inevitably, many turbines in the field will be operating at less than the peak aerodynamic efficiency at which they were initially tested—thanks to normal, minor wear of blades and/or elevated flow noise caused by inflow turbulence—so that the source sound levels of turbines in the field will vary to some degree. Because sound attenuates by 3-6dB for each doubling of distance, an increase in source sound level of a few decibels will mean that sound levels are higher than expected at any given distance, or will reach a threshold of interest (e.g., the regulatory limit) at a greater distance than models suggest.

Surprisingly, very little study appears to have taken place to quantify just how much variation in turbine sound levels there may be in practice, either over a turbine's lifetime or in response to transient atmospheric conditions. A recent study (CS Pedersen et al, 2012) begins to rectify the situation. Researchers measured the effective sound power levels, per IEC 61400-11, of 23 large turbines (2.3-3.6MW), and these field measurements found that individual turbines did indeed have significantly varied sound output: the standard deviation of identical models was 1.6-3.5dB, resulting in a 90% confidence interval of 2.6-5.75 around the mean. They then modeled propagation from the individually measured turbines out to the point that turbine sound would drop below 35dB (they chose this threshold because it's the level required in quiet areas of Sweden, and it's the level at which Pedersen-Waye found annoyance begin to spike beyond 5-10%), and the distance to which sound from an array of twelve turbines would drop to 44dB (the Danish noise limit). For both cases, the distance necessary to meet the regulatory criteria varied dramatically, from about 600m to over 1200m (about a third of the turbines required distances of 1km or more).

In addition, the low-frequency content of the sound spectrum at the distance where dBA drops to 44dB also varied greatly, ranging from 34.5-41.8dBA$_{lf}$. (DBA$_{lf}$ is a new Danish "audible low frequency" metric meant for measuring sound inside homes; it applies standard dBA weighting, but only to the sound frequencies from 10-160Hz.)

This variability is based solely on differences in source levels of similar machines; no consideration is added for propagation conditions; when the authors did model for sound-channeling conditions, the distances required to meet regulatory criteria roughly doubled. This study did not investigate the causes of this source level variability, but with wind measurements made per IEC 61400-11 (wind speeds constant across all measurements; sound measured close enough to avoid propagation variability), it seems likely that the measured differences can be attributed to either normal, minor surface or edge wear, or to elevated flow noise caused by inflow turbulence.

While of course these results apply only to the particular turbines measured, this study is an important reminder that our reliance on idealized sound power levels as the starting point for sound modeling likely neglects important real-world variability in turbine source levels, and therefore in peak sound levels at nearby receptors.

Notably, the effect of inflow turbulence on turbine sound levels has not been studied in detail. Researchers at both Sandia National Laboratory's Scaled Wind Farm Testing (SWiFT) facility and the National Renewable Energy Laboratory's Wind Technology Center are interested in looking more closely at these questions, although many hurdles remain, including funding and, ultimately, the difficulty of modeling such effects in a way that can be applied in practice (personal communication, 2013). The noise impacts of inflow turbulence (Lundquist and Clifton, 2012), including wake effects from other turbines (Churchfield, 2012), and of directional shear (Freedman and Moore, 2012) may be particularly relevant to peak sound levels as observed by Hessler and by Pedersen et al, above, and to triggering sound qualities that are especially intrusive for neighbors, as discussed in Section 2.2.3, below.

2.1.2 Propagation Variability

Propagation variability is much more widely recognized than source level variation—and is considered in most sound modeling—so this paper will mention just a couple of relatively recent contributions.

First, two recent papers (HGC/Ontario MOE 2010 and Møller and Pedersen 2011) stress that lower frequencies appear to drop by more like 3dB per doubling distance (cylindrical spreading), rather than the 6dB (spherical spreading) as with most audible sound and as assumed in most dBA sound models, especially when atmospheric refraction creates a sound channel with the ground below. This can create higher sound levels than expected at distances beyond a few hundred meters. At greater distances, the sound that makes it that far will be mostly low frequencies, which can be one of the major issues for wind farm neighbors inside their homes. As Møller and Pedersen note, "Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away."

