5th International Conference
on
Wind Turbine Noise
Denver 28 – 30 August 2013

Application of Phased Array Techniques for Amplitude Modulation Mitigation

Steven Buck University of Colorado Boulder[1]
E-mail: Steven.Buck@colorado.edu
Scott Palo University of Colorado Boulder[1]
Email: Scott.Palo@colorado.edu
Patrick Moriarty National Renewable Energy Laboratory[2]
Email: Patrick.Moriarty@nrel.gov

Summary

Amplitude modulation (AM) is a periodic variation in the sound pressure level (SPL) of wind turbine noise caused by directivity and convective amplification of aeroacoustic sources. It is perceived as a "swish" and is audible at distances exceeding a kilometer from wind farms. An AM acoustic signal can be characterized by its envelope waveform, which can be found by calculating the root-mean-squared pressure over finite-length sections of acoustic data. Envelope waveforms have been shown to be periodic at the blade passing frequency. This implies that the phase of an AM envelope waveform is tied directly to the rotational position of the turbine rotor. It should therefore be possible to use turbine control mechanisms to force destructive interference between AM envelope waveforms from several turbines, resulting in a minimal net AM level in a chosen direction.

This paper details an AM mitigation technique based on control of the relative phase of turbine rotor positions. A wind farm is viewed as an ad hoc phased-source array that can be controlled to direct minimal AM signals in specified directions, such as toward residential or wildlife regions. The merits of such a method are explored based on experimentally determined AM characteristics and fundamental mathematical analysis. A method is developed for designing a phasing scheme based on turbine locations and the locations of desired "quiet regions". Several simplifying assumptions are involved in the derivation of the algorithm, including sinusoidal envelope waveforms, constant and equal rotor speeds between turbines, and a perfectly planar wind farm. The limitations of the technique are discussed, and provisions for practical implementation are offered. Simulations of nominal system performance based on a representative turbine acoustic field are discussed.

1. Introduction

The noise caused by wind turbines has become increasingly problematic with growth in the wind energy industry. In particular, it has been shown that noise from wind farms is especially irritating to local residents when compared to other types of noise pollution. Pederson et al. [1] showed, based on a sample of 240 residents near wind turbines, that the amount of people claiming to be "highly annoyed" by wind turbine noise was far greater than the results of dose-response relationships that have been established for road traffic noise, aircraft noise, and railway noise. In other words, it is apparent that wind turbine noise is more irritating for a given A-weighted sound pressure level (SPL) than the other three source types. Furthermore, the qualitative descriptions of aerodynamic noise "swishing" and "pulsating" were

[1] University of Colorado, Department of Aerospace Engineering Sciences, 429 UCB, Boulder CO 80303
[2] National Renewable Energy Laboratory, 15013 Denver West Parkway, Denver CO 80401

among the three most frequently used descriptors of irritating characteristics (the other was “whistling”).

“Swish” noise is more technically referred to as amplitude modulation (AM). Physically, AM is a periodic variation in the broadband SPL of wind turbine noise due, at least in large part, to the directivity of trailing edge noise from the blades and due to convective amplification [2]. A semi-empirical acoustic simulation of trailing edge noise from a moving turbine rotor lead to this conclusion and was in good agreement with experimental measurements. There is also evidence showing that differential loading caused by varied wind speed across a rotor may contribute to such a periodic variation [3]. Note that all three cited causes of AM noise levels relate to blade position and are periodic with blade passing frequency (BPF). This periodicity was shown definitively for directivity and convective amplification effects by Oerlemans et al. [2].

Lee et al. [4] conducted a listening test of a smaller sample than Pederson et al. [1] but dealing specifically with the perception of wind turbine AM noise. Acoustic signals over a range of AM levels were generated by mixing a manufactured, representative unmodulated turbine signal with a modulated signal at five different ratios. The results clearly showed that increase in AM level leads to increased mean annoyance rating by the subjects. Zwicker et al. [5] attest that the fluctuation strength—an experimentally determined measurement of human perception—of general modulated broadband noise is highest between modulation frequencies of 1 and 8 Hz. Wind turbine blade passing frequencies are on the order of 1-3 Hz [6], which illustrates why the phenomenon has such an effect on humans. This is not to say that removal of AM from wind turbine noise would eliminate the irritation caused by turbine noise, but these studies suggest that it would be a vast improvement. The difference between the sound of a faucet dripping and the sound of a heavy rain draws an intuitive parallel.

The proposed method of mitigating the AM level is based on vector destructive interference of AM envelope waveforms of individual turbines. Envelope waveforms are the temporal variation in RMS pressure in the acoustic field of a turbine (SPL is a logarithmic measure of RMS pressure). The technique borrows from the established methods and analysis used in phased array signal processing. A wind turbine farm is viewed as an ad hoc source array, with the source-elements being the individual turbines. Whereas established techniques often involve electromagnetic waves or acoustic waves, the turbine farm can be effectively modeled as an array of sources emanating AM envelope waveforms. The phases of these waveforms are controlled by adjustments to the relative phases of rotor azimuths, and a phasing scheme is designed to direct minimal AM levels in chosen directions.

This paper discusses a method of designing a nominal phasing scheme based on the location of turbines in a farm and the locations of desired “quiet regions” where the net AM should be minimized. The implementation of this phasing scheme using turbine control mechanisms is only briefly discussed, but an argument for the feasibility of such implementation is made. Finally, simulation results from a reduced complexity model are used to show the potential of the proposed method using a representative turbine noise field.

2. Preliminary Considerations

2.1 Rotor Azimuth and AM Phase On a fundamental level, the rotor-phasing method of AM mitigation assumes that the phase of an AM envelope waveform can be adjusted by control of the relative phase in rotor azimuth between turbines. This requires that the phase be directly tied to the rotor azimuth. Oerlemans et al. [2] showed this to be true based on both simulation and experimental data. Figure 1 shows the SPL as a function of rotor azimuth for their experimental and simulated acoustic data. Three distinct peaks are apparent in their results, driven by three blade passages. The periodicity of the waveforms in this figure with the blade passing frequency (BPF) and the similarity of waveforms between the three shown periods support the hypothesis that envelope waveform phase is tied directly to rotor azimuth and can be controlled via rotor

azimuth. This hypothesis is also supported logically by the mechanisms that drive AM—directivity and convective amplification—which are a function of rotor azimuth.

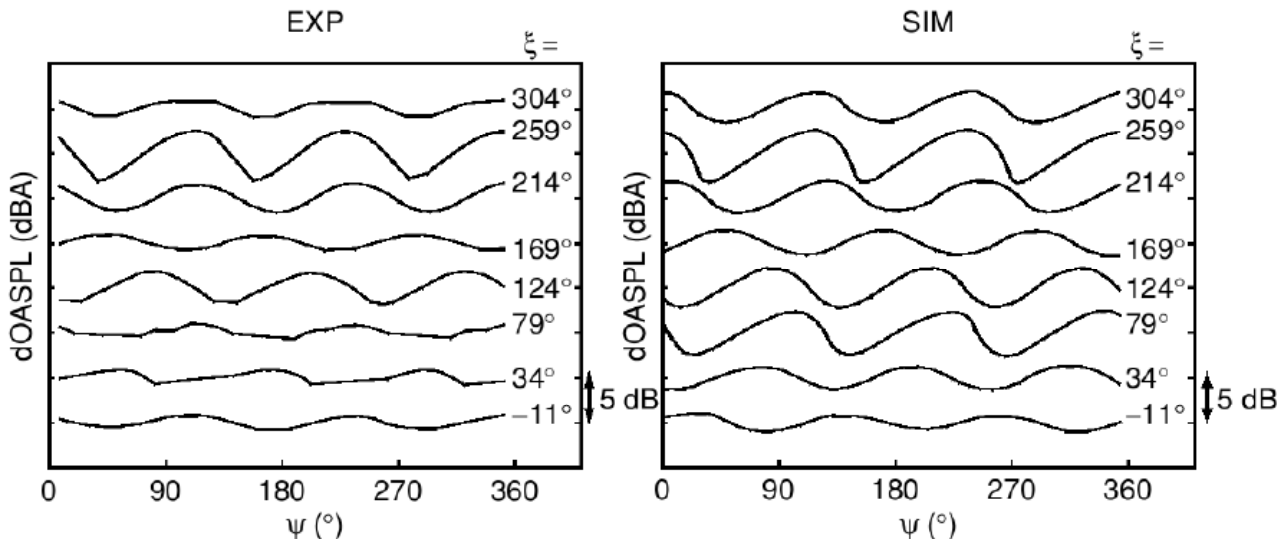

Figure 1: Variation in A-weighted SPL with rotor rotational azimuth Ψ averaged over numerous experimental measurements (left) and corresponding simulation results (right) for 45° increments in azimuth about the turbine tower axis ξ. The azimuth ξ is measured counter clockwise from the downstream direction as viewed from above. *Credit for this figure goes to S. Oerlemans and J. G. Schepers [2].*

2.2 Directionality of Modulation It is shown in Figure 1 that the phase of AM modulation varies with radial direction from the turbine. The most prominent case of this variation shown is a phase difference of approximately 180° with a difference in azimuth angle of 45° about the turbine tower ($\xi = [214°, 169°]$). (Note that azimuth here is not the same as rotor azimuth, as discussed above. "Azimuth" alone refers to the angle with respect to the downstream direction, measured counter clockwise from above, whereas "rotor azimuth" refers to the rotational position of the turbine rotor.) This feature may become problematic depending on the position of the desired quiet regions, particularly as the quiet regions approach the location of the wind farm. A geometrical analysis illustrates this.

Consider the simple case where the AM envelope waveforms of two turbines are to be phased to minimize AM levels at a single location—perhaps a home. A turbine cross-wind spacing of 5 rotor diameters has been shown to yield array losses typically less than 10% [7], so this spacing will be used as representative of a modern wind farm. A turbine rotor diameter of 94 m was studied by Oerlemans et al. [2] and is assumed here. Figure 2 shows the case where a house is located 541 m upwind of the two turbines. Without going into detailed analysis at this time, it is intuitive that the two rotors should be phased to produce approximately 180° phase difference between the two turbines' envelope waveforms at this location. However, if this directionality is not taken into account, an additional 180° phase would result for this particular layout, causing constructive interference of the AM waveforms. That is, if the rotors are phased with the intention of forcing destructive interference at the residence but without consideration of directionality, the phase offset due to the azimuthal dependence of AM—shown in Figure 1, $\xi = [214°, 169°]$—will result in an *additional* 180° phase and constructive interference.

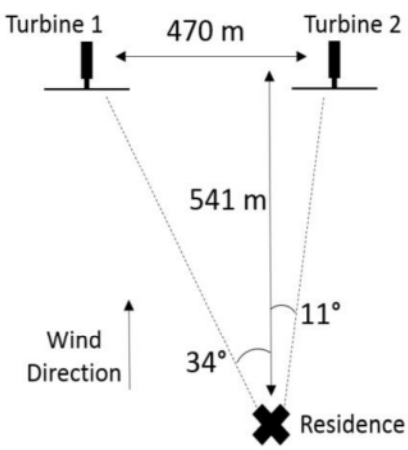

Figure 2: Geometrical layout that causes inadvertent constructive interference of AM envelope waveforms from two wind turbines.

The depth of SPL modulation—peak minus minimum SPL—also varies with azimuth. As is discussed further below, a signal of relatively low modulation depth will be less effective at cancelling modulation of larger depth. A similar geometrical analysis could show that this will play a role in the level of AM envelope waveform cancellation that occurs, for example, between azimuths of 304° and 259°.

The effects of such directionality will become less severe at larger distances from the wind farm, at different azimuths, and for tighter turbine spacing. It is apparent, though, that the directional phasing and variation in modulation depth of AM envelope waveforms must be taken into account in order to effectively design a phasing scheme for a turbine farm.

2.3 Effects of Wind Speed and Spatially Variable Wind Conditions Wind conditions will affect the AM signal that reaches any given point in the acoustic field of a turbine. Consider a quiet region location in the cross-stream direction relative to a turbine. An acoustic signal that would reach this location in still air will propagate to a location downstream due to sound convection. For a constant wind speed of 25 m/s—the cut-out wind speed for the GE 2.5 MW series [8]—and a speed of sound equal to 340 m/s, the angular offset associated with this convection is 4.2° downwind of the cross-stream direction. Figure 1 shows that, in either crosswind direction, this will not cause a significant difference in AM envelope waveform phase or modulation depth. In addition, the initial simulations described in Section 3.2 show that AM levels only increase about 0.2 dB from the minimum level at an angular offset of 4.2°. Based on the above considerations, the effects of wind speed on rotor phasing design are assessed as minimal.

Turbine farms are often expansive and will have variations in wind speed and direction throughout. This affects the presently considered design problem in two ways. The first is that variations in wind direction will result in variation in nacelle yaw angles between turbines and, in turn, the directional differences in AM characteristics described above. Second, variation in wind speed throughout the wind farm may result in variable rotor speeds and, thus, blade passing frequencies, significantly complicating the presently considered method. This second concern is aided by the current trend towards pitch-regulated turbines [7], whose rotor speeds reach a constant level for winds above their rated wind speed. The rotor speed and blade passing frequency will therefore be the same between turbines of the same model when the wind speed is above the rated speed. For the present analysis, small blocks of adjacent turbines are considered. It is assumed that the wind speed and direction do not vary appreciably over the geographical span of the hypothetical turbines, so both of these issues are neglected. In practice, the nacelle yaw azimuth and rotor speeds will need to be taken into account. This may be realizable by implementing a supervisory control algorithm that adaptively selects groups of turbines under similar wind conditions for rotor phasing. However, this topic is beyond the scope of this paper.

2.4 Addition of AM Envelope Waveforms AM envelope waveforms comprise the temporal variation in RMS pressure of a broadband signal. The proposed method of mitigating AM levels is based on destructive interference of AM envelope waveforms. However, RMS pressures from two sources, e.g., two turbines, do not add linearly. This is shown by consideration of the definition of RMS pressure given by Equation 1.

$$P_{RMS} = \left[\frac{1}{T}\int_0^T p^2(t)dt\right]^{1/2} \qquad \text{Eqn. 1}$$

Here, $p(t)$ is the time domain acoustic pressure signal and T is an averaging time window large enough to capture the acoustic signal. For the purposes of AM analysis, T will be taken as 50 ms, which is the period of a 20 Hz signal. The root-mean-squared operator acting on $p(t)$ is non-linear, confirming that RMS pressure from two sources will not be the sum of the RMS pressures resultant from each source.

Now, consider the mean-squared (MS) acoustic pressure—the square of Equation 1, or the pressure variance—resultant from addition of two sources' signals.

$$P_{MS} = \frac{1}{T}\int_0^T [p_1(t) + p_2(t)]^2 dt$$

Expanding the squared term out yields

$$P_{MS} = \frac{1}{T}\int_0^T [{p_1}^2(t) + p_1(t)p_2(t) + {p_2}^2(t)]dt$$

Noise from modern, large turbines is dominated by broadband, aerodynamic noise induced by turbulence in the atmosphere and in the boundary layers surrounding the blades [7]. Because of the stochastic nature of turbulence [9] it is reasonable to assume that the acoustic signals from the two turbines is uncorrelated, so the cross-correlation term $\int_0^T p_1(t)p_2(t)dt$ above is zero. The MS acoustic pressure is then given by Equation 2.

$$P_{MS} = \frac{1}{T}\int_0^T {p_1}^2(t)dt \ + \frac{1}{T}\int_0^T {p_2}^2(t)dt \ = P_{MS,1} + P_{MS,2} \qquad \text{Eqn. 2}$$

The above argument could be extended to more than two turbines. RMS acoustic pressure from multiple sources do not add linearly, but the MS pressure from multiple turbines does add linearly.

Lundmark [10] showed that variation in RMS pressure is primarily sinusoidal at the BPF. The effects of BPF harmonics are ignored for the remainder of this investigation, but are a topic that will be investigated in the future. Consider a sinusoidally varying RMS pressure level from a single turbine. The envelope waveform at a point in the acoustic field can be generally described by the form of Equation 3, where A is the DC value of the RMS pressure, B is the amplitude of the modulation about the DC value, and ω is the blade passing angular frequency ($2\pi BPF$). Finally, φ is a phase term.

$$P_{RMS}(t) = A + Bcos(\omega t + \varphi) \qquad \text{Eqn. 3}$$

The MS acoustic pressure for this signal is the square of Equation 3. Expending the square and invoking the trigonometric identity for the square of a cosine yields the MS acoustic pressure temporal variation described by Equation 4.

$$P_{MS}(t) = \left(A^2 + \frac{B^2}{2}\right) + 2ABcos(\omega t + \varphi) + \frac{B^2}{2}\cos(2\omega t + 2\varphi) \qquad \text{Eqn. 4}$$

Note that the MS pressure variation contains not only a DC and fundamental frequency term, but also a double frequency term. Equation 4 is used in the present analysis to predict the resulting AM levels in the acoustic field of multiple turbines. As was just shown, the MS acoustic signals of two sources add linearly. Consider, for simplicity, a two-turbine case. Furthermore, assume the envelope waveforms described by Eqn. 3 for each turbine are identical at the location being considered, aside from the phase, i.e. $A_1 = A_2 = A$ and $B_1 = B_2 = B$. If the two rotors are phased to cause or 180° offset for the fundamental BPF, e.g. $\varphi_1 = 0$ and $\varphi_2 = 180°$, the resulting, net MS acoustic pressure variation is given by

$$P_{MS}(t) = P_{MS,1}(t) + P_{MS,2}(t) = 2A^2 + B^2[1 + \cos(2\omega t)] = 2A^2 + 2B^2\cos^2(\omega t) \qquad \text{Eqn. 5}$$

Here, it has been included that a phase of 180° negates a sign, and a phase of 360° is equivalent to a phase of 0°. Thus, the 180° rotor phasing causes a cancelation of the fundamental frequency term on the right hand side of Equation 4, but a doubling of the DC term and constructive

interference of the double-frequency term. The resulting RMS pressure temporal variation is described by the square root of Equation 5, given in Equation 6 below.

$$P_{RMS}(t) = \sqrt{2A^2 + B^2[1 + \cos(2\omega t)]} \qquad \text{Eqn. 6}$$

This result is tested by creating two representative AM signals that are modulated 180° out of phase. A BPF of 1 Hz and a modulation depth of 3.5 dB are used. 3.5 dB is approximately the median modulation amplitude depth by Oerlemans et al. [2], though it is not A-weighted here. For generality of this analysis, the temporal variation in P_{RMS} has been normalized by the mean value. This AM signal is generated by modulating a pseudo random number sequence of variance 1 by Equation 7. The two modulated signals are then summed, and P_{RMS} is calculated for 50 ms segments of the simulated data, giving the simulated net signal's envelope waveform. An acoustic sampling rate of 200 kHz is used to increase the number of samples over which P_{RMS} is calculated.

$$P_{RMS}(t) = 1 + 0.2\cos(\omega t + \varphi) \qquad \text{Eqn. 7}$$

A second envelope waveform is generated using Equation 6 with $A = 1$ and $B = 0.2$, which is referred to as the theoretical envelope waveform. The mean value of each envelope waveform is subtracted from the respective waveforms to remove the DC P_{RMS} component, as in [10], and an FFT is taken. The FFT is normalized for the number of samples over which it is calculated and converted to a dB scale that gives the peak SPL minus the minimum SPL. The resulting frequency content for the simulated and theoretical envelope waveforms are given in Figure 2 and show good agreement.

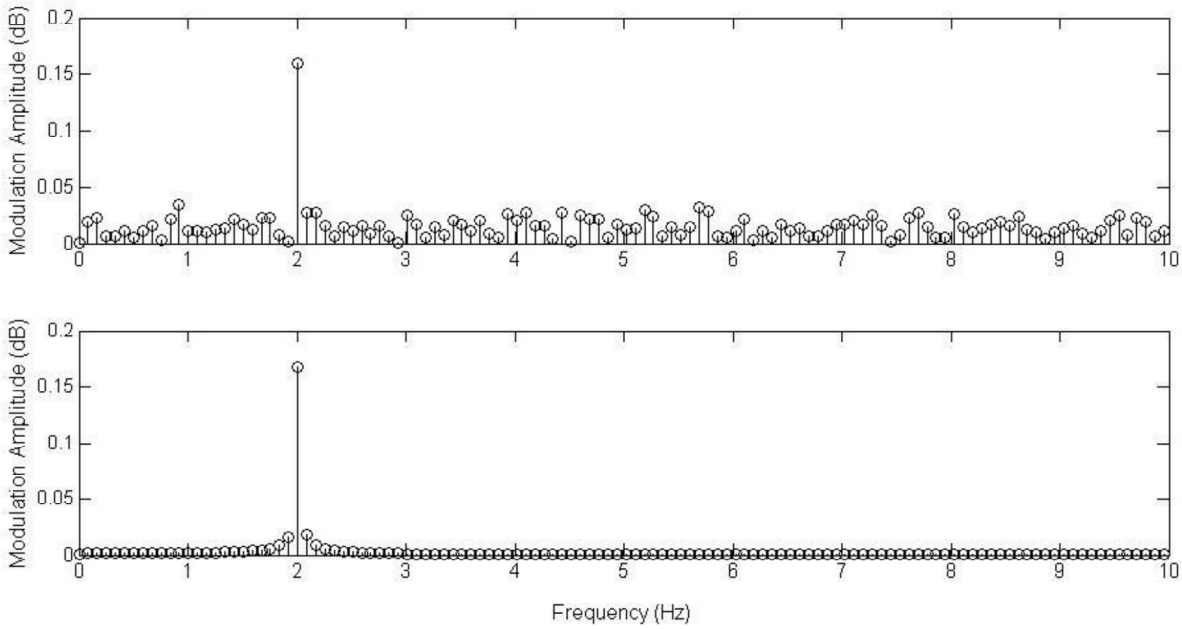

Figure 3: Frequency content of simulated (top) and theoretical (bottom) envelope waveform resultant from the destructive interference of two constituent envelope waveforms of normalized amplitude (mean $P_{RMS} = 1$). A blade passing frequency of 1 Hz and a modulation depth of 3.5 dB were used for the two constituent envelope waveforms.

The noise in the top plot of Figure 3 decreases with increased sampling frequency due to averaging over a higher number of samples. The ramp-like approach to the peak in the bottom plot of Figure 3 is non-physical and becomes tighter with increased frequency resolution.

Figure 4 shows the spectral content of resultant envelope waveforms for constructive interference and destructive interference of two constituent envelope waveforms. Net envelope waveforms

are generated using Equation 4, summed and square-rooted. The same envelope waveform structure described above is used, and again the DC component of the envelope waveforms are removed.

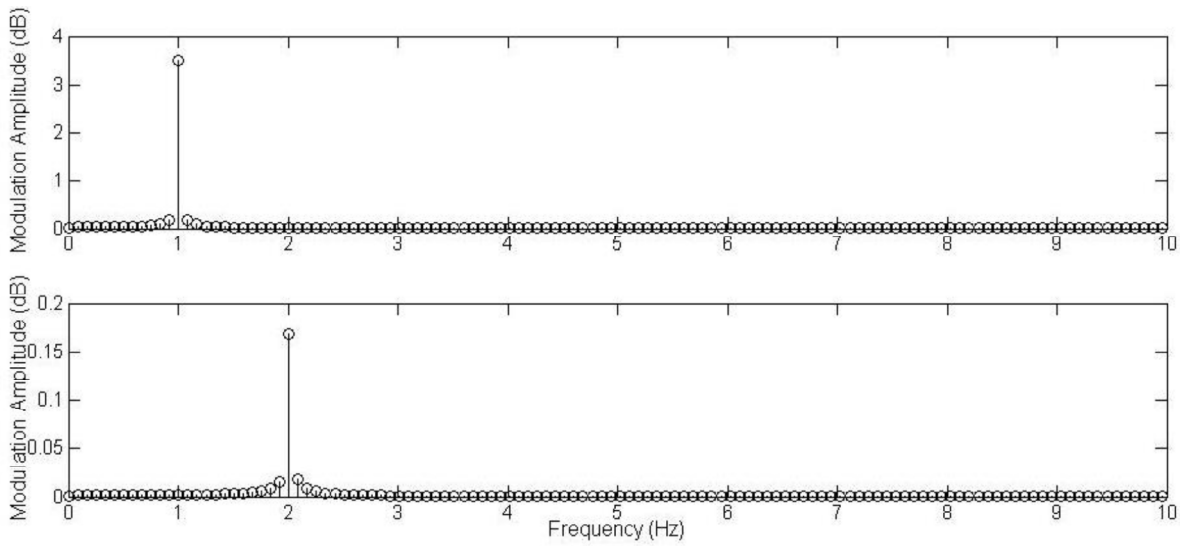

Figure 4: AM envelope waveform frequency content for constructive (top) and destructive (bottom) interference of two constituent envelope waveforms. A blade passing frequency of 1 Hz and a modulation depth of 3.75 dB were used for the two constituent envelope waveforms.

Figure 4 illustrates several characteristics of the non-linear addition of RMS pressure. The first is that the envelope waveform modulation depth resultant from constructive interference of two constituent envelope waveforms is identical to that of the constituent waveforms when measured in dB, as noted by Bowdler [11]. However, the mean SPL is increased by 3 dB (not shown). In the case of destructive interference, the fundamental BPF component of the AM envelope waveform has been completely eliminated, but a component at double the BPF is present a level decreased by 3.33 dB.

The proposed method will therefore greatly reduce the modulation in SPL at locations of destructive interference of envelope waveforms. The residual modulation will, at best, have a component at double the BPL but a significantly reduced modulation depth. If the two envelope waveforms are not of the same modulation depth, Equation 4 shows that the resultant net AM will have a component at the BPF as well as double the BPF. Note that all of the presented analysis assumes that a phasing of 180° is optimal, which is not necessarily the case.

3 Phasing Design and Simulation

3.1 Choice of Turbines A wind farm may be broken into cells of several turbines in order to simplify the design process. This increases the potential for simplifying conditions such as reduced variation in wind conditions throughout a cell and minimal AM directionality effects, as discussed in Section 2.2. To begin the phasing design process, one must chose the turbines to include in a given cell.

Several design trade-offs are present in choosing the size of a cell. The choice depends not only on the wind farm layout, but also the relative location of the desired quiet regions. On one hand, a small cell—say, two adjacent turbines—provides the highest correlation between wind conditions at the two turbine locations. The two turbines then have the highest chance of holding the same nacelle yaw angle and rotor speed. The AM directionality effects will also be minimized. Because of the latter benefit, small cells may be the best choice if a quiet region is relatively close to the wind farm, particularly in the streamwise direction. Though, if directionality effects are properly taken into account, this feature may be circumvented.

Using only two turbines in a cell has the drawback of reduced flexibility. If multiple, widely dispersed quiet regions surround the farm, a two-turbine cell may not effectively reduce AM at all locations. If the cell is designed to direct a null at a single quiet region, the beampattern of the cell—the modulation depth of the net AM envelope waveform throughout the acoustic field—determines the AM level that is present at the remaining quiet regions. Using more than two turbines increases flexibility in this respect. Several mathematical formulations of the multi-turbine, multi-quiet region problem have been considered. However, no analytical or numerical solution has been found at this time, so this is left for future research.

Finally, established array design methods are considered. Several trends are noted in [12] that are taken into account, although modified for this application. First, the beamwidth of the mainlobe in the beampattern of an array is inversely proportional to the number of sensors, or in our case sources, in the array. This argument is made in consideration of a mainlobe being a peak, but it is geometrically similar to the consideration of a mainlobe null. Furthermore, the beamwidth of a linear array is broadest in the direction aligned with the array axis. As we are seeking a broad beamwidth null in order to minimize AM at and near a quiet region, two-turbine cells most closely aligned with the quiet region are used for the simulations below.

3.2 Beampattern for a Single Two-turbine Cell A simulation of the acoustic field of two turbines is conducted. A single quiet region is included, and the turbines are phased such that the two constituent AM envelope waveforms are 180° out of phase at the point specified for the quiet region. Sinusoidal envelope waveforms of equal mean-value and modulation depth are generated by the turbines. Directionality effects are neglected for simplicity. Acoustic signals are attenuated as the inverse of the range from the turbines [13], but frictional losses are neglected. A speed of sound of 340 m/s was used. A blade passing frequency of 1 Hz and modulation depth of 3.5 dB are used. Cylindrical propagation is assumed because the envelope waveform wavelength of 340 m is larger than the turbine dimensions.

