Published in Institute of Acoustics Bulletin Vol 33 no 4

Amplitude Modulation of Wind Turbine Noise.

A Review of the Evidence

Dick Bowdler

New Acoustics, 34 Old Mill Road Duntocher, Clydebank, G81 6BX, UK
dick@newacoustics.co.uk

1. Introduction

Many of the complaints in the UK relating to wind farm noise appear to be due to the amplitude modulation (AM) of the aerodynamic noise from the blades, sometimes referred to as "swish" or "thump". The mechanism of this noise is not known though various possible reasons have been put forward. Although the prevalence of complaints about AM is relatively small it is not clear whether this is because it does not occur often or whether it is because housing is not in the right place to observe it. Furthermore the fact that the mechanism is unknown means that it is not possible to predict when it will occur.

A report by Salford University commissioned by BERR[1] concluded that "the incidence of AM and the number of people affected is probably too small at present to make a compelling case for further research funding in preference to other types of noise which affect many more people." Consequently BERR decided not to fund further research. However, the opinion of the Noise Working Group that advised BERR (then the DTI) was that, although the incidence was small it might become greater with larger turbines and "a greater understanding of the effects and causes relating to AM [is] required to ensure that this phenomenon can be managed." Specifically the first stage objective was to "Identify up to 10 potential sites which could be used to carry out objective noise measurements"[2]. The government decided not to accept the groups advice.

This paper does not pretend to present any substantial new evidence but I have tried to review the current situation in order to provide some direction for future work.

Where "upwind" and "downwind" are insufficient descriptions, references to observer positions in this paper are made by compass bearings on the assumption that the wind direction is from the North. The turbine is assumed to rotate clockwise as viewed from upwind. The phrase "axis of the turbine" in this context means on the north-south line passing through the centre of the turbine.

2. Early References

There are a number of references in the mid-90s to blade swish but largely to confirm the frequencies at which it occurs. J Jakobsen and Pedersen[3] showed that modulation occurs most prominently in the octave band frequency range 500Hz to 2kHZ. Dunbabin[4] in 1997 also showed that blade swish occurred mainly in the three octave bands 500, 1k and 2kHz. ETSU-R-

97[5] says that blade swish is centred around 800 to 1000Hz and suggested it might be due to directivity of trailing edge noise.

Jiggins[6] examined AM from several turbines in some detail. He concludes several points of interest. The time between peaks suggests only a vague relationship with the rotational speed of the turbine and indicates that one positive peak for each blade passage is not typical, especially as observer distance increases. The different frequency bands are not modulated in phase. He seems to be the first to report "beating" as a possible interaction of noise between two or more turbines.

A report for ETSU in the UK in 1999 concludes that "The analysis suggests that the experimentally observed modulation is due to a combination of tower shadow effects as the blades pass the tower plus the preferential radiation of noise into some directions in preference to others."[7] Note that this is a tower shadowing effect as described in the next section not an interaction of the tower and the blades which was sometimes thought to be a cause at that time.

3. Oerlemans

In papers to the Conference Wind Turbine Noise 2005 in Berlin[8] and Wind Turbine Noise 2007 in Lyon[9] Oerlemans describes the noise sources close to a turbine. The paper demonstrates that the aerodynamic noise from a turbine comes from near the end of the blade and that it has the greatest amplitude, when viewed from upwind, as the blade passes the horizontal position in a downward direction so giving the well known "swish". As the authors say, this is due to the directional nature of the sound from the blades that means it predominantly radiates forward of the blade as it moves and about 45 degrees to the upwind direction. Oerlemans also confirms that the sound radiates in the same manner downwind[10]. The diagram below shows the direction of the predominant noise generation as the blade passes the horizontal on the way down.

Fig 1

The veracity of these findings can be checked subjectively on site near to a wind turbine though care needs to be taken because the blades of a typical medium sized turbine will rotate about 20 degrees in the time that the sound travels 50m from source to observer. Upwind and downwind on the axis of the turbine the swish is heard as described by Oerlemans and Lopez on the downstroke as the blade passes the horizontal. The same is the case in the north-west and south-west. On the east and west, underneath the blades, the swish reduces and, with some turbines, is almost undetectable. To the north-east the swish is heard as the blade approaches the lowest point of its travel, that is to say as it approaches the observer. The most conclusive demonstration occurs in the south-east where the swish appears near the lowest point of travel but is split in two by the shadowing of the tower. The effect is that the swish starts to rise, is suddenly cut off and suddenly re-appears as it is receding. Oerlemans has confirmed that these observations are generally consistent with his research[11].

Hayes of Hayes McKenzie Partnership says, in a commentary of Oerlemans findings[12], “Movement of the observer up to the same height as the hub of the turbine should result in the noise being more evenly distributed around the described disk of the rotor. . . . . However, a similar effect can be obtained through movement away from a wind turbine which reduces the modulation of the noise. In other words the blade swish near to the turbines is a feature of the observers position relative to the turbine and will disappear with distance from the turbine.” This would certainly seem to be the case upwind or downwind but closer inspection of the mechanism suggests that it will not necessarily be the case in other directions.

Fig 2

Fig 2 shows a view of a turbine from above with the direction of sound radiating from the blade when it reaches the top of its trajectory. The sound is radiated to the north west and the south west. Similarly when the blade reaches the bottom of its trajectory sound is radiated to the north east and south east. It is possible that the noise of the turbine could appear as a swish in these four directions over a significant distance. These directions all have different propagation characteristics. To the north east and north west the propagation is upwind and so will probably be attenuated fairly rapidly with distance. That leaves two possibilities for the swish to be propagated over longer distances. The first is propagation to the south west as each blade passes the top of its trajectory. The second is propagation to the south east as each blade passes the bottom of its trajectory. This latter is potentially more interesting as it would also incorporate the shadow effect of the tower, as noted in ref 7, which might make it more noticeable.

The swish heard in these directions by this mechanism is merely a function of the position of the observer in relation to the turbine and not a variation of noise level created by the turbine blade as it rotates.

4. van den Berg

In "Do wind turbines produce significant low frequency sound levels?"[13] G.P. van den Berg says "Because of atmospheric turbulence there is a random movement of air superimposed on the average wind speed. The contribution of atmospheric turbulence to wind turbine sound is named 'in-flow turbulence noise' and is broad band sound stretching over a wide frequency range. For turbulent eddies larger in size than the blade this may be interpreted as a change in the direction and/or velocity of the incoming flow, equivalent to a deviation of the optimal angle of attack. . . . . When the blade cuts through the eddies, the movement normal to the wind surface is reduced or stopped, given rise to high accelerations and thus sound." In the same paper and elsewhere van den Berg describes how "clapping or beating" occurs when wind shear is higher at night for the same reason of differential wind velocities across the rotor. Thus it is van den Berg's view that amplitude modulation is caused by the blades passing through air with varying speeds and directions whether this is due to wind shear, meteorological turbulence or turbulence created by topography or other turbines.

Van den Berg also observes the difference between "thump" and "swish" As he says in one paper[14] "In the wind park the turbines are audible for most of the (day and night) time, but the thumping is not evident, although a 'swishing' sound—a regular variation in sound level caused by the pressure variation when a blade passes a turbine mast—is readily discernible". Whilst it seems likely from Oerlemans work that the "swish" is not due to the tower the distinction is nevertheless made.

It is also Van den Berg's view that the impulsive noise from several turbines can run in and out of phase (in phase in the sense that the maximum noise level from each arrives at the receiver at the same time). This reflects Jiggins comments referred to earlier. In the same paper van den Berg says that "this pattern is compatible with a complex of three pulse trains with . . . slightly different repetition frequencies. . . when two of them are in phase pulse height is doubled (+3dB) and tripled (+5dB) when all three are in phase." To analyse this a little more, if we have two turbines whose sound level modulates between a maximum of +3dB and a minimum of -3dB then, when the modulations are in phase, they will vary between a maximum of +6dB and a minimum of 0dB and when they are out of phase they will be more constant at a level of around +4dB. Not only will the maximum levels be increased by 3dB but the minimum levels will as well. Similarly with three turbines in phase the sound will range from 2dB to 8dB and when out of phase be a relatively constant 6dB. So the variation between maximum and minimum of several turbines in phase cannot be any more than the variation of a single turbine although the maximum level increases with the number of turbines – just as it would with steady sound. This might result in the maximum to minimum range increasing if there were a relatively constant background noise level masking the minimum levels of the turbines. So it is perhaps more correct to suggest not that, when turbine noises are in phase the level increases but rather that when they are out of phase the modulation is reduced because they average each other out. The other alternative explanation would be that changes in meteorological conditions vary the source noise from the dominant turbine but there is insufficient evidence to know which might be the true explanation.

5. Hayes

On p 52 of "The Measurement of Low Frequency Noise at Three UK Wind Farms"[15] by Hayes McKenzie for the DTI it says "However, the presence of high levels of modulation at Site 1: Location 1 is associated with wind direction and the inappropriate aerodynamic conditions seen by the closest three wind turbines to the dwelling." That is to say these three turbines have turbulent air striking them.

Hayes goes further in the description of the problem in his evidence to the court in the case of nuisance brought by objectors[16] where he stated that "the source of modulation may be related to wind shear by which I refer to changes of wind speed and direction at different heights above ground level. I consider it likely that wind shear effects caused by the topography of the site and (for specific wind directions) wake effects caused by turbines upwind of the turbine exhibiting the noise may cause the direction of the wind at some points on the arc of the blades to be different from that measured by the turbine anemometer at the hub height of the wind turbine. Thus the blades at these points in the arc may not be fully pointed into the wind which may result in increased aerodynamic noise in the frequency region where amplitude modulation has been measured."

Further information is provided in a report by the University of Salford[17]. At para 5.4 it says "Aerodynamic noise generation depends primarily on the rotor tip speed, but there is also some dependence on wind speed. Therefore, if wind speed is not even across the rotor plane then some fluctuation in level can be expected as the blade turns."

In the UK DTI report on low frequency noise[18] Hayes also draws the distinction between modulation due to directivity of the sound as described by Oerlemans and Lopez and modulation due to uneven wind velocities at different points of the blades rotation due to wind shear or turbulence.

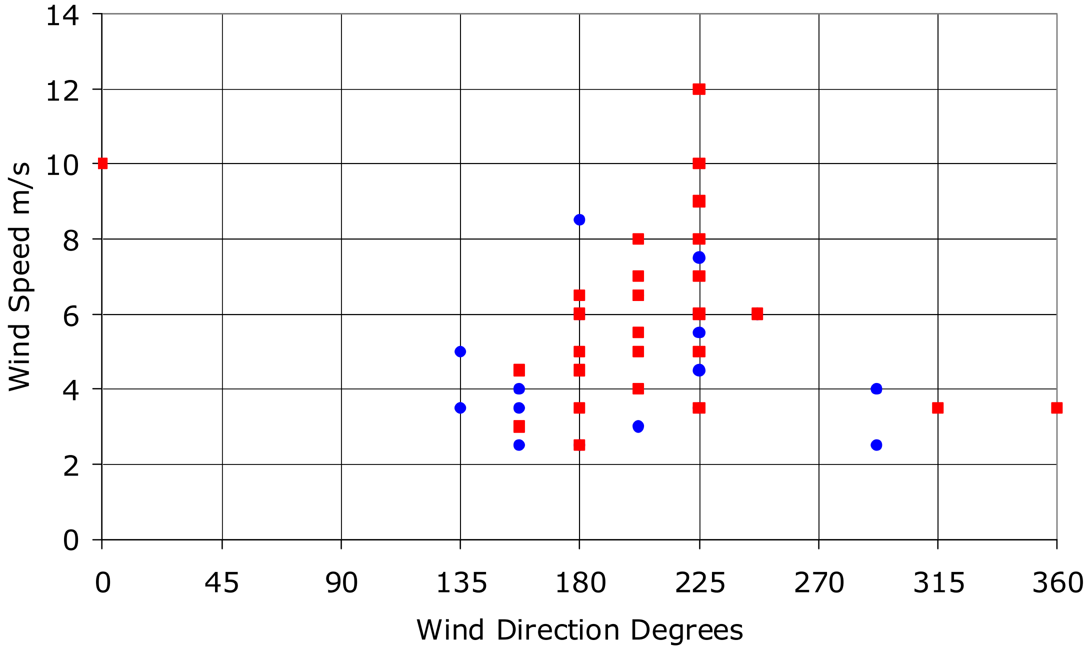
6. Deeping St Nicholas

From the subjective point of view there seem to be two separate descriptions of what would appear to be different phenomena. The first is "swish" which immediately suggest the relatively benign modulation of the sound at middle to high frequencies as it is heard near a turbine. The second is "thump" which suggests an impulsive sound with a rapid rise time. This distinction was made by van den Berg as described earlier.

The occupiers of a property near the wind farm of Deeping St Nicholas have kept a record of the time that amplitude modulation occurred and particularly describe what they heard. They initially did not object to the wind farm and they were unaware of the phenomenon of AM. Accordingly they had no pre-conceptions about the likely character of the noise. They describe "swish" and "thump" as distinct sounds. Thumping is normally accompanied by swishing but swishing is not usually accompanied by thumping.

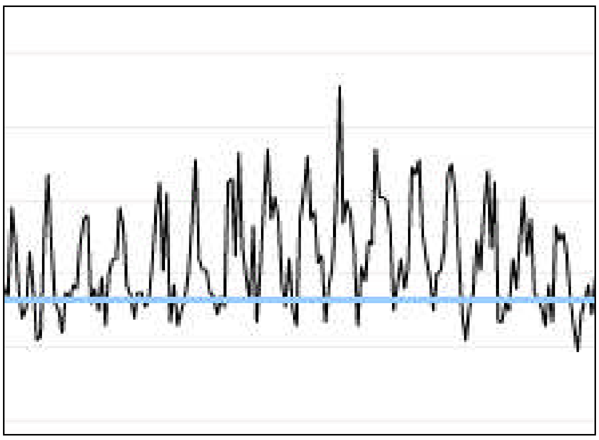
The turbine layout consists of two rows of turbines angled along lines about lines 130/310 degrees. The property is about 160 degrees and 950m from the nearest turbine and the next one in the same row is about 1200m distant. The nearest turbine in the second row is about 2,500m away and it seems unlikely that the second row would have a significant influence on the perceived noise.

The complainant's log has been analysed and the subjective response plotted against wind conditions. In the plot below the blue circles represent thumping – whether or not accompanied by swishing. The red squares represent swishing only. The accuracy of the graph is limited because the wind speeds and directions used were taken from publicly available data gathered at Wittering Meteorological Station which is about 20 km from the site.



Thumping is well spread over wind direction. However, swishing seems to be centred at about 200 degrees and 80% of swish occurs in the three directions 180, 202 and 225 degrees which are not downwind directions. This is the direction of the "south-easterly" swish propagation with the tower shadow as described in section 3 above. This may be significant or it may simply be that there were insufficient periods of easterly and south-easterly winds to provide data points in those directions. However, although it was not documented in the early log, the complainant reports that "swish" is a normal occurrence in easterly winds[19]. This would be the "south-westerly" direction as described in section 3.

However, there is another piece of evidence that suggests that further investigation would be worthwhile. Recordings have been made by Stigwood[20] of AM inside one of the rooms of the complainants house. A typical trace of this is shown below.

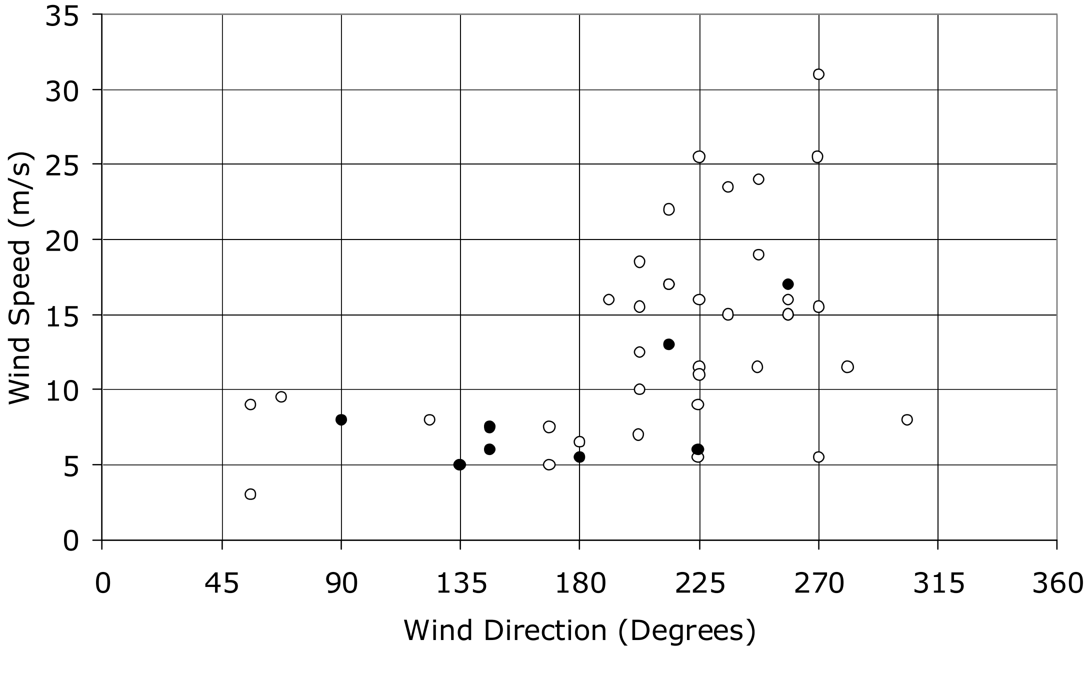


The vertical scale is noise level and the horizontal scale is time. Each of the peaks is one blade swish so they are separated by about one second. What is evident is that a large proportion of the modulations have a notch or partial notch which could be due to the blade passing the tower and the noise being shadowed. The wind direction was about 200 degrees during the measurements which is consistent with the "south-east" position in section 3 above.

7. Wharrels Hill

Wharrels hill was commissioned in August 2007. The complainant is situated about 840m from the nearest turbine and in a direction of 200 degrees from it. There is another turbine about 860m away with an angle of 220m to the property and a third turbine 930m away between these two. The house is near a main road so that turbines are not heard during the day. The problem arises at night when the complainant tries to get to sleep. He complains only of swish and specifically stated that the noise was not a thump.

In this case there is both positive and negative data so it is possible to identify conditions when swish occurs and when it does not. Weather data was more difficult to obtain and was finally taken as an average of Prestwick airport (120km to NNW) and Leeds Bradford Airport (150km to SSE). Where either of the met sites recorded a wind speed of less than 3m/s or the variation in direction between the two was more than 45 degrees the data was discarded. In the chart below the open circles represent records where there is no swish recorded and the solid circles records where swish is recorded.



The majority of the records in the downwind situation (between about 180 and 225 degrees) show no swish whereas more than half of those between 135 and 180 (the "south-west" sector as described in Section 3) have swish.

8. Conclusions

It seems probable that there are two distinct mechanisms in operation to create AM. The first is swish which is a function of the observers position relative to one turbine. The second is thump which is due to turbine blades passing through uneven air velocities as they rotate. In the second case the uneven air may be due to interaction of other turbines, excessive wind shear or topography. These two mechanisms are entirely separate though it is possible that they interact. If this is the case there is little that can be done about swish but further research into thump would help to avoid excessive AM in future developments.

References

[1] Research into Aerodynamic Modulation of Wind Turbine Noise. Final report. July 2007. Contract no NANR233

[2] Minutes of the Noise Working Group http://www.berr.gov.uk/files/file34759.doc

[3] J. Jakobsen and T Pederson: Noise from wind turbines and the masking effects of the wind. Report 141, April 1989 (in Danish). Lydteknisk Institut, Lyngby, Denmark,

[4] P. Dunbabin: An investigation of blade swish from wind turbines. Proc of Internoise 96, I.O.A. 463-469.

[5] The Assment and Rating of Noise from Wind Farms. ETSU-R-97. Department of Trade and Industry 1996.

[6] M.Jiggins. Subjective Perception of Wind Turbine Blade Noise. IOA Diploma Thesis 1997.

[7] Wind Turbine Measurements for Noise Source Identification: ETSU W/13/00391/REP: Flow Solutions Ltd, Hoare Lea & Partners Acoustics: Renewable Energy Systems Ltd.: 1999

[8] Stefan Oerlemans and Beatriz Méndez López. Localisation And Quantification Of Noise Sources On A Wind Turbine. First International Meeting on Wind Turbine Noise: Berlin 17th and 18th October 2005.

[9] Stefan Oerlemans and Gerard Schepers. Prediction Of Wind Turbine Noise and Comparison To Experiment. Second International Meeting on Wind Turbine Noise, Lyon, France, September 20–21, 2007.

[10] Answer to question at Wind Turbine Noise 2007, Lyon, France.

[11] Private communication with Oerlemans 7th April 2007.

[12] p52 of "The Measurement of Low Frequency Noise at Three UK Wind Farms" produced for the DTI in the UK.

[13] G.P.van den Berg "Do wind turbines produce significant low frequency sound levels?" 11th International Meeting on Low Frequency Noise and Vibration. 2004.

[14] G.P.van den Berg. "Effects of the Wind Profile at Night on Wind Turbine Sound", J. Sound Vib. 277 (4-5), 955-970 (2004)

[15] "The Measurement of Low Frequency Noise at Three UK Wind Farms" produced for the DTI in the UK.

[16] Nicols and others v Powergen Renewables and another. South Lakeland Magistrates Court.

[17] "Research into Aerodynamic Modulation of Wind Turbine Noise: Final report" by the University of Salford. BERR, UK

[18] "The Measurement of Low Frequency Noise at Three UK Wind Farms" produced for the DTI in the UK.

[19] Private communication with Julian Davis.

[20] Private communications with Jane Davis and Mike Stigwood.