Bob Thorne has introduced the concept of Heightened Noise Zones (HNZ), in an attempt to understand what may drive experiential reports of turbine sounds changing dramatically in relatively short time spans or across relatively small distances (recall Thorne's observation, above, of frequent 10-20dB variations in sound levels over the span of a minute). He (Thorne, 2013) has laid out a detailed description of possible factors that may contribute to HNZ's, though field measurements that could begin to clarify the complex interactions he suggests remain to be done. (The concept sparked interest from an NREL researcher when presented there this spring.)

A root cause of HNZ's is the constructive and destructive interference of sound waves from multiple turbines operating out of phase with each other, as illustrated here (Thorne, 2013, Figures 18 and 19, p14):

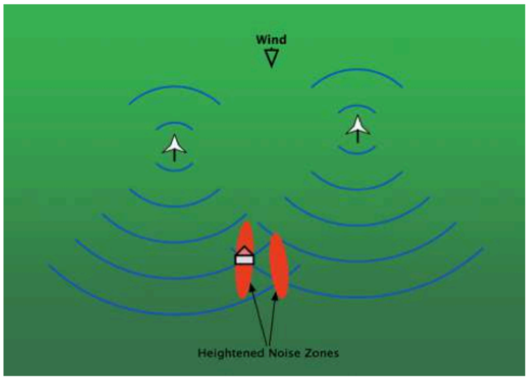


Figure 18: Noise from 2 turbines creating Heightened Noise Zones

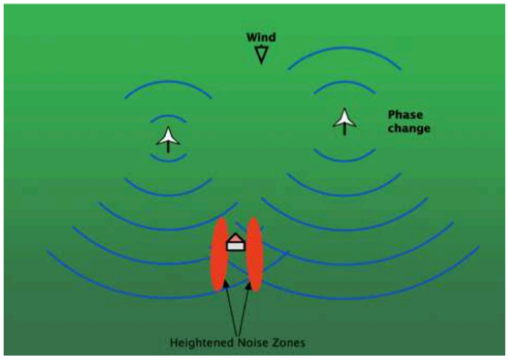


Figure 19: Noise from 2 turbines under slightly different conditions moving Heightened Noise Zones

This simple additive and subtractive effect is further enhanced and complicated by propagation effects between the source(s) and receiver, including wind speed/direction and temperature variations, transient changes in the boundary of sound-channeling layers, and "wake and turbulence effects (that) modify sound propagation from turbines." Thorne elaborates:

> The Heightened Noise Zones can be small in extent – even for low frequencies – leading to turbine sounds 'disappearing' and 'appearing' in areas spaced only a few metres apart. The concept of Heightened Noise Zone goes a long way to explaining the problem of wind farm noise and its variability on residents. The other factor is the variability of the background sound levels as affected within the Heightened Noise Zones. The turbine sound levels have the effect of lifting the background (when in phase or acting together). The background drops when in the trough between the crest of the Heightened Noise Zone levels. However, this effect can change quite quickly depending on wind direction, temperature conditions and turbine activity.

He reports (Thorne, 2011) that "the effect has been consistently measured at a residence 1,400 to 2,000 meters (roughly three quarters of a mile to a mile and a quarter) downwind from a row of turbines."

2.2 Other variability factors relevant to received sound at homes

2.2.1 Low frequency considerations

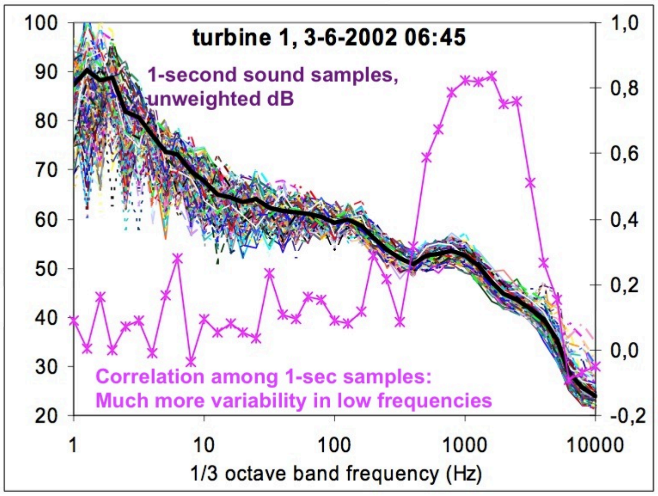
While much public concern has focused on questions about the effects of exposure to infrasound, both research and the experiences of those living near turbines points to *audible* low frequency sound as a key factor in community responses (Cummings, 2012). The predominance of low frequencies in the sound spectrum of wind turbines leads to several important consequences:

- As suggested in the previous section, low frequency sound propagation (especially when sound channeling conditions are present) may increase the zone of audibility of wind turbines well beyond that assumed by many sound models

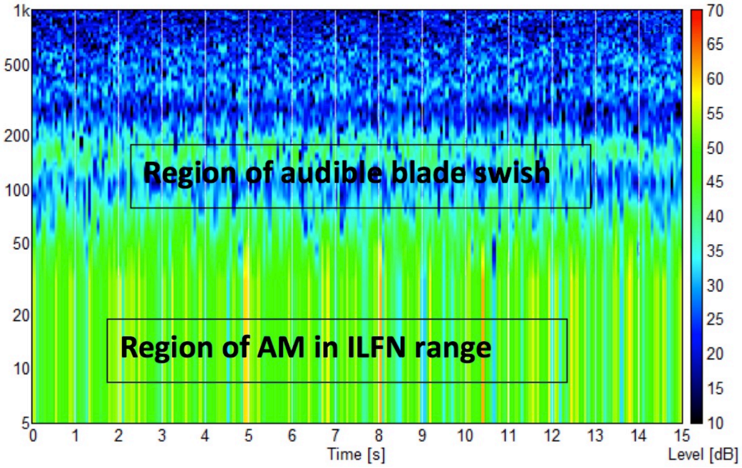
- Low frequency annoyance (and sleep disruption) often occurs at sound levels close to the audibility threshold. This is in part because at lower frequencies, a small decibel difference is perceived as a greater change in sound volume, which also makes the higher variability of low frequency sound content (to be introduced below) more of an factor in turbine sound perception and annoyance.
- Masking assumptions may not apply, since masking occurs between sounds with similar frequency spectrums. In practice, wind in the trees does not mask turbine sounds as reliably as some planning provisions have assumed. Especially at greater distances, as mid-frequency content of turbine sound is absorbed, leaving a sound spectrum even more weighted toward lower frequencies, turbine sounds can be audible at or even slightly below the level of local ambient noise.
- Low frequency sound is more perceptible and annoying when there's less mid- and high-frequency sound content in association with it (Doolan, 2013; Salt et al, 2012). Again, this becomes potentially more problematic at greater distances, and inside homes.
- Several researchers have investigated reports of low-frequency noise inside homes (Nobbs, et al 2012; Bray and James, 2011; Thorne, 2011), which can be more perceptible inside than outside.

One acoustician looking closely at audible low-frequency sound (Doolan, 2013) suggests, "it is not clear what an acceptable level of impact is. Annoyance by low-frequency noise occurs usually at low levels, often in the range of a person's hearing threshold and can vary significantly between individuals." Denmark's new dBA_{lf} standard aims to keep indoor low frequency turbine noise below 20dBA.

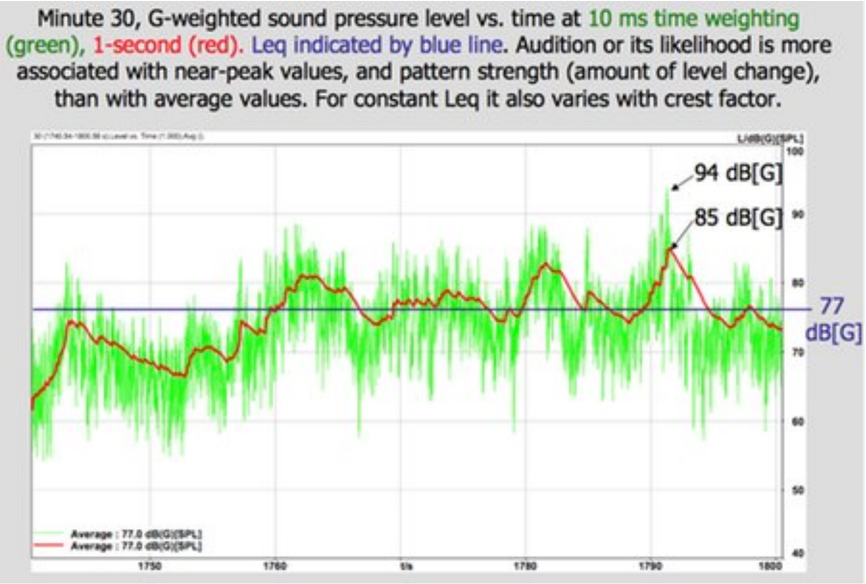
Variability is also a key factor in considering the low-frequency components of wind turbine noise. As illustrated several years ago (van den Berg 2006, Figure V.1, p70; annotation added by current author), turbine sound levels are significantly more variable below about 200Hz:



More recently, an investigation of sound at a home where residents were complaining of low-frequency noise (Bray and James, 2011, additional unpublished data analysis) found a surprising degree of extremely rapid low-frequency amplitude modulation: 20-40dB variation at frequencies up to 50Hz. These pulses occur several times per second, so do not reflect blade-pass effects (the peak levels reported here are near typical perceptual thresholds of about 50dB at 50Hz).



Pursuing this investigation further (Bray and James, 2011), utilizing a filtering technique designed to more closely match the time-response of human hearing, resulting in 10ms time segments, rather than the typical “fast” 1-second sampling or more common 10-second or 1-minute averages reported in many sound studies, they find rapidly fluctuating sound, with peaks approaching typical perceptual thresholds. One minute of data, 1500 feet downwind from an operating turbine, is presented using dBG weighting, which accentuates sound between 10-30Hz, and includes 2-70Hz (thus incorporating both audible low-frequencies and infrasound):


Minute 30, G-weighted sound pressure level vs. time at 10 ms time weighting (green), 1-second (red). Leq indicated by blue line. Audition or its likelihood is more associated with near-peak values, and pattern strength (amount of level change), than with average values. For constant Leq it also varies with crest factor.

The human perceptual threshold is 95-100dBG, with 10dB of individual variability. Thresholds are determined using pure tone signals; the authors suggest that pulses of sound with high crest factors as observed here may be perceived at lower levels than a pure tone. This one-minute sample is one of several louder sections of a 105-minute data set, most of which had more typical SPLs,10-20dB lower than these peaks.

This novel line of study needs to be replicated in more locations and by others, and the filtering technique affirmed by other acousticians; if the extreme pulses noted here are found to be widespread, and if peaks approach perceptual thresholds with some regularity, it could be an important contribution to our understanding of some of the relatively rare, but at times profound, responses reported by wind farm neighbors.

2.2.2 Dominance of turbine sounds in ambient

A somewhat different sort of variability that is also a key contributor to community response is the varying dominance of turbine noise within existing community ambient noise. For many rural residents, a key complaint is that turbine sounds are too often the dominant sound in their otherwise pastoral landscape. This is an especially important factor at night, as illustrated here (van den Berg, 2006, figure IV, p55):

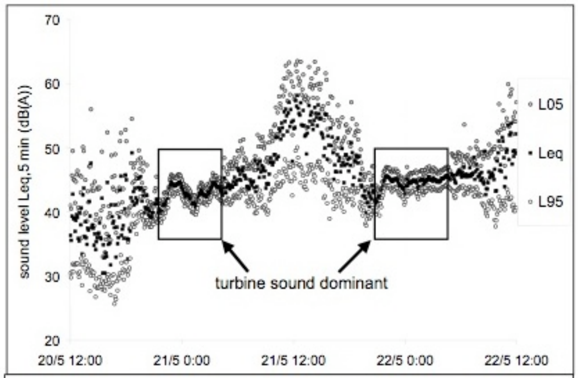


Figure IV.4: 48 hour registration of immission level (L_5, L_{eq} and L_{95}) per 5 minutes at location A; turbines are considered the dominant sound source if L_5-$L_{95} \leq 4$ dB

In this study, which included about a week of measurements, turbine sounds were dominant during 72% of night time hours at 400m, and 38% of night time hours at 1500m (at times dropping to inaudibility at this greater distance).

While regulating and monitoring turbine noise relative to existing ambient conditions presents numerous technical challenges, many states and localities include such criteria in their noise ordinances. Likewise, it's been a standard metric at least since the EPA developed its community noise program in the 1970's; EPA research suggested that as a noise source rises above 5dB over ambient, complaints will become more common, with "widespread complaints" at 10dB over ambient and "vigorous community action" at 20dB. Many of the areas where wind turbine noise has become an issue have been experiencing night time turbine noise of close to, or over, 10dB above ambient.

Relatedly, even moderate turbine noise can be routinely heard out to a half-mile or more. Hessler's Best Practices paper (Hessler 2011, p20-21) notes that the "region between 40 and 35 dBA generally represents the area where in all likelihood project noise would still be readily audible some of the time, if not much of the time, but at a fairly low magnitude….Complete inaudibility does not occur for quite some distance from most projects in quiet areas because of the distinctive, periodic nature of wind turbine noise. The actual distance to the point of inaudibility varies amorphously with atmospheric conditions and is generally much further at night than during the day."

This widespread audibility is reflected on noise maps submitted with wind project sound assessments, which suggest that the 45dB contour occurs anywhere between 1200-3000 feet from turbines, and the 40dB contour extends to 2100-6600 feet from turbines (Cummings, 2012, p12-15). These contours are based on nominal turbine source levels and some enhanced propagation conditions, but do not account for increased turbine noise in turbulent conditions: "When unsettled air or gusty winds interact with the rotor, or the airflow is not perfectly perpendicular to the rotor plane, an increase in turbulence and noise results….There may be times…when project sound levels temporarily increase to levels that are significantly higher than the predicted mean levels" (Hessler, 2009, p32). As Hessler also points out, there are times, probably most of the time, when sound levels are lower than the sound maps predict.

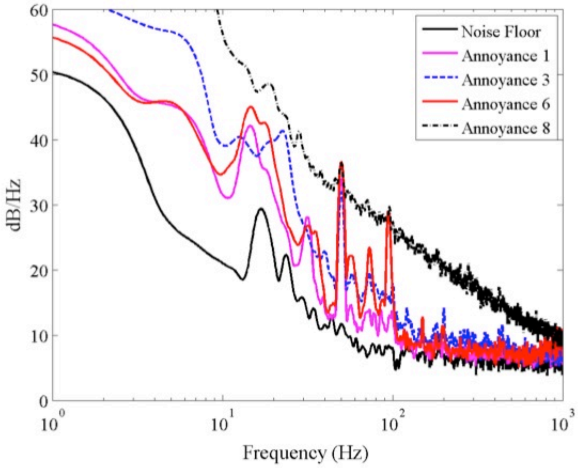
2.2.3 Sound quality

Most of what is presented above relates to the simple measured noise level of turbine sound, the variability of which differs from many other noise sources. Yet perhaps even more difficult for many wind farm neighbors is the varying sound *quality* of turbine noise.

