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Research into aerodynamic modulation of wind turbine noise: final report

Moorhouse, AT, Hayes, M, von Hünerbein, S, Piper, BJ and Adams, MD

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DEPARTMENT FOR BUSINESS
ENTERPRISE & REGULATORY REFORM

Research into aerodynamic modulation of wind turbine noise

Report by University of Salford

URN 07/1235

University of Salford
A Greater Manchester University

Research into Aerodynamic Modulation of Wind Turbine Noise: Final report

July 2007
Contract no NANR233

Prepared for Defra by
Dr. Andy Moorhouse, Malcolm Hayes, Dr. Sabine von Hünerbein, Ben Piper, Dr. Mags Adams

CONTENTS

1. Summary

The study described in this report has been commissioned by Defra, BERR (formerly DTI) and CLG. It follows on from a report by the Hayes McKenzie Partnership to DTI in 2005 in which reports of low frequency noise emission from windfarms were investigated. Their report concluded that the complaints were not caused by low frequency noise, but by amplitude modulation of aerodynamic noise (AM) from the wind turbines. The term AM indicates aerodynamic noise from wind turbines, but with a greater than normal degree of regular fluctuation at blade passing frequency, typically once per second. The aims of this current study are to ascertain the prevalence of AM on UK wind farm sites, to try to gain a better understanding of the likely causes, and to establish whether further research into AM is required. The study was carried out in four parts, a survey of local authorities with windfarms in their areas, further investigation of sites for which AM was identified as a factor, a literature review and a survey of wind turbine manufacturers.

The survey of local authorities was in two parts, a scoping survey aimed at identifying problem sites, and a detailed survey to establish whether AM could have been a factor in causing complaints. The response to both parts of the survey was 100%, although full information was not available for all sites at the detailed stage. The results showed that 27 of the 133 windfarm sites operational across the UK at the time of the survey had attracted noise complaints at some point. An estimated total of 239 formal complaints have been received about UK windfarm sites since 1991, 152 of which were from a single site. The estimated total number of complainants is 81 over the same sixteen year period. This shows that in terms of the number of people affected, wind farm noise is a small-scale problem compared with other types of noise; for example the number of complaints about industrial noise exceeds those about windfarms by around three orders of magnitude. In only one case was the windfarm considered by the local authority to be causing a statutory nuisance. Again, this indicates that, despite press articles to the contrary, the incidence of windfarm noise and AM in the UK is low.

AM was considered to be a factor in four of the sites, and a possible factor in another eight. Regarding the four sites, analysis of meteorological data suggests that the conditions for AM would prevail between about 7% and 15% of the time. AM would not therefore be present most days, although it could occur for several days running over some periods. Complaints have subsided for three out of these four sites, in one case as a result of remedial treatment in the form of a wind turbine control system. In the remaining case, which is a recent installation, investigations are ongoing.

The literature review indicated that, although there has been much research into the general area of aerodynamic noise it is a highly complex field, and whilst general principles are understood there are still unanswered questions. Regarding the specific phenomenon of AM there has been little research and the causes are still the subject of debate. AM is not fully predictable at current state of the art. The survey of wind turbine manufacturers revealed that, although there was considerable interest, few have any experience of AM.

The low incidence of AM and the low numbers of people adversely affected make it difficult to justify further research funding in preference to other more widespread noise issues. On the other hand, since AM cannot be fully predicted at present, and its causes are not fully understood we consider that it might be prudent to carry out further research to improve understanding in this area.

2. Introduction

In 2005 the DTI commissioned the Hayes McKenzie Partnership to investigate claims in the press that infrasound or low frequency noise emitted by wind farms were causing health effects. Their report, published in 2006, concluded that there was no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines. The report went on to note that the cause of complaints was not low frequency noise or infrasound, but was audible modulation of aerodynamic noise, i.e. aerodynamic noise which displays a greater degree of fluctuation than usual. This phenomenon is referred to as AM in the rest of this report. This AM was, in some isolated circumstances, occurring in ways not anticipated by the government guidance document on noise from windfarms known as ETSU-R-97. The Government therefore took the view that more work was required to determine whether or not AM is an issue which may require attention in the context of the rating advice given in the ETSU guide.

2.1. Aims and objectives

The aims of this study are to ascertain the prevalence of AM from UK wind farm sites, to try to gain a better understanding of the likely causes, and to establish whether further research into AM is required.

The objectives of the study are as follows:

(a) To establish the levels and nature of the reported noise complaints received across the UK relating to noise issues from wind farms, both historic and current, and determine whether AM is a significant effect;

(b) To review and understand the level of knowledge/understanding that exists throughout the world on AM, and whether AM can be predicted;

2.2. Organisation of the project

The study has been organised into four main tasks in order to achieve these objectives:

a. Survey of Local Authorities;
b. Further investigation into sites with AM
c. Worldwide literature search;
d. Survey of Manufacturers Worldwide;

Sections 3-6 of this report describe tasks a-d respectively, followed by overall Conclusions in Section 7.

3. Survey of Local Authorities

A two-stage survey of local authorities was conducted with the aim of establishing the presence of noise complaints, in particular about AM, from UK windfarms. A database of all operational wind farms in the UK was provided to us by BWEA. This gave us a total of 136 wind farms that were operational at the end of December 2006 to investigate. Four of these are offshore sites, which were initially excluded from the survey on the grounds that they are far from habitation, but were later included after it emerged that one of them had in fact received complaints (which later turned out to be from foghorns, not the wind turbines). The BWEA list includes some windfarms, that are extensions of existing sites, as separate developments. Such extensions are not considered as separate sites by the local authority, and so were merged together on the database. The total number of separate windfarm sites then becomes 133, of which 4 are offshore. Smaller wind energy developments, for example single wind turbines, were not included in the survey because there is no is no definitive list of such developments and it would therefore be difficult to ensure we were dealing with a representative sample.

The BWEA database also provided information about the number of wind turbines in each wind farm, their capacity, the name of the developer, the country and county of location within the UK and the LA responsible for giving planning permission.

We confirmed that noise nuisance is dealt with by either Unitary Authorities or District Authorities and then identified specific contacts within each local authority. It was felt that where possible we should identify a named individual within the local authority rather than sending a general enquiry to the head of department or ‘enquiry’ email address. Using the membership list of the Institute of Acoustics we identified names, email addresses and telephone numbers of Environmental Health Officers within each local authority with expertise in noise and acoustics. We also used the Noise Abatement Society’s on-line database of local authority contacts for noise complaints to identify contact details for local authorities which did not have individual members of the IoA. We also used a database of Local Authorities held at the University of Salford. If no contact was found we directed our enquiries to the head of the Pollution Control Section or Environmental Health. Any missing contacts were identified by phone calls to the local authority.

On a map we identified all wind farms that were on local authority borders so that we could check if any noise complaints were received by neighbouring local authorities. 47 windfarms were identified as being close to the border with a neighbouring authority, and these authorities were added to the database of local authorities to be contacted.

To respect confidentiality the names of individual windfarms will not be used in this report, nor will the names of specific local authorities or their members of staff. Each windfarm will be referred to by a letter or letters of the alphabet.

3.1. Scoping survey

The first stage of the survey, a scoping survey, aimed to identify those local authorities who had received complaints about windfarm noise. The questionnaire was sent out by email to named individuals and was designed to be as simple as possible to answer with a simple Yes/No, so as to maximise the chances of a reply.

Several points on the questionnaire required careful consideration. One of the main decisions was the question of how far back to go with complaints. It is known that some early installations produced complaints about tonal noise from wind turbine nacelles, which are not related to AM. After some discussion it was decided that to specify a start date might weaken any conclusions that could be drawn. On the other hand, not to specify any date could lead to inconsistencies in the responses. It was therefore decided to specify that complaints should be included from any time since the windfarms have been operational.

A copy of the final phase 1 questionnaire is shown in Figure 1.

Dear NAME

We at Salford University in conjunction with Hayes McKenzie have been appointed by the UK Government (funded by Defra, DTi, and DCLG) to undertake research into noise from windfarms. For details of why this work was commissioned please see http://www.dti.gov.uk/files/file35043.pdf . The aim of the work is to provide clearer advice to planning authorities about wind turbine planning applications.

We would appreciate it if you could take a couple of minutes to answer the following question.

Have you had any noise complaints about any of the wind farms in your area or any windfarms in a bordering authority any time since they have been operational?

If the answer is 'NO' please respond by pressing REPLY in your browser window and simply type NO. We will not trouble you further.
If the answer is 'YES' please respond by pressing REPLY in your browser window and simply list the names of the windfarms about which there have been noise complaints. If the answer is 'yes' then we will need to follow up with a further survey in which we will ask for further details.

We appreciate your help with this matter as the Government wants a 100% response to this question and would be grateful if you could reply by DATE.

Sincerely, Anne Marie Lavin

Sent on behalf of
Head of Survey of Local Authorities
Government Survey into Noise from Wind Turbines (REF: NANR233)
Dr Mags Adams
Senior Research Fellow
Acoustics Research Centre
University of Salford M5 4WT

Figure 1 Phase 1 scoping survey questionnaire

After some follow up emails and, where needed, telephone reminders we were successful in achieving a 100% response to the scoping survey.

3.2. Detailed survey

The aim of the detailed survey was to obtain information about the number and nature of complaints, and in particular to establish the contribution of AM. Every local authority that responded with a positive noise complaint in the scoping survey was sent the detailed questionnaire, to be completed for each wind farm in their area for which they had received noise complaints. In total, 23 LAs were contacted about 27 windfarms.

The detailed questionnaire was developed by the team at Salford, was reviewed by EHOs on the Noise Working Group and by the Hayes McKenzie Partnership, and then sent out via email to the Local Authorities. A complete copy of the final questionnaire is given in the Appendix. The questions include a combination of open and closed questions with tick-boxes to simplify responses where possible. It was decided not to mention AM until the final question so as to encourage EHOs to provide information about all noise complaints and not just to focus on those that might fit the description of AM problems.

Details about the number of complaints and number of complainants were requested along with detailed descriptions of the noise itself and the investigation that took place. A list of terms to describe noise from wind turbines was provided and the EHOs were requested to indicate which of them corresponded to the complaints they had received from each wind farm. Details of any action that had been taken was also requested. Finally, the EHO was asked to indicate whether they felt that the complaint conformed to a description of Amplitude Modulation of Aerodynamic Noise.

Local Authorities were asked to respond within a week and were sent a reminder email and follow up phone calls as necessary.

3.3. Survey results and analysis

We obtained a 100% response rate from both the scoping and detailed questionnaires. However, complete information for the detailed survey was not always available. This was particularly the case for complaints from the 1990s since many local authorities did not keep computer records at that time.

Number of complaints and complainants

From the results of the scoping survey we determined that 27 out of the 133 windfarms operating in the UK at the time of the survey have attracted formal complaints about noise. This represents 20% of the total, i.e. one in five windfarms has attracted complaints about noise at some point. One other site, an offshore site, received complaints about foghorns, and this case has been excluded in the statistics since the wind turbines themselves did not generate the noise. These figures are based on 100% returns from local authorities throughout the UK over the entire period since the first windfarms became operational in 1991, and can therefore be treated as a comprehensive and definitive picture of formal noise complaints about windfarms in the UK.

Complete results obtained for the numbers of complaints, numbers of complainants, and the years in which complaints were received are shown in Table 1. Note the distinction between complainant and complaint, where complainant refers to the individual who makes the complaint and complaint refers to each time they log a complaint with the local authority. One complainant may make a number of complaints and therefore the number of complaints can exceed the number of complainants. In order to provide some context for the complaint histories the bottom row of Table 1 gives the number of sites on-line at the end of each year.

We have specific information on the number of complaints from 19 of the 27 windfarms. The total number of complaints received by local authorities relating to these 19 sites was 206, 152 of which were received for a single windfarm. By excluding this untypical figure we see the number of noise complaints about each windfarm varied between 1 and 10 with an average of 3. We can use this to estimate the total number of complaints across the UK by assuming that this average number also applies to the eight sites for which no specific complaint data was available. The result of this projection is that the total number of complaints across the UK is approximately 230 since records began, 152 of which were from a single site. These statistics about the number of complaints should be treated with some caution because there is not complete consistency in the way local authorities count complaints: some would count several complaints from the same person as a single complaint, others would log each separate complaint individually. For this reason it is probably more reliable to count the number of premises affected, i.e. the number of *complainants* as described in the next paragraph.

We now consider the results for the number of complainants. The number of complainants will generally be less than the number of complaints because the same complainant may make several complaints. We have firm information about the number of complainants from 16 sites, with a total of 53 complainants (these are the entries in the rightmost column of Table 1 without an asterisk). No complainant data was available for the remaining 11 sites. For sites marked with an asterisk in the rightmost column of Table 1 the number of complainants was estimated. We did this by making the conservative estimate that each complaint was made by a different complainant. These estimates may be slightly on the high side, but since in every case the numbers are low we would not expect this to have a large influence on the totals. Using this approximation we estimate the number of complainants relating to the 25 windfarms for which we have either complainant or complaint data to be 75. The number of complainants per windfarm varied from 1 to 9 with an average of 3. As before, we can project the total number of complainants across the UK by assuming this average applies to each of the two sites for which no definitive information is available. The final result is that an estimated total of 81 households have complained about windfarms in the UK since records began in 1991.

Windfarm	Total	2007	2006	2005	2004	2003	2002	2001	2000	1999	1998	1997	1996	1995	1994	1993	1992	Year of complaints	No of complainants	
	Complaints per year and total complaints																			
A	3		2	1														2005	3	*
B	10			10														2005	1	
C	1														1			1994	1	
D	152	1	7	10	9	52	50	23										2001	9	
E	4			3		1												2003	4	*
F	2										1		1					1996,1998	2	
G	4		1	1			1		1									2000, 2002, 2005, 2006	2	
H				1														2005	1	
I																		before 2003	1	
J	2			2														2005	2	*
K	7		7															2006	7	
L	2				2													2004	2	*
M	4		1	1							1	1						1997,1998,2000,2004	4	*
N	2		1				1											2002, 2006	2	*
O	1	1																2007	1	*
P																		1993,1994,1995,1996	5	
Q																		2001, 2002, 2003, 2004	4	
R																		1992,1993	10	
S																		before 1997	2	
T																				
U	1		1															2006	1	
V	1				1													2004	1	
W	2	2																2007	2	*
X	2		2															2006	2	
Y																				
Z	2							1	1									2000, 2001	2	*
AA	4		1	3														2005, 2006	4	
No of entries	19																	No of entries	25	
No of windfarms	27																	No of windfarms	27	
% coverage	70%																	% coverage	93%	
Total complaints	206	4	23	32	12	53	52	24	2	0	2	1	1	0	1	0	0	Total complainants	75	
Total less D	54	3	16	16	3	1	2	1	2	0	2	1	1	0	1	0	0	Average per windfarm	3.0	
Ave (less D)	3.0																	Total projected	81	
Total projected	230																			
Total proj. less A	78																			
Sites on line at end of year			136	114	95	83	75	64	56	45	40	36	31	24	18	14	7			

*No separate information given on number of complainants, assumed same as number of complaints.

Table 1 Summary of complaint and complainant history data. Shading indicates the years in which complaints occurred when year by year numbers are not known. Blank entries indicate no data was available.

Windfarm	train never gets there	Distant Helicopter	Thumping	Thuddng	Pulsating	Rythmatical Beat	Beating	Throbbing	Lapping	Wooshing	Swish	Swoosh	Ghostly noises	Wooh Wooh	Grinding	Rumbling	like motion sickness'	Whistling	Other please list	Other (describe)	Noise heard by EHO?	Noise nuisance	EHO suspects AM?	AM
A		Y						Y		Y	Y				Y				Y	aircraft landing, distant jet, rhythmical	Y	P	DK	N
B					Y		Y	Y	Y	Y	Y					Y						N	DK	N
C																					N	N	DK	N
D	Y		Y	Y	Y	Y	Y			Y	Y	Y							Y	train in next field, percussive	Y	Y	Y	Y
E			Y		Y					Y									Y	churning head	Y	P	DK	M
F																					Y		N	N
G																							N	N
H																								M
I																								M
J				Y	Y			Y		Y	Y	Y							Y	mechanical	Y	P	DK	M
K						Y	Y			Y	Y	Y							Y	aeroplane overhead doesn't disappear	Y	N	N	M
L													Y						Y	low frequency droning	N	N	N	N
M			Y	Y	Y	Y	Y			Y	Y	Y									Y	N	Y	Y
N																			Y	whine	Y	N	N	N
O			Y	Y			Y			Y	Y	Y		Y							Y	N	DK	N
P																						N	DK	M
Q																					Y	N	Y	Y
R																						N		N
S																						N	DK	N
T																								N
U												Y							Y	Mechanical whine and monotonous drone	N	N	N	N
V							Y														N	N	N	N
W																					N	N	DK	DK
X		Y			Y		Y	Y		Y	Y	Y		Y	Y	Y			Y	Hum	Y	P	Y	Y
Y																								N
Z			Y	Y						Y			Y						Y			N	DK	M
AA																			Y	like a washing machine	Y	N	N	M
																					NO	16	8	14
																					YES	1	4	4
																					Don't know (DK)	0	10	1
																					Maybe (M)	0	0	8
																					Pending (P)	4	0	0
																					Total	21	22	27

Table 2 Summary of detailed survey returns and analysis to determine the prevalence of AM

Prevalence of AM

In this section we consider the extent to which AM may have been a factor in the complaints. Summarised in Table 2 are the results from the part of the survey where local authorities categorised the noise associated with each site based on complainants' descriptions. Also given in this table are columns indicating whether the investigating environmental health officer (EHO) heard the noise, whether they considered it a nuisance and whether they considered the noise to be consistent with the description of AM.

In order to determine whether AM was a factor for each site we took into account several pieces of information: the tick box descriptions of the noise, any other description of the noise, general descriptions of the EHO's investigation, the timing of the complaints, and in some cases a personal knowledge of the site in question. We also considered the EHO's opinion as to whether the noise was consistent with AM, and this information was assigned more confidence if they had heard the noise themselves.

Columns 2-20 are the results from the tick box questions on the survey. The columns have been arranged so that those on the left are the most likely to indicate AM, i.e. "like a train that never gets there", "distant helicopter", "thumping", "thudding", "pulsating", "thumping", "rhythmical beat", and "beating" could be indicative of AM. The terms on the right are generally associated with some other noise source such as gear box noise or blade resonance.

For several sites, particularly early ones, the complaint was cause by a mechanical fault or a gearbox and therefore AM can be excluded. Five sites (F, G, M, N and T) were clearly stated in the returns to be in this category, and four others were possible or probable (P, R, S and Y) on the grounds that they were early problems that have not attracted complaints in recent years. AM was therefore not considered to be the cause of these complaints, the only exception being site M where there were two types of complaint, one indicating mechanical sources and the other indicating possible

AM[1]. From the tick-box descriptions we also concluded that sites L and U were unlikely to involve AM. The 'other' descriptions given by complainants further suggested that mechanical noise was a factor for sites J, L, N, and U. Altogether, AM could be excluded as a factor from eleven sites on the grounds that the complaints were about mechanical noise sources.

The penultimate column of Table 2 indicates that of the 27 sites considered, eight EHOs said AM was not a factor, four said it was, ten did not know whether it was a factor or not and five offered no opinion. The final column in Table 2 gives our opinion as to whether the complaints could be associated with AM taking into account all the information available. In all cases, except one, where the EHO had given a clear Yes or No answer to whether AM was a feature our opinion was consistent with theirs. The one exception was for windfarm AA where the EHO's opinion was 'No' but where we felt that some of the descriptions could have indicated AM. We therefore entered this site as a 'Maybe'.

The final tally is that AM is thought to be a factor in four cases, is not a factor in fourteen, and eight cases are marginal. One is too recent to have sufficient information to form an opinion and has been entered as 'Don't know' on Table 2.

Significance of complaints

In this section we discuss the significance of the complaints by comparing statistics for windfarms with similar statistics for other noise sources. There are two possible ways in which to make comparison, in terms of absolute numbers of complaints, or in terms of the relative number of installations attracting complaints.

Considering a comparison in terms of absolute numbers of complaints, the Chartered Institute of Environmental Health (CIEH) publishes statistics annually on the number

[1] This site is the only site in the UK still to employ outdated two-bladed rotors, which are known to cause greater modulation than more modