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THE RELEVANCE OF AM MITIGATION

Frits (G.P.) van den Berg

Mundonovo sound research
Baflo, the Netherlands

ABSTRACT

The rhythmic character of wind turbine sound contributes significantly to the annoyance of the sound. In field studies the most often mentioned description refers to this rhythmic character (swishing, lashing, swooshing). A rhythmic variation of wind turbine sound has the frequency at which a blade passes the tower and is produced in two different ways. 'Normal' Amplitude Modulation (NAM) is caused by an increase in sound level when a blade moves towards a listener. 'Other' Amplitude Modulation (OAM) is most likely caused by flow separation at the blade tips. Long term measurements show that AM can be measured for a considerably percentage of time in a wide area around a wind turbine or wind farm. It occurs predominantly in two directions relative to the wind turbine(s): either in or close to the rotor plane or approximately perpendicular to the rotor plane. The two directions agree with what is expected for NAM and OAM, respectively. Although there are numerous studies on the modelling of wind turbine sound, as yet there are no methods to predict the presence or magnitude of OAM sound and hardly any effort to reduce it.

Keywords:
wind turbine, amplitude modulation, annoyance

1. INTRODUCTION

There are numerous studies on the modelling of wind turbine sound, but most of these focus on the (average) sound level of leading and trailing edge sound in relation to wind and blade speed. Little or no attention is paid to modelling other wind turbine sound sources (tip vortex, machinery), or tonal and amplitude modulated (AM) sound. Similarly the measurement of wind turbine sound mostly concerns the average sound level in relation to wind speed.

As yet there are no methods to predict the presence or magnitude of tonal or AM sound. There have been efforts to study the prevalence of AM sound in relation to weather conditions and in practical situations tonal or amplitude modulated sound is measured in reaction to complaints.

Already in 2008 Bowdler gave an overview of the causes of AM [1]. At present there are two dominant explanations for AM of wind turbine sound. AM is the periodic variation of the broadband aerodynamic sound at the blade passing frequency, which is usually about 1 Hz. Oerlemans gives a concise description of both [2]: "…… close to the turbine (within 1-2 rotor diameters), substantial swish (2-6 dB) is perceived in all directions. At larger distance no swish should be perceived in the upwind and downwind directions, but swish amplitudes up to 5 dB are still expected in cross-wind directions. These characteristics can be explained using trailing edge noise directivity and convective amplification, and are referred to as 'normal swish' or 'Normal Amplitude Modulation' (NAM)." As a result of his study he could explain a second mechanism [2]: "However, in some cases periods of increased swish or thumping are reported. This phenomenon, here denoted as 'Other Amplitude Modulation' (OAM), can be characterized by sound level variations of more than 6 dB and/or substantial far field swish in upwind or downwind direction, often accompanied by more low-frequency content in the sound. (….) as long as the flow over the blades is attached, wind shear has practically no effect on amplitude modulation. However, strong wind shear can lead to local stall during the upper part of the revolution [of the rotor]. This can yield noise characteristics

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***Corresponding author**: fvdberg@mundonovo.nl.*

which are very similar to those of OAM." Local stall can also be the result of turbulent vortices as a result of flow over complex topography or in the wake of an upstream turbine.

In a recent paper an Australian research group notes that "Previous studies have not systematically investigated long-term low-frequency AM. Furthermore, although indoor noise is more relevant to annoyance and sleep disturbance than outdoor noise, previous studies have not attempted longterm characterisation and quantification of indoor AM, particularly at long-range distances to a wind farm. Hence, only a few studies have attempted long-term wind farm measurements to date and therefore the prevalence and characteristics of outdoor and indoor AM for a range of setback distances and climates remains unknown." [3]

This paper is an attempt to review the literature with respect to four aspects of AM sound from WTs:

- Measurement and prevalence of AM in field studies
- The audibility according to residents in field studies
- The perception and associated annoyance in lab studies
- Mitigation

2. MEASUREMENT AND PREVALENCE OF AM IN FIELD STUDIES

Vos and Houben [4] measured the prevalence and depth of WT AM near a farm of 2 MW WTs in a flat polder in the Netherlands, during eight nights over a full year between approx. 22 and 03 hours in conditions with sufficient wind for the operation of WTs but not too strong to allow correct measurement and no rain. Over a total of almost nine hours net measurement time, the modulation depth was 1 to 2 dB for 79% of the time, 2-3 dB for 18% of the time and 3-4 dB in 1% of the time. Modulation depth was determined as the ratio of the highest spectral peak (< 2 Hz) and the DC component. Based on literature, it was estimated that a depth of 1 to 2 dB may be audible for experience listeners and 2 dB and more should be audible for most persons.

Larsson and Öhlund [5] performed continuous sound measurements over one year near two wind farm sites in south and north Sweden. Modulation depth was measured similar to Vos and Houben. At the southern site the microphone was about 400 m ESE of one and 300 m ENE of a second WT. AM occurred for 33% of the time and most often downwind of the closest turbine, less often in crosswind. At the northern site AM the microphone was about 1 km NE of a row of 6 WTs in a NW-SE direction with a parallel second row of 6 WTs. Here, AM occurred for 19% of the time, predominantly downwind from the wind farm. At both sites AM was more prevalent when the sun was near or under the horizon, at low turbulence intensities and positive sound speed gradients. When AM was present at the northern site, there was typically about 15 s of distinct AM followed by a minute of steadier sound levels. Simultaneous measurements near a WT and at a distant measurement point showed that enhanced AM (= strong modulation) at the distant point could not be explained by enhanced AM at the nearby point. The authors suggest that this may be an effect of interference between sound from several WTs or of different ray paths of the sound from one turbine.

Paulraj and Välisuo [6] published results from one year of measurements about 1 km almost S from a cluster of 9 WTs in SW Finland. The measurement method proposed by the Amplitude Modulation Working Group of the UK Institute of Acoustics was used to detect AM. On average AM was detected for about 30% of total time, but less often in April and May (9%) and more often in December (46%). At moderate hub height wind speeds (6-13 m/s) AM occurred about 40% of the time. At higher and lower wind speeds this occurred less often (10-30%). Although AM was detected at all wind directions, modulation depth was stronger with SW and W winds (that is: measurement upwind or crosswind relative to the wind farm). However, in their Conclusion the authors state that the microphone was located at the downwind and crosswind directions during these times with respect to the turbines. Figure 1 (taken from their paper) shows the distribution of modulation depths in different frequency bands over all measurement time.

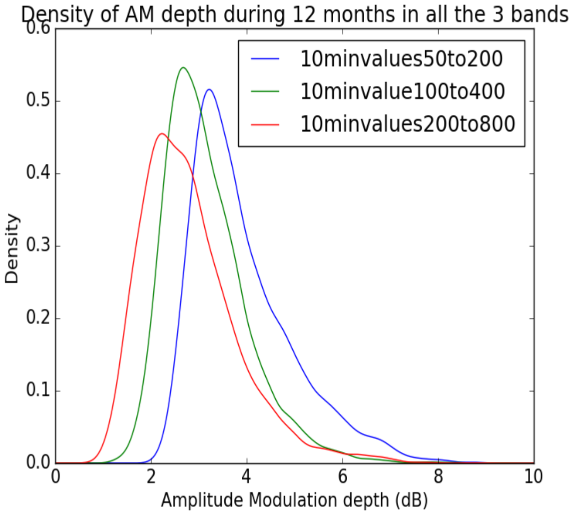

Figure 1. Relative prevalence AM depths over one year in frequency bands 50-200 Hz, 100-400Hz and 200-800Hz (figure from [6]).

Conrady et al. [7] measured AM near a wind farm in northern Sweden. The 22 2 MW WTs were in a sector from W to NW from the measurement position at approximately 1 km from the nearest WT. In each month (October 2016 – May 2017) AM with a depth of at least 0.4 dB occurred for up to 15-30% of the time that the WTs rotated at at least 10 rpm. For an AM depth of 0.6 dB or above this was 4-15%. In spring (April through June) this was less than in winter (October through March). At all times there was a distinct diurnal variation in the prevalence of AM. AM occurred most often with a SW crosswind (modulation depth $\geq$ 0.6 dB for 26% of the time in this condition), somewhat less downwind (12%) and far less upwind or with a NE crosswind (each 2%). There was also an increase of AM prevalence with increasing wind speed gradient (between near-ground and hub height) up to 0.06 s^{-1}, but with a lower prevalence for the highest gradients (> 0.06 s^{-1}).

Sedaghatizadeh et al. [8] investigated noise complaints from 13 residences between 1 and 7.5 km from one of four wind farms. They noted the wind direction at the time of each complaint and concluded that complaints within a distance of 2.5 km to the nearest WT more often occurred at angles from 60° to 85° from the line normal to the chord of the blade root (so 90° corresponds to the blade root chord). In contrast, complaints from distances over 2,5 km more often occurred at angles below 40° from the line normal to the chord of the blade root, which is downwind nearer to the rotor axis. The authors conclude that the complaints are predominantly from residents at downwind locations and local stall at the blades explains the measured and perceived increase in noise far behind wind turbines.

Hansen et al. [9] investigated the prevalence and characteristics of wind farm AM at nine different residences located near a South Australian wind farm. An audible indoor low-frequency tone was found to be amplitude modulated at the blade-pass frequency for 20% of the time up to a distance of 2.4 km. The audible AM occurred for a similar percentage of time for 40 and 85% of the wind farm output power capacity, showing that AM analysis is not restricted to high power output conditions. The number of AM events was reduced at a distance of 3.5 km.

Cand et al. [10] explored the presence of AM at six wind farms to demonstrate the use of the AM detection method of the UK Institute of Acoustics. Their paper only gives limited information per site, but AM prevailed in all cases downwind and somewhat less in the upwind direction from the wind turbines. Modulation depth was often above 3 dB. In some cases AM also occurred at a crosswind and in that case usually with the downward moving blade going towards the measurement position. The wind directions where AM occurred could be in a relatively narrow or a broad range, depending on local conditions. At one site a resident gave annoyance ratings at specific time periods and these corresponded with heightened modulation depths with the WTS upwind.

Okada et al. [11] performed field measurements under various wind conditions at receiver points in a circle around a single wind turbine. The method for assessing AM components was based on the difference between a ‘fast’ and ‘slow’ weighted sound pressure level (‘F-S method’) in 100 ms intervals. The results showed that the magnitude of AM sound becomes lower in the downwind directions and is highest in the direction approximately 60° relative to the front of the nacelle. The magnitudes of AM sound predominantly was above 2 dB at least up to a distance of 200 m where the A-weighted sound pressure levels were lower because of the increased propagation distance.

Kendrick et al. [12] showed that wind induced noise can severely influence measurements to detect AM. They used simulated wind induced microphone noise and synthesized (‘clean’) wind turbine sound including AM to investigate the effect of wind noise on the detection of AM detection (using the AM detection method provided by the Institute of Acoustics [13]). They found that wind noise could substantially affect AM as it introduced substantial error in the estimate of modulation depth. The error increased to 9 dB at true modulation depths of 14 dB. With a method to detect wind induced noise, affected data could be rejected and the error was reduced to less than 1 dB.

3. AUDIBLE AND TEMPORAL CHARACTERISTICS OF WIND TURBINE SOUND

In a study amongst Swedish residents who noticed noise from wind turbines [14], it was concluded that wind turbine noise was most often described as ‘swishing’ (by 33% of those who noticed the sound), ‘whistling’ (26%), ‘pulsating/throbbing’ (20%), and ‘resounding’ (16%). These descriptors were all highly correlated to noise annoyance. Other, less often mentioned, descriptors of sound characteristics (‘low frequency’, ‘scratching/ squeaking’, ‘tonal’, ‘lapping’) were also statistically significantly correlated to noise annoyance, but to a lower degree. ‘Swishing’ had the highest correlation to annoyance due to noise from rotor blades, whereas ‘scratching/ squeaking’ had the highest correlation to annoyance due to noise from the machinery.

In a field study amongst Dutch residents [15] the most common description of wind turbine sound was ‘swishing/lashing’. Two descriptors (‘swishing/lashing’ and ‘rustling’) were mentioned in about the same proportion by those annoyed by WT sound and those not (Fig. 2). The other characteristics were mentioned relatively more often by those annoyed, with the exception of ‘a pure tone’.

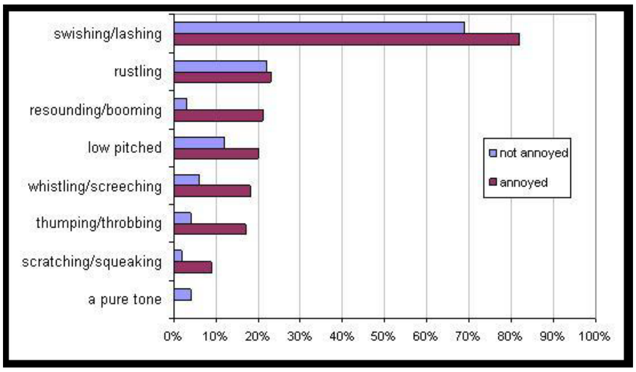

Figure 2. Percentage of residents (annoyed or not by wind turbine sound) who chose predefined wind turbine sound descriptions (figure from [16]).

In a field study amongst Polish residents [17] the most frequent verbal descriptors of noise characteristics were “rustling” (28%), “swishing” (27%) and ‘quiet’ (23%).

In Canadian and Japanese wind turbine noise field studies no question on the sound character was included. The Canadian results [18] showed that WTN annoyance occurred more often during the summer and during evening and night time. In the Japanese study [19] high percentages of the residents were annoyed by WT sound at night.

In an Australian measurement campaign over one year of WT sound at two residences [20] it was concluded that in at least 50% of the diary entries mentioning annoyance, participants described the noise as “swish” or “swoosh.” The annoyance recordings occurred predominantly at night and in nearly morning.

In a survey amongst German residents [21] questionnaires and complaint sheets were distributed and residents could make audio recordings. Annoying WT noise occurred most frequently in the evening and at night. Those annoyed described WT sound as swooshing (76%), rumbling (73%), buzzing (24%) or grumbling (18%). The documented complaints could not be explained by loudness or tonality or impulsivity of the WT sound; the variation of loudness with the frequency of the rotating rotor blades primarily caused complaints. The highest physical modulation depth and psychoacoustic loudness variation or fluctuation strength were found during night time. According to the authors, this AM can explain the annoyance of WT noise, as unexpected and irregular stimuli attract attention and trigger an orientation reaction and an alarm reaction in the case of a danger signal.

Of the respondents who noticed wind turbine noise in the Swedish study [14], 54% stated that they could hear the noise more clearly than usual when the wind was blowing from the turbines towards their dwelling. Only 9% reported that the noise was heard more clearly when the wind was from the opposite direction. The noise was also more clearly noticed when a rather strong wind was blowing (39%), but 18% reported that the noise was more clearly noticed in low wind. For warm summer nights, 26% noticed the noise more clearly than usual. In the Dutch study 69% [15] of the respondents reported that the sound was louder than average when the wind was blowing from the wind turbines toward the dwelling (downwind conditions), vs 5% who reported that it was less loud under those conditions. Also, 67% reported that the sound was louder downwind when the wind was strong vs 18% who reported that it was less loud, and 40% thought the sound was louder at night while 22% thought it was less loud. In the Polish study [17] 40% of all respondents could hear the noise more clearly than usual when the wind was blowing from turbine towards their dwelling, and only 6% when the wind was from the opposite direction. The noise was more clearly heard when a rather strong wind was blowing (47%) and during warm summer nights (31%). However, 10% noticed the noise more clearly in low wind. Unfortunately, in these three studies it is not clear what height the respondents had in mind when referring to the wind because this was not indicated in the question: they may have thought of the near ground wind -which they could feel- or the hub height wind as indicated by the speed of rotation.

As mentioned in the previous section, Sedaghatizadeh et al. [8] investigated noise complaints from 13 residences between 1 and 7.5 km from one of four wind farms (in Australia, the UK, and two in New Zealand). In the complaints the sound was described as ‘a thumping quality’, a ‘ “swish” or “whoosh” noise perception’, a perception of ‘rumble, hum or annoying thumping sound’, and a ‘thumping and pulsing noise’.

Hansen [3] carried out acoustic and meteorological measurements for a one year period at three residences near different wind farms. At two residences the perceived annoyance was recorded. The study showed that AM occurred 2 to 5 times more often in night time compared to daytime. Annoyance from the windfarm was reported most often during night time and early morning and was consistent with the measured AM prevalence. The sound was most often described as a “swish” or “swoosh”. In a further study Hansen et al. investigated the prevalence and characteristics of wind farm AM at nine different residences. An audible indoor low-frequency tone was amplitude modulated at the blade-pass frequency for 20% of the time up to a distance of 2.4 km. Audible indoor AM still occurred for 16% of the time at a distance of 3.5 km, rarely at larger distances (7.6 and 8.8 km). At night-time, audible AM occurred indoors at residences located up to 3.5 km from the wind farm for up to 22% of the time.

The Dutch Association of Wind turbine local Residents (in Dutch: Nederlandse Vereniging Omwonenden Windturbines or NLVOW) receives complaints about wind turbines on their website [22]. Within about 8.5 months 268 complaints were registered from 193 different IP-addresses; 33% had two or more complaints. These complaints have been analyzed with regard to the descriptions of wind turbine sound. In 50 of these registrations there was a remark on the character of the sound. These can be classified in three categories: A) low frequency or tonal character; B) short term variation in loudness and/or related to rotation; C) other or not clear. The descriptions can be puzzling: does the “sound as if airplanes always take off” refer to the spectral content or a periodic variation? What is a “raging sound”? But most refer more clearly to the character of the sound: “33x per min. a swish sound from the wind turbines in the low humming sound” or “an annoying low frequency sound”. The 50 descriptions are classified in Tab. 1 and this shows that in most cases a tonal or temporal character is mentioned as the annoying feature of the sound.

Table 1. Classification of Dutch wind turbine noise descriptions as tonal or temporal variations or other.

Low frequency/ tonal	**Rythmic/turning /variation**	**Other / unclear**
8		
	2	
19	**11**	**11**

4. PERCEPTION AND ASSOCIATED ANNOYANCE IN LAB STUDIES

In this section, the text is mainly based on the study abstracts.

Ioannidou et al. [23] used realistic stimuli synthesized to be able to systematically vary AM depth, frequency and type (NAM or OAM) as determined from real on-site recordings. Listening tests with original and synthesized stimuli showed that a reduction in mean AM depth led to a significant decrease in annoyance. It was concluded that for NAM, at a given overall level, AM depth is the most crucial parameter for annoyance from wind turbine sound.

Yoon et al. [24] performed two experiments. In the first, 12 participants determined the detection thresholds of six target sounds in the presence of background noise. In the second experiment, 12 participants matched the loudness of modified sounds without amplitude modulation to that of target sounds with amplitude modulation. The results showed that: 1) the detection threshold was lowered as the modulation depth increased, 2) sounds with amplitude modulation had higher subjective loudness than those without amplitude modulation.

Yokoyama et al. [25] performed auditory experiments by using a facility that was capable of reproducing low frequency sounds including infrasound. In the first experiment, the fluctuation sensation caused by AM sounds was examined with recorded wind turbine sounds limited in steps by low-pass filtering with cut-off frequencies of 20 to 1000 Hz. As a result, it was found that the perception of four AM sounds (‘audible/sensible’) was reduced or absent at frequencies below 50-80 Hz. A fluctuation sensation was felt at frequencies above about 125 Hz. In the second experiment, the noisiness of AM sounds was examined by comparing a standard synthesized sound at 35 or 45 dBA and spectrally similar to wind turbine sound to the same sound with AM at various modulation depths. A fluctuating sensation was perceived as soon as the AM depth exceeded 2 dB. To find the same perception of the noisiness of the sound, the AM sound was adjusted in level to the standard sound. A higher modulation depth corresponded to a lower level of the AM sound. A modulation depth ($D_{\mathrm{AM}} = \Delta L_{\mathrm{A},5} - \Delta L_{\mathrm{A},95}$) of about 7 dB corresponded to a level difference of about 2 dB (± 2 dB s.d.).

Lee et al. [26] performed a listening test to investigate the relationship between annoyance and the amplitude modulation of wind turbine noise. Sound samples were recorded at a 1.5 MW wind turbine. The stimuli for the listening tests were created by reducing the modulation depth spectrum of the sound samples. 30 participants were involved in the listening tests. The results of the listening tests showed that equivalent sound level and amplitude modulation both significantly contribute to wind turbine noise annoyance.

Von Hünerbein et al. [27] did extensive auditory experiments to assess the added effect of AM on annoyance. The stimuli presented were at 30, 35 and 40 dB(A) and modulation depths of 0 (the reference stimulus) to 12 dB. Modulation depth here was the difference between the maximum and minimum 100 ms L_{Aeq} levels. The effect of AM -the added annoyance- was expressed as the level difference between the modulated sound and the level-adjusted reference sound. The effect increased consistently with modulation depth. At modulation depths above 1 dB the effect increased slightly with modulation depth, but not significantly, apparently because of the small number of participants. The adjustment was higher (on average 3.5 dB) for the 30 dB(A) than was found for the 40 dB(A) test sound (on average 1.7 dB). Further tests at two additional levels of 45 dB(A) and 25 dB(A) conformed this trend.

B. Schäffer et al. [28] studied annoyance reactions to different broadband sounds (realistic outdoor wind turbine sound, LF and pink noise) at 40 dBA in a controlled laboratory listening experiment. The design of the experiment and the sounds used, allowed to separate the effects of three acoustical characteristics on annoyance, *viz.* spectral shape, depth of periodic amplitude modulation (AM), and occurrence (or absence) of random AM. Fifty-two participants rated their annoyance with the sounds. Annoyance increased with increasing energy content in the low-frequency range as well as with depth of periodic AM, and was higher in situations with random AM than without. Similar annoyance changes would be evoked by sound pressure level changes of up to 8 dB.

Apart from wind turbine noise research, Heynckes et al. [29] investigated the effect of 'acoustic rhythms' on listeners' detection performance and reaction times (it did not concern annoyance). Narrowband quintets (interval with upper frequency = 1.5 times lower frequency) were centered around carrier frequencies of 200 Hz, 1100 Hz, or 3100 Hz and presented at rates between 1–8 Hz. Rhythmic sequences were compared to control conditions (periodicity reduced or absent). It was found that (1) the slowest rate (1 Hz) led to the largest behavioral effect on sensitivity; (2) this sensitivity improvement is carrier-dependent, such that the largest improvement is observed for low-frequency (200 Hz) carriers compared to 1100 Hz and 3100 Hz carriers; (3) the predictive value of a temporal cue and that of a temporal rhythm similarly affect perceptual sensitivity: both the cue and the rhythm induce confident temporal expectancies in contrast to an aperiodic rhythm; (4) periodic stimulation reduces reaction times compared to aperiodic stimulation, both at perceptual threshold as well as above threshold. The authors conclude that the results are consistent with the hypothesis that periodicity leads to optimized predictions and processing of forthcoming input and thus to behavioral benefits. However, when applied to a sound with negative associations, this means that a periodic (AM) sound is easier recognized and 'prepares' a person for each next peak. According to the authors, several neural mechanisms may underlie their findings, including the entrainment of oscillatory activity of neural populations.

5. MITIGATION

Only two studies of AM mitigation could be identified. Cand and Bullmore [30] used two methods to reduce AM in wind turbine sound through modification of the turbines' blades and/or operational characteristics. These modifications were aimed at reducing OAM by reducing the occurrence of transient blade stall. One was with a 'kit' (no further description given) installed on the rotor blades of 'more than 5 turbines' (> 2MW) to modify the air flow on the blades. The other was a change in pitch angle of the blades of 5 wind turbines (>2 MW) for wind speeds where OAM had been detected. The results at the first site show a clear reduction in the prevalence of AM, predominantly occurring at hub height wind speeds of 7 – 10 m/s and at the second site a reduction in modulation depth (to about 1.5 dB), predominantly at wind speeds of 4 – 6 m/s.

The second study, by Mackowski and Carolus, proposed to mitigate the effects of NAM by changing the blade pitch angle in order to direct the impact of NAM away from a receiver.

To reduce NAM, the only feasible way seems to be to reduce the speed of the blades. This will reduce the Doppler amplification and hence the level of sound radiated in the forward direction of the blade. In situations with a clearly dominant wind direction there will also be a dominant direction of a wind turbine. In such a situation the wind turbine can be erected at a location where there is no neighbouring receiver in the rotor plane.

The reduction of OAM needs other solutions. Perhaps it may help to lower rotational speed, but only if this reduces the occurrence of local stall. A better solution in the case of strong wind gradients is to prevent local stall by changing the angle of attack; Cand and Bullmore have demonstrated this works [30]. Although no details were given, it is likely that they applied a constant change in pitch angle in conditions with a high prevalence of OAM. The best solution may be to adapt the pitch angle. In helicopter operation this is standard practice, in fact to address the same problem: changes in angle of attack due to differences in incoming air speed on the blades (the incoming air at the forward going blade is equal to blade speed plus helicopter ground speed, at the backward going blade it is blade speed minus ground speed). For example, a Chinook CH-47D/F has two 60 feet (18 m) diameter rotors that rotate at 225 rpm driven by 2.8 MW engines. Of course, helicopter and wind turbine dynamics and their operational conditions are very different. Oerlemans suggested another way to mitigate AM [32], based on reducing stall noise by using vortex generators. These could be thin vanes on and perpendicular to the blade surface meant to delay flow separation.

6. CONCLUSION

Measurements show that AM modulation is not a rare phenomenon and can be heard and measured at large distances (at least several kilometers) from a wind turbine of wind farm. Results show that audible AM can be measured for 10-30% of the time, most often after sunset. They also show that AM is most prevalent either sideways (in the rotor plane) or downwind (direction close to the normal on the blade surface near tip). This is consistent with the two causes of AM. One cause is the forward (towards leading blade edge) directivity of trailing edge sound and the Doppler amplification due to the high speed of the blade tip (approximately Mach 0.25): this 'normal' AM (NAM) is always audible near a wind turbine and further away in the plane of the rotor. The most likely second cause is a difference in wind speed over the rotor plane which causes changes in angle of attack on the blades. For larger angles locally the flow can separate from a blade (local stall) and this is associated with a higher sound production. This 'other' AM (OAM) is predominantly radiated perpendicular to the blade surface (which is not quite perpendicular to the rotor plane). A number of studies show that amplitude modulation of wind turbine sound contributes significantly to the annoyance related to wind farms. Descriptions of the sound and complaints about wind turbine sound often refer to the periodic or rhythmic variations in loudness or sound level (and also to a low frequency or tonal content). Laboratory studies show that AM leads to added annoyance at modulations depths of 1.5-2 dB and it increases for higher modulation depths.

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