While turbine sound is widely considered to be a gentle "swish," at times including the more discernable pulsation of amplitude modulation, neighbors express particular frustration with several more intrusive types of sound qualities, including knocking, banging, thumping, and sounds widely reported as "like sneakers in a drier," all of which may be related to periods of increased inflow turbulence (perhaps especially directional shear). In addition, noises described as roaring or "like a jet that never lands" may well be associated with enhanced propagation conditions, and sounds described as whining and whistling may occur in association with mechanical issues or blade damage.

If researchers can identify the conditions that give rise to these more intrusive kinds of noise, it's possible that turbine operations could be altered or curtailed during relatively rare and transient times when they are occurring, greatly reducing negative community responses. One recent study (Nobbs, et al 2012) began such an investigation, recording sound in a home at the same time that the resident rated the annoyance triggered by the sounds, on a scale of one to ten.

Interestingly, there was virtually no difference in the dBA sound levels triggering the full range of annoyance, though there was a subtle yet discernable trend line in the dBC levels. Only one sound quality descriptor that triggered high annoyance ("thumping," rated at 8) was associated with significantly higher noise levels. The other descriptors that triggered high annoyance included "pounding," "roaring," and "rumbling." Most striking is that the sound spectrums of many of these sounds appear to be quite distinct (Nobbs et al 2012, Figure 4, p4):

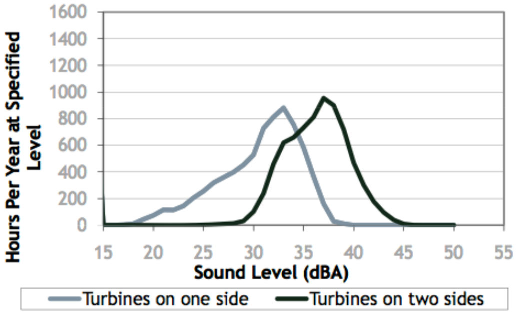


The authors did not attempt to definitively identify the spectral components that relate to each sound quality, but did offer some initial speculations. More research along these lines could bear valuable fruit.

2.3 Proportion of time with peak sound

If the variability of turbine sound is indeed a primary factor driving negative community responses, then the key question is "how often do peak sound conditions occur?" The analysis that follows describes peak sound levels; it is likely that the intrusive sound qualities described above also occur only during a small proportion of operating hours, tough it's unclear whether they are present more or less often than peak dB levels.

There are few publicly available, long-term noise monitoring records from operating wind farms that might give us a sense of how often peak sound levels occur. But a study by Ken Kalisky (Kalisky, 2010, and Kalisky and Duncan, 2010) gives us a clue about generalized patterns of wind farm sound variations, reflecting standard modeling procedures based on manufacturer's rated sound power levels and several contributors to enhanced propagation. Kalisky used meteorological records to model the sound levels likely to be experienced near a wind farm over the course of a year, on an hourly basis. He found that sound levels would be within 5dB of the peak level just 12% of the hours that turbines were operating (Kalisky, 2010, slide 7):



Of course, turbines don't operate all the time. The current author applied an extremely conservative equivalence between operating time and a typical 33% capacity factor, which suggests that peak sound levels would occur about 4% of the hours in a year. This sounds very reassuring; surely anyone should be able to live with peak sound (or transient intrusive sound qualities) for such a small proportion of the time.

Running the numbers, though, produced some surprising results. Four percent of the hours in a year amounts to 350 hours, which could lead to:

- 58 days with peak sound for 6 hours, or
- 116 days (a third of the days in the year) with peak sound for 3 hours, or
- Peak sound occurring every day for 57 minutes

In practice, louder times (and turbulence-driven intrusive sound qualities) are more likely to cluster seasonally, when high winds, shear, or turbulence are more common, making peak conditions more frequent in these seasons.

The surprising bottom line is that turbine neighbors may plausibly consider peak sound conditions occurring 4% of the time to be a chronic or frequent experience. Remember, too, that our 33% correction to Kalisky's findings is extremely conservative, surely an under-estimate of total hours operating. Many of the extra hours will be at less than full power, with lower average sound levels, but when the most variability occurs in turbine sound levels and perhaps sound quality (as seen in the first graph in this paper).

Another important consequence of this thought exercise is that short-term monitoring of turbine noise may be likely to miss the relatively rare times when peak sound levels or more intrusive sound qualities are occurring. Many post-construction noise monitoring programs last for a single night, or for a two or three day period; often, monitoring is timed to get a spot-check of sound levels at a variety of wind speeds or directions. This may well capture typical average sound levels in each condition, but could well miss peaks triggered by inflow turbulence or enhanced propagation, especially if they occur as rarely as suggested here.

3.0 Variability of community responses

Community responses to wind farm noise have received far more attention than many of the factors covered above. In particular, this author has assessed the community response literature and anecdotal reports in detail in several annual reports (Cummings, 2010b; Cummings, 2011; Cummings, 2012) and in presentations for the New England Wind Energy Education Project (Cummings, 2010a), Sandia National Lab and the National Renewable Energy Lab (Cummings, 2013). This section will very briefly review the key factors identified by community response research.

3.1 Place identity

Most wind development still takes place in areas with relatively few (or no) homes within regular earshot, and/or in landscapes dominated by working ranches and large farms. By contrast, most of the towns in which widespread complaints have occurred are in areas where most residents have chosen to settle for the relative peace and serenity of rural or small town living; often there are dozens or hundreds of homes within a half mile or so of turbines.

In the wake of their still best in class community response surveys, the Scandinavian research team (Pedersen et al, 2007) conducted a series of detailed interviews with people exposed to similar noise levels, but who rated their annoyance on the opposite ends of the 5-point scale. The results led to their proposing the concept of "Place Identity" as a key factor in response to turbine noise. Those who see their region as a working landscape, places for economic activity and technological development and experimentation tend to find turbine sound to be an insignificant addition to the local sounds cape, and easy to live with. By contrast, those who see their rural landscape as a tranquil refuge, places for peace and restoration, find turbine sound to be an intrusion, easily getting under their skin. Siting standards could be adjusted in response to such differences.

3.2 Noise sensitivity

Annoyance rates in nearly all communities where surveys have taken place line up remarkably closely with widely accepted noise sensitivity patterns in the population as a whole. Noise sensitivity has been studied since at least the 1970's, and is an innate personality characteristic, not related to auditory acuity and not something that can be controlled or changed. There are many proposed causes and correlations with other personality characteristics, though all studies find a generally consistent proportion of the population exhibiting the three classic categories (Cummings, 2010a). About 15-20% of the population is Noise Sensitive, for whom any audible noise is likely to be attention grabbing and potentially bothersome. By contrast, about 50% of the population is Noise Tolerant, and don't particularly attend to sounds, rarely being perturbed even by loud noise; this is reflected in community surveys, where about half the population reports not being annoyed at all by turbine sound. In between is 30-35% of the population that's classed Moderately Noise Sensitive, who notice most sounds, with reactions being dependent on the type of sound and the situation; this may well be the chunk of the population that does not expresses annoyance at turbine sound unless they are close enough for it to approach or exceed 40-45dB.

3.3 Annoyance and complaint rates

Very few comprehensive community response surveys have taken place that distinguish between responses based on distance and likelihood of hearing turbines. In recent years, most such surveys have been in towns where noise issues already cropped up, leading some to question their broader applicability. Only the classic Scandinavian studies avoid this pitfall, though the results there are not dissimilar to the results of the more recent and disputed surveys. (See Cummings, 2012 for a detailed analysis of the historic body of surveys.)

The three Scandinavian surveys show the common pattern of widespread acceptance of the wind farms in the greater community (Cummings, 2010). Combining data across all three studies, only 8-9% express annoyance about turbine noise (annoyance is marked by ratings of 4 or 5 on a 5-point scale). However, when narrowed to those close enough to actually hear turbines, annoyance rises to 22%; and, in rural areas, 25-45% of those hearing 40dB or dislike the noise. Interestingly, complaint severity in the more noise sensitive communities appear to line up rather closely with the EPA's community response profiles, when sound levels are normalized per EPA recommendations for rural areas and unfamiliar noise sources (Ambrose 2013).

4.0 Discussion

Surprisingly little is known about the effects of inflow turbulence on the sound output of wind turbines. In large part, this is due to the daunting challenges in modeling turbulence and its interactions with turbine blades. A useful start would be to make field measurements of the apparent sound power level of turbines in a variety of topographical and atmospheric conditions. If turbines in flat, open country do indeed operate with more consistent sound output than those in rolling or mixed forest/open landscapes, this would be valuable information in wind farm siting and layout decisions. As noted in Section 2.3 above, it may be necessary to either monitor for extended time periods and in a variety of seasons, or to engage acousticians that can respond quickly when turbulent conditions arise, in order to capture what may be conditions (and noise levels or qualities) that occur during a relatively small proportion of total operating time.

Studies such as the one from Nobbs et al reported in Section 2.2.3 above, which begin to correlate subjective descriptions of sound quality with objective sound spectrum data, could play an important role in understanding some of the triggers of negative community responses. This sort of research could lead to identification of relatively rare or short-lived conditions that cause much of the community annoyance and sleep disruption; if such conditions can be identified (whether by association with atmospheric conditions monitored on site, or with sound spectrum data assessed remotely using automated algorithms), and turbine operations adjusted accordingly, siting within audible proximity of more sensitive rural residents may become less problematic.

There is a pressing need for more comprehensive community response surveys, in a wide variety of types of communities. This would help to clarify whether Place Identity does, in fact, play a role in annoyance rates, and will also better capture community response as a whole. Relying solely on formal complaints to project operators, government authorities, or the press (Hessler and Hessler, 2011; Chapman, 2013) is likely to significantly underestimate the degree of moderate annoyance among nearby residents, thanks to several personality and social factors, including reticence to speak publicly or stand out on topics of controversy within a small town or one's family; this may especially be the case in sparsely populated areas where most landowners are benefiting from wind energy and public complaints are rare. Formal complaints are likely to reflect most (though not all) of the *extreme* annoyance, along with a smaller proportion of moderate annoyance, and some of the slight annoyance. Well-designed surveys in a variety of types of communities would help resolve much of the ambiguity that currently exists about how many people who live within routine earshot of wind farms are actually bothered by turbine noise.

Individual responses to wind farm noise also show a wide range of variability. Severe reactions to turbine noise, including health effects that most research associates with sleep disturbances and stress responses (Cummings, 2012), appear to be relatively rare, perhaps not occurring at much higher rates than seen in response to other new intrusions near one's home (though many other noise intrusions abate at night, and may therefore cause less sleep disruption than can occur near turbines). Meanwhile, though, at least in some communities (and in all the surveys of those living close to turbines), a surprisingly large number of those living with routine audibility of turbine sound report higher levels of annoyance than we typically would expect or hope to find in response to a community noise source. Recall the 22%-45% of those hearing turbines that expressed moderate or higher annoyance, as mentioned above. Public discussion has recently been dominated by health effects concerns, which may be obscuring the more widespread impacts of moderate turbine sound on rural quality of life and sense of place.

Unlike most other community noise source, turbine sounds vary rather dramatically in both dB levels and sound quality. Both host communities and the wind industry should acknowledge this variability, and consider developing siting and operational standards that are flexible enough to allow wind development to move forward without higher levels of negative community response than are considered acceptable for other community noise sources.

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Regarding rural/suburban figures in annotation, added by the current author (Cummings 2010)