Fourth International Meeting on Wind Turbine Noise

Rome Italy 12-14 April 2011

Detection and Quantification of Amplitude Modulation in Wind Turbine Noise

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Abstract

This paper is based on the results of research work carried out by the author through the University of Western Ontario (London, Ontario, Canada) and HGC Engineering (a consultancy based near Toronto, Ontario, Canada).

Some international research into the annoyance associated with wind turbine noise suggests that there may be more annoyance associated with the sound of wind turbines than with other sources of environmental noise, for comparable sound levels. The characteristic 'swish', the amplitude-modulation of the broadband sound, is frequently suggested as one qualitative factor which may increase the annoyance.

In many jurisdictions, including Canada, there is growing attention paid to methods for quantifying the noise impact of wind turbines at noise receptor locations. Accurate measurement of sound levels at typical receptor distances is difficult, particularly in the presence of wind. It is postulated that in the longer term, an efficient means of detecting and quantifying amplitude modulation could be used during such measurements, offering a method by which wind turbine noise could be identified in the presence of wind-induced background sounds.

This presentation describes research into methods of detecting and quantifying the amplitude modulation as part of an acoustic measurement campaign, both near wind turbines and at typical receptor distances, with comparisons between the calculated degree of modulation and wind related phenomena.

Introduction

Annoyance with certain noises is a universal human experience, and many types of sounds can cause annoyance. The World Health Organization states that "noise annoyance is a global phenomenon" [1].

There is a great deal of scholarship available which deals with annoyance associated with noise, and it is clear that a wide variety of factors influence the degree of annoyance associated with a noise [2, 3, 4, 5], in addition to the overall sound level.

Specific to wind turbine noise, much recent scholarship has focussed on the relationship between noise and annoyance. [6] and [7] showed a relationship between noise annoyance related to wind turbine noise and the predicted overall A-weighted sound pressure levels at a location.

However, it appears that wind turbine noise may cause more annoyance than other forms of community noise, for similar sound levels [7]. Although there are likely many reasons for this, and some may not be primarily acoustic in nature, literature suggests that the regular amplitude modulation, or temporal variation of wind turbine noise (the repetitive ‘swish’) may be a significant factor, tending to increase the relative annoyance of wind turbine sounds over other types of sounds [6, 8, 9, 17].

There are well-known difficulties associated with long term noise monitoring in wind plants, such as the problems associated with accurate measurements of noise from wind turbines, in the presence of wind. These problems become more acute as the distance from the turbines to the microphone increases, and the level of the noise drops relative to the background.

With this in mind, the work described here was conceived to develop and investigate a practical approach to the detection and quantification of amplitude modulation of the noise from wind turbines, and to begin to investigate possible correlations between the degree of modulation and various metrics describing the wind.

In the longer term, such a measurement protocol could be used in various ways:

1. The procedure could be used as part of a wind turbine noise measurement program, with modulation used to correlate sound pressure levels measured near a turbine with sound pressure levels remote from the turbine, where the influence of background sound may be more significant. In this way, the influence of background sound could potentially be quantified.

2. Modulation measurements could be used to investigate how much ‘swish’ or ‘thump’ residents are exposed to at existing wind plants, and could potentially be used in future as part of acceptance measurements (acoustic audits) required by regulatory bodies, as a proxy for the potential degree of annoyance.

3. A modulation measurement protocol would provide a practical research tool for future work examining the psychoacoustic annoyance of wind turbine sound, leading to the use of modulation data as a predictor of annoyance.

4. Such measurements would be useful in examining the conditions under which wind turbine amplitude modulation may increase beyond the 5 dB (crosswind) and 2 dB (up and downwind) values demonstrated by [10].

5. Measurements using such a method could form the basis of a semi-permanent monitoring station installed near residences where potential out-of-compliance noise issues have been demonstrated, and be used by a wind farm operator to curtail operations of key wind turbines during periods of increased amplitude modulation, and therefore annoyance.

Amplitude Modulation

In [10], the authors use the term ‘swish’ to describe “the amplitude modulation of broadband aerodynamic blade noise at the blade passing frequency (typically around 1 Hz)”. The authors drew a distinction between this typical ‘swish’, and periods of “increased amplitude modulation (also referred to as 'thumping'), which could be observed at large distance”. This highlights an important idea, that some degree of amplitude modulation is normal in wind turbine noise, and can be observed at nearly

any time near a wind turbine. However, at times the degree of amplitude modulation may increase and become more pronounced.

The degree of amplitude modulation is affected by many factors. In [10], it was found that the amplitude modulation was highest in the crosswind directions, and concluded that modulations of up to 5 dB are expected in the crosswind direction, even far from the turbine. The data seem to suggest swish amplitudes closer to 2 dB in the up- and downwind directions. Analytical modelling described in [11] showed similar results: about 5 dB of modulation in the crosswind directions, and little or no amplitude modulation in the up- and downwind directions.