Figure 5 shows the layout of the turbines and quiet region used for the simulation, as well as the resulting AM field. The quiet region is set approximately in the cross stream direction and nearly aligned with the two-turbines. Note that due to neglecting the effects of AM directivity, much of the AM field will be different in practice, particularly in the streamwise direction and near the turbines. The difference in azimuth for the quiet region as viewed from the two turbine locations is only 8° in this case, so directionality effects at the quiet region should be minimal (see Figure 1).

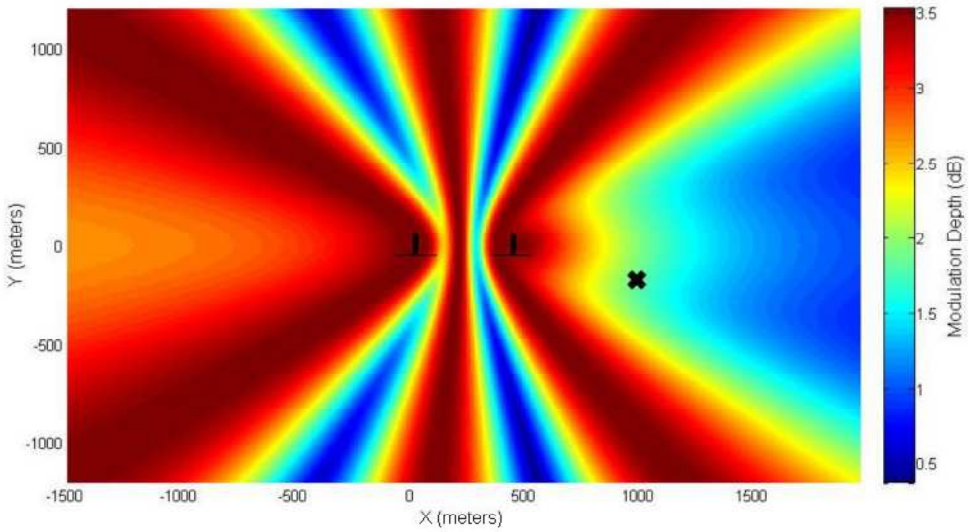

Figure 5: The modulation depth in the acoustic field surrounding two turbines. The “X” denotes the quiet region, where the two constituent envelope waveforms are phased at 180°. Wind is in the positive Y direction.

The resulting modulation depth at the quiet region location is reduced from 3.5 dB to 1.84 dB. The depth was not reduced to 0.17 dB as in Figure 4 because of the difference in range to the quiet region from the two turbines. That is, the signal from the turbine at location (0,0) is approximately half as strong at the quiet region as the signal from the second turbine. This effect is reduced as the quiet region becomes further from the turbines, as can be readily viewed in Figure 5. This illustrates another design trade-off: If the quiet region were located in a direction perpendicular to the line connecting the two turbines, its range from either turbine would be equal. The AM cancellation would then be far more effective at close ranges, but directivity effects would become significant and the beamwidth would be decreased, reducing the area over which the modulation depth is minimized.

4.0 Conclusions

A preliminary investigation had been conducted into the potential for using phased array techniques to mitigate AM of acoustic signals from a wind farm. By forcing destructive interference of the AM envelope waveforms from multiple turbines, the modulation depth of the total signal is significantly reduced. For two identical envelope waveforms phased at 180°, it was shown that a residual modulation remains at double the blade passing frequency but a significantly reduced modulation depth—from 3.5 dB to 0.17 dB in the case presented. The tradeoffs involved in designing a phase scheme for a turbine farm were discussed, and an initial take on design strategy was presented. The modulation depth throughout the acoustic field of two turbines—the beampattern for this ad hoc source array—was shown by simulation, illustrating that range attenuation causes mismatched signal amplitudes and reduces the effectiveness of AM cancellation relatively close to the turbines.

Ultimately, it is concluded that the method has the potential to mitigate effects of AM and reduce annoyance caused by wind turbine noise. However, the intricacies discussed herein show that the phasing design process is not a simple one, and that conditions such as directivity of AM and varied wind conditions throughout a turbine farm present significant challenges to the process.

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