Measurements of amplitude modulation conducted at various wind farms and described in [12] indicated that while the overall sound of the turbines varied between 3 to 5 dBA, in individual 1/3 octave bands, the sound levels varied by up to 15 dB.

Amplitude Modulation and Wind

Elevated levels of amplitude modulation are thought to be associated with certain wind profile conditions or other changes in wind speed with height [13, 14].

In [13], it is shown that amplitude modulation can occur more clearly at night than during the day, and that elevated levels of amplitude modulation occur in stable atmospheres (generally associated with nighttime hours) where wind speeds can increase dramatically with height.

That different hours of the day have different typical wind shear patterns, and that dramatic differences in typical diurnal wind shear exponents are found during different months of the year has been shown in [15].

Two simple methods for quantifying the wind profile are in common use, the wind shear exponent (1), and the logarithmic height formula (2):

$$v_h = v_{ref}\left(\frac{h}{h_{ref}}\right)^{\alpha} \qquad (1)$$

$$v_h = v_{ref}\left(\frac{\ln\frac{h}{z_0}}{\ln\frac{h_{ref}}{z_0}}\right) \qquad (2)$$

In (1), the wind velocity at height h, (v_h) is related to the wind velocity at a reference height h_{ref}, (v_{ref}) by the ratio of the two heights, and the wind shear exponent α, also termed the Hellmann's exponent. The wind profile is thus quantified by the wind shear exponent.

In (2), z_0 is the roughness length, a factor quantifying the wind profile. The roughness length accounts for the various degrees of friction which can act on moving air at the ground surface. IEC 61400-11 explicitly incorporates the logarithmic height function in the required normalization of site effects to a reference roughness length and height (0.05 and 10 metres, respectively).

Equations (1) and (2) yield similar profiles. For example, Figure 1 illustrates the profile calculated using both equations, with a roughness length of 0.05 metres and a wind shear exponent of 0.16.

In general, these equations can be viewed only as helpful approximations, as there is no physical reason why a simple profile must exist. There are more sophisticated methods for describing the wind profile, but there is difficulty involved with the measurement of various other relevant factors [16].

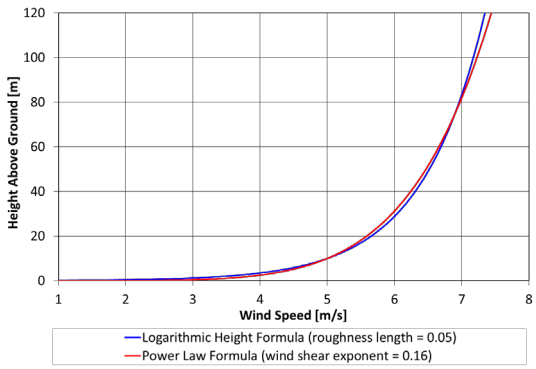

Figure 1: Simple Wind Profile Formulae.

In [15], the wind shear exponent formulation was used, and the work found the largest nighttime wind shear exponents in June, July, August, and September. The smallest nighttime exponents were found in December, January, February, and March.

Frequency Dependance

Various authors have described the spectral make-up of the amplitude modulated sound, and the frequency bands containing most of the modulation. It is clear that variation exists, but that typically, most modulation is in the middle of the audio range [9, 12, 16, 17, 18].

Regulation

There appears to be little regulation or legislation addressing wind turbine noise which explicitly deals with amplitude modulation, although at least one recent standard (New Zealand standard NZS 6808:2010) allows for a sound level penalty if amplitude modulation is judged to be “clearly audible … at a noise sensitive location” and there is a “greater than normal degree of fluctuation as a function of the blade passing frequency”.

Analysis

Various methods have been used in the literature to describe the degree of amplitude modulation present in wind turbine noise. In [18], measurements were described, but no robust metrics for quantification were discussed. The fluctuation strength metric model of Zwicker and Fastl [19] has been used [9, 8]. A different approach was discussed in [20]; a method involving the discretization of a recorded waveform of wind turbine noise into time periods short enough that subsequent processing will show modulation, computing a fast Fourier transform of each time step, then aggregating each set of the resulting frequency-domain data, and finally computing a second Fourier transform from the resulting sets of data.

By computing a spectrum of sound levels rather than of a sound signal (i.e., by computing the second Fourier transform), the authors of [20] calculated a spectrum of the envelope of the original signal, or the original signal’s analytic signal. Another method for the determination of the analytic signal is through the use of the Hilbert

transform. The Hilbert transform ($h(t)$) of a real function $s(t)$, is defined in (3), and can be represented in terms of convolution as (4) [21].

$$h(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} s(\tau)\frac{s(\tau)}{t-\tau}d\tau \qquad (3)$$

$$h(t) = \frac{1}{\pi t} * s(t) \qquad (4)$$

The convolution shown in (4) can be represented by multiplication of the Fourier transform of the various components:

$$H(\omega) = Q(\omega)S(\omega) \qquad (5)$$

where $Q(\omega)$ is the Fourier transform of $\frac{1}{\pi t}$

The analytic signal, $a_s(t)$ is defined as a complex function comprised of the original signal and its Hilbert transform:

$$a_s(t) = s(t) + jh(t) \qquad (6)$$

The envelope ($E_s(t)$) of the original signal can then be found by computing the amplitude or absolute value of the analytic signal:

$$E_s(t) = \sqrt{s^2(t) + h^2(t)} \qquad (7)$$

Any regular harmonic variation in the envelope signal represents modulation of the amplitude of the original signal. Thus, modulation will be shown in a Fourier transform of the envelope signal, as spectral peaks in the frequency domain.

Once spectral modulation has been quantified in this way, the relative magnitude of any modulation can be represented in terms of modulation factor, m, calculated as:

$$m = \frac{2A_1}{A_0} \qquad (8)$$

Where A_1 represents the amplitude of the harmonic component of interest, and A_0 is the constant value at f=0. This same method of quantifying the modulation was used in [20] and is used elsewhere [22].

Measurements

The work described in this paper is based on a series recordings obtained in a large wind plant consisting of many commercial 1.5MW wind turbines with a hub height of nearly 80 metres, with each wind turbine generator spaced irregularly over a large geographic area.

The recordings were made over several weeks: roughly 8 days in November/December, and 31 days May/June. This paper focuses on the November data.

In order to attempt to collect recordings under a wide variety of wind conditions, while still limiting the number of recordings to a manageable amount, one 65 second recording was made every 15 minutes during the measurement periods. Recordings

with post-processing were used to allow experimentation with various analysis strategies, and to simplify the equipment requirements in the field.

The data collected in November consisted of measurements made simultaneously at two areas, one approximately 87 metres from one of the turbines, and one approximately 450 metres from the same turbine. At this second location, the turbine in question was the closest turbine, although others were located within a radius of twice that distance.

Measurements of wind speed were made simultaneously with the acoustic recordings. Wind speed was measured at a height of about 1.5 metres, at a height of 10 metres, and at hub height.

Instrumentation

To minimize wind-related noise induced at the microphone, ACO Pacific 175mm windscreens were used throughout. Anticipated difficulties associated with rain, snow, growth of vegetation, etc. affecting the long term practicality of the horizontal ground board technique described in IEC 61400-11 precluded its use.

The use of two different recording systems was explored, and both were used in acquiring the audio recordings.

The first system consisted of a laptop-based system. A Brüel and Kjær type 4188 1/2” microphone and ACO Pacific model 4212 preamplifier were used, connected via a BNC cable to a PCB 480E09 IEPE signal conditioner, and then to a NI 9201 analog input module connected to the computer. This system is cumbersome and requires AC power, and as such is most suitable for deploying in a house or similar structure. For the November measurements, this system was used at the 450 metre location.

The second system was deployed at the 87 metre location, and was based on a commercial acoustic instrument, and consisted of a PCB type 377B20 1/2” microphone and Larson Davis model PRM831 preamplifier connected via an extension cable to a Larson Davis model 831 instrument. This setup can easily be powered with external DC batteries, and was much more practical.

To collect wind data, an RM Young model 05103-10 mechanical wind sensor was installed on a 10 metre high tower. A battery-operated Campbell Scientific model CR200X data logger located at the base of the tower was used for the data acquisition. Ground level wind speed data was collected with various Davis Instruments equipment. Hub-height wind speed and direction data was obtained from the wind farm operator.

The instrumentation and data collection procedures suffered various interruptions over the course of the work, with the result that some recordings are missing and some of the key meteorological data is missing, limiting the amount of useful data sets.

Analysis Methodology

LabView was used for the analysis.

1. Digital recordings were made of the sound, at a high sample rate.

Modern wind turbines operate at a rotor speed within a fairly narrow band. Depending on the make and model, this may be about 10 to 22 revolutions per

minute, or about 0.17 to 0.37 Hz. The blade passing frequency (BPF) of the three-bladed rotor is therefore between about 0.5 Hz and 1.1 Hz. Since this relatively limited range is the entire range of interest for the modulation rate, it is important that the Fourier transform should provide a fine frequency resolution. The frequency resolution (f_s) of a computed Fourier transform is equal to $1/T$ where T is the length of the data in seconds, a 65 second measurement means that the Fourier transform will result in a frequency resolution of approximately 1/65 = 0.01538 Hz. The selection of 65 seconds is somewhat arbitrary, but it was chosen to still allow at least 60 seconds of useful data after the 1/3 octave band filters had settled.

Figure 2 illustrates a portion of a time signal obtained near a wind turbine using a 48 kHz sample rate, but the signal has been downsampled for illustrative purposes. Note that modulation is clearly present in this signal.

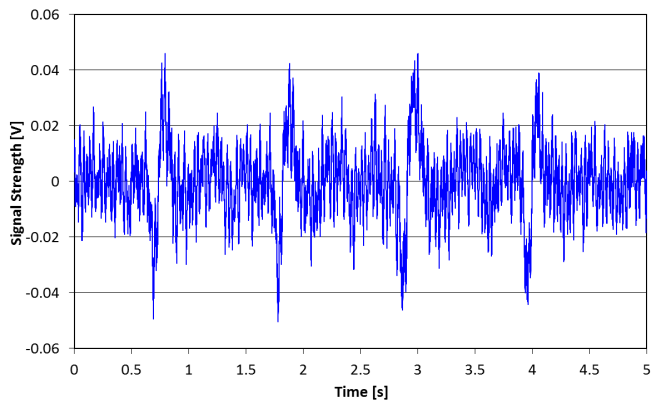

Figure 2: Part of a Time Signal Recorded near a Turbine

2. Each entire digital waveform was filtered into frequency bands one-third of an octave in width, yielding a separate one-third octave band-limited digital time signal for each one-third octave band. The 250 Hz 1/3 octave band signal based on the data shown in Figure 2 is shown in Figure 3. Note the modulation of the amplitude of the signal at roughly 1 Hz which is evident in this frequency band.

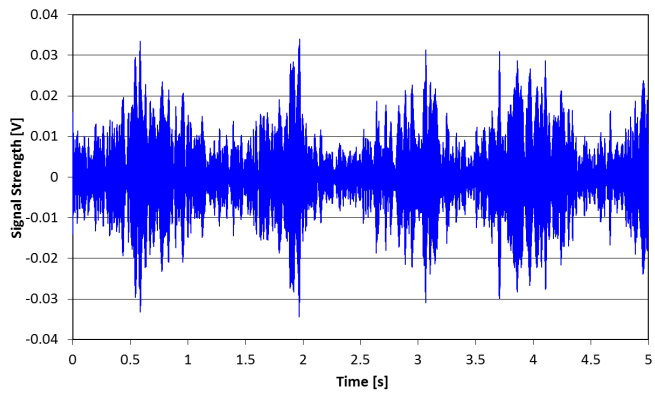

Figure 3: Filtered Time Signal: 250 Hz 1/3 Octave Band

3. The preceding step results in 30 individual signals, one for each 1/3 octave band. Computing a Fourier transform of these signals would yield spectra with content only in the 1/3 octave band of interest. Instead, the analysis requires the computation of the Fourier transform of the signal envelope.

To yield the envelope, the Hilbert transform was applied to each filtered digital time signal. The original filtered signal and the Hilbert transform of the signal are combined to form the analytic signal. The magnitude of this signal is computed to form the signal envelope.

Figure 4 illustrates the filtered time signal of the 1/3 octave band signal shown in Figure 3 (light line; light blue colour), and also the envelope of the signal (heavy line; dark blue).

4. A Fourier transform is computed for each band-limited enveloping signal described in step 4. Peaks in the resulting frequency-domain data illustrate any modulation contained in the original data.

The resulting series of 30 envelope signals (one for each 1/3 octave band) are now passed through a Fourier transform, as implemented by a Discrete Fourier Transform (DFT) algorithm.

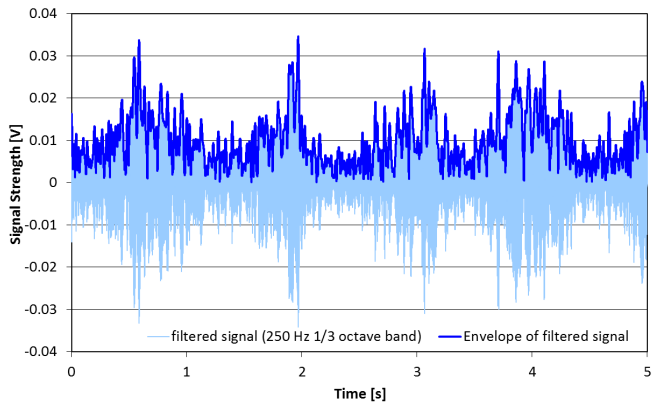

Figure 4: Filtered Time Signal and Envelope Signal

Figure 5 illustrates an example spectrum computed using Fourier analysis. The input signal is the envelope signal shown in Figure 4. For this application, only modulation rates in the range of 0.5 to 1.1 Hz were considered, as this is the blade passing frequency range.

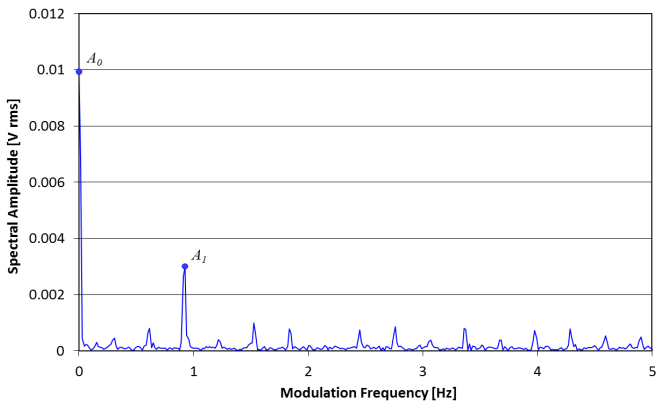

Figure 5: Example Spectrum Computed from Envelope Signal

Note the relatively strong peak at a frequency of slightly under 1 Hz. This peak represents the modulation shown in the earlier figures. Since the modulation is caused by the rotating blades, this modulation frequency corresponds to the BPF, or 3 times the rotor rate.

6. A peak detection scheme was applied to each spectrum to detect any significant peak in the modulation rate range of interest. The frequency of the peaks and the amplitudes of each peak are determined.

Since amplitude modulation in the original signal, associated as it is with the rotation of the wind turbine rotor, must exist at a constant modulation rate in all of the component frequency bands, the dominant peak across each of the 1/3 frequency bands was computed. This value represents the dominant modulation rate in the signal, and to the extent that the turbine noise modulation rate is correctly identified, the corresponding frequency represents the BPF. The rotor rate n can be calculated according to (9), which can be used to acoustically determine the speed of the rotor from the dominant modulation rate.

$$n = \frac{BPF * 60}{t} \qquad (9)$$

7. The amplitude of the dominant peak in each 1/3 octave band spectrum is compared to the value at f=0 to determine the modulation factor. One modulation

factor is thus computed for each fractional octave band. The average of these values represents the average modulation factor for each original time signal.

Each of the peak levels detected as described above is converted into a modulation factor, by dividing twice the value of the peak by the steady component of the same frequency spectrum at f=0, as described in (8). As the dominant modulation rate has already been determined in the preceding step, only those peak values at the known rate (there will be 30, one for each 1/3 octave band) need be converted into modulation factors. The average value across each 1/3 octave band is the average modulation factor for each original recording.

Results

Blade Pass Detection

Figure 6 and Figure 7 illustrate the acoustically-detected blade passing frequencies determined from the recordings made at 87 metres and 450 metres from a turbine. Ignoring the data for which only one of the relevant data sets is available, the two figures indicate that the acoustically detected blade passing frequencies from the location close to the turbine correspond to the blade passing frequencies determined from the operational data, at least to a degree. The correlation coefficient for data shown in Figure 7 (considering only the data for which both data sets are available) is 0.9, indicating good correlation.

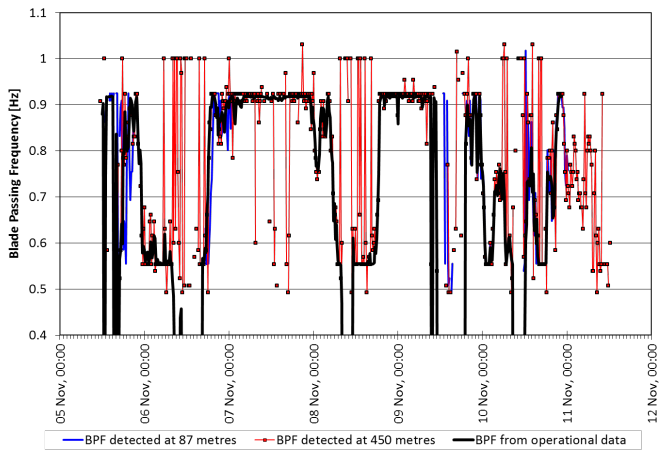

Figure 6: Comparison of Blade Passing Frequencies, November

However, for the data shown in Figure 6, the calculated correlation coefficient is only 0.4 for the location near the turbine, although the last portion (after about 20:00 on November 9), shows much better correlation (about 0.8). Even for the recordings made at 450 metres, the correlation coefficient is about 0.4.

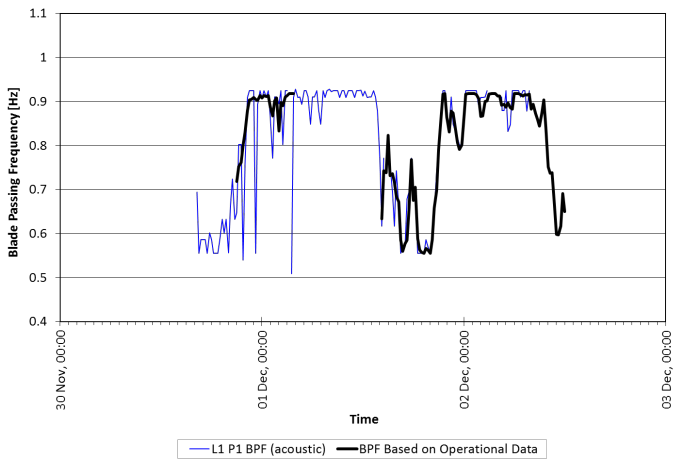

Figure 7: Comparison of Blade Passing Frequencies, December

When some smoothing is applied to the data shown in the figures (by computing a running average

of the 5 data points closest in time), the correlation improves (0.5 overall for the two locations shown in Figure 6).

All in all, it is apparent that the acoustic determination of the BPF functions well in some conditions, but there is scatter, and the correlation with operational data is not perfect.

Examining the data from 450 metres from the turbine (the most complete data set represented in Figure 6), the calculated modulation factor is shown in Figure 8. Smoothing has been applied by computing a linear average of the five values closest in time. Anecdotal and subjective listening tests by the author suggest that recordings from which a high modulation factor is calculated do contain more audible modulation than do recordings from which a low modulation factor is calculated.

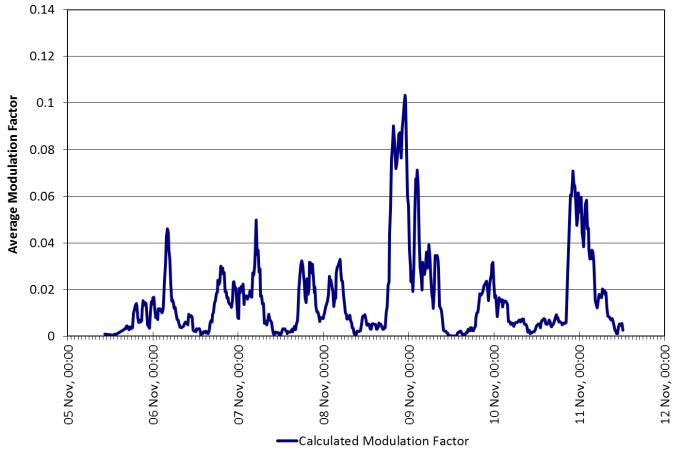

Figure 8: Calculated Average Modulation Factor, (with smoothing)

The modulation factor chart is superimposed on a chart of wind speed data in Figure 9. As expected, the modulation factor does not appear to track the wind speed data. The two midday periods on November 7 and November 8 in the figure are of particular interest. On November 7, the modulation factor is at a minimum around midday, while the wind speed data is peaking, and on November 8, a similar modulation factor minimum is present around midday, but the wind speed data is also very low. To illustrate this lack of correlation another way, the calculated correlation coefficient between the modulation factor and any of the wind speed data sets is 0.2 or less (n=572).

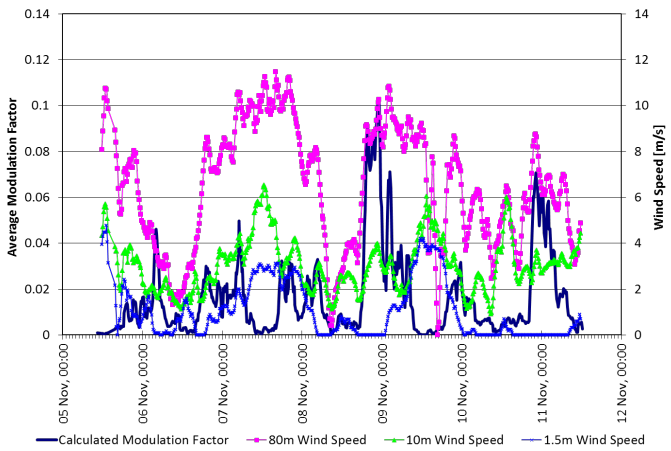

Figure 9: Average Modulation Factor vs. Wind Speed (with smoothing)

By contrast, there is a clear degree of correlation between sound level and wind speed. Figure 10. Correlation coefficients are 0.50 for the 80 metre wind speeds, 0.51 for the 10 metre data, and 0.54 for the ground level data.

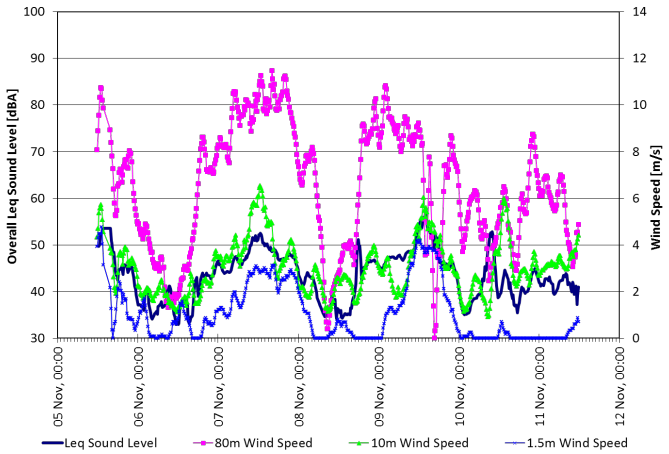

Figure 10: Leq Sound Level vs. Wind Speed (with smoothing)

Figure 11 illustrates the wind shear exponent calculated according to (1) using the hub height and 10 metre height wind speed data. Although far from perfect, the modulation factor appears to track the wind shear exponent far more closely than it did the wind speed data. Nonetheless, there is a great deal of deviation from the trend, as in the preceding figures, and the correlation coefficient is only 0.4.

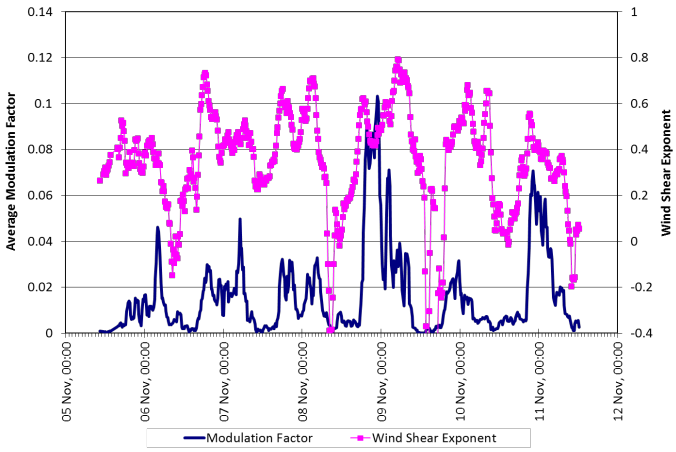

Figure 11: Average Modulation Factor vs Wind Shear Exponent (with smoothing)

The data summarized in Figure 11 is illustrated another way in Figure 12. This figure shows the hypothesized dependence of the average modulation factor on the wind shear exponent by plotting each data pair. The points have been colour coded to roughly illustrate the BPF occurring at the time, as described in the figure legend. Figure 13 illustrates the same data with smoothing applied. These charts clearly suggest that while the correlation between a simple wind shear exponent and the average modulation factor is imperfect, periods with a high average modulation factor tend to be associated with both a high wind shear exponent and with high rotor rates.

There were fewer successful recordings made near the turbine, and there is therefore less useful data, but the average modulation factor and wind shear exponent data from this location is shown in Figure 14 and Figure 15. Again, higher wind shear and higher BPF values tend to be associated with higher average modulation factors, but the relationship is far from perfect.

There are a number of reasons why any specific quantification method for describing the amplitude modulation in wind turbine noise would not track closely the wind shear calculated using any specific metric. One reason is that the modulation is necessarily also affected by the background sound at the microphone (i.e., the sound due to things other than the wind turbine, such as wind-induced vegetation noise) which will mask the wind turbine noise at times and therefore mask any modulation in the signal.

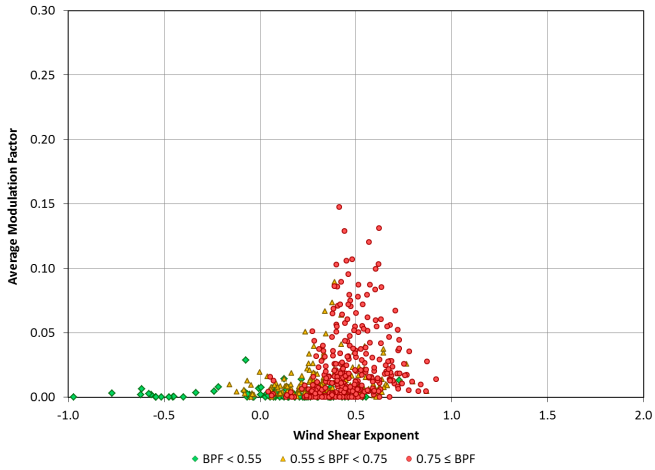

Figure 12: Average Modulation Factor vs. Wind Shear Exponent

Another reason is that the wind direction plays a role: during periods when the wind blows from the turbine to the microphone, the sound level of the turbine and its modulation will be greater relative to the background than when the wind is blowing in the opposite direction. Similarly, other research has shown more modulation in certain directions relative to the nacelle position. Also, in a wind farm, many receptors will have several wind turbines around them, each at a different distance, complicating both the determination of the degree of modulation and the detection of the BPF.

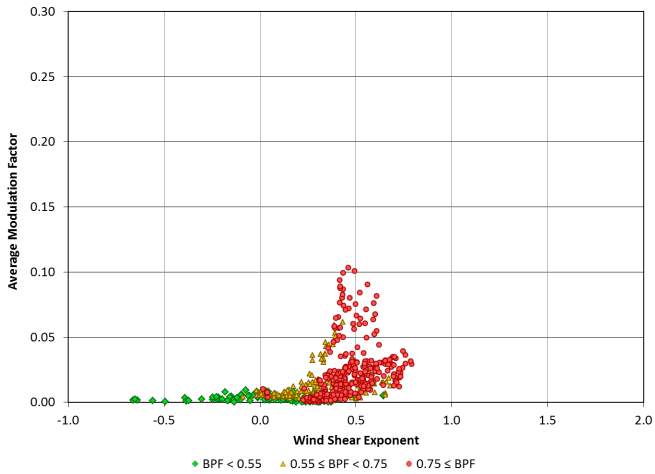

Figure 13: Average Modulation Factor vs. Wind Shear Exponent (with smoothing)

A third reason, and perhaps the most important, is that wind shear is difficult to quantify. The wind shear calculation used in this document is based on two wind speed values, one at a 10 metre height, and another at hub height. In reality, there is no reason why the actual wind profile must follow the idealized profile assumed by (1) or (2), and in fact the wind profile can be affected by turbulence. A more robust wind profile quantification method would make use of many more data points, perhaps obtained by a SODAR or LIDAR system, rather than relying on a small number of mechanical or ultrasound anemometers.

Conclusions

The analysis method described in this paper has had success in correctly identifying the amplitude modulation frequency in wind turbine noise, even at several hundred metres distance, although imperfectly.

The modulation factor metric appears to be effective in quantifying amplitude modulation in wind turbine sound, but more work is needed.

There is a high degree of variability in the calculated modulation factor over time, indicating that the degree of modulation experienced by residents near wind turbines is not constant.

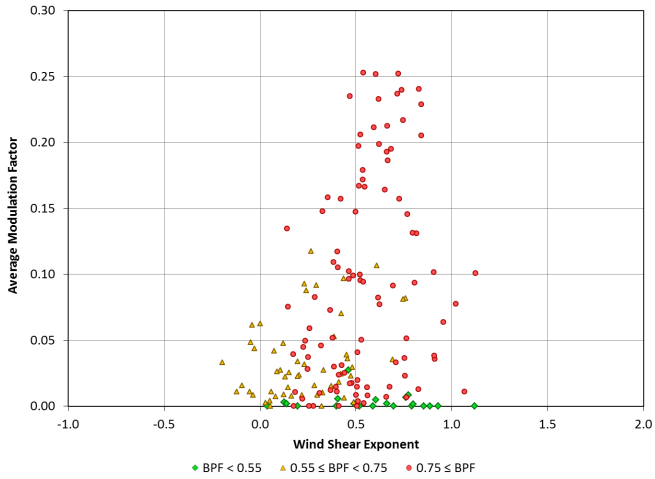

Figure 14: Average Modulation Factor (at 87 metres) vs. Wind Shear Exponent (with smoothing)

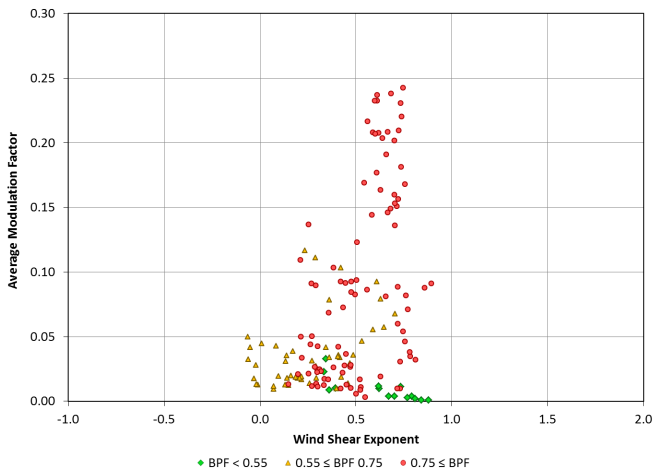

Figure 15: Average Modulation Factor (at 87 metres) vs. Wind Shear Exponent (with smoothing)

When taken as a whole, the data support the idea that increased periods of amplitude modulation occur when the wind profile corresponds to a larger wind shear exponent. However, the wind profile, which in reality is not constrained to describe a logarithmic or exponential profile at all, can be quantified in only rough and approximate terms using the limited data collection available for this study. The data also indicate that a high rotor rate tends to be required for high degrees of modulation, and wind direction clearly affects the degree of modulation at any given location.

Although high rotor revolution rates, and therefore relatively high hub-height wind speeds, were found to be necessary for high degrees of amplitude modulation, the data indicate that the calculated modulation factor does not correlate closely with wind speed alone. This is not surprising, as there is little evidence to suggest that any such correlation between the degree of modulation and the wind speed should exist.

The data also indicate that the L_{EQ} sound level correlates more closely with wind speed than it does with the wind shear exponent.

The modulation factor metric can be implemented into software. It is therefore possible that such a metric could be used in a system capable of automatically detecting high degrees of amplitude modulation, and reducing or curtailing operations during these periods to minimize the potential annoyance to nearby residents. This could be particularly useful for wind farm operators who have legal or regulatory requirements to curtail operations under certain conditions to minimize the noise impact on nearby residences. Literature suggests that since amplitude modulation may be responsible for the increased annoyance, a system which quantifies amplitude modulation, such as the method described in this study, could be used for this purpose.

Recommendations for Future Work

An external validation of the relationship between the average modulation factor and the subjective degree of modulation is required. This would most effectively take the form of a properly controlled listening test where the degree of modulation is rated by participants, and compared to the calculated average modulation factor.

A dose-response relationship between the degree of amplitude modulation in wind turbine noise and the potential for noise annoyance is needed. A controlled listening test could also be designed to provide this information, correlating actual human annoyance with amplitude modulation using the alternate metrics for its quantification, including the average modulation factor.

A more comprehensive investigation of the connection between modulation and wind profile is required. A longer term assessment of amplitude modulation should be undertaken at different sites, in conjunction with more sophisticated methods of quantifying the wind profile or the degree of turbulence arriving at a wind turbine. Such work would ideally utilize SODAR or LIDAR equipment which is capable of highly detailed descriptions of the wind profile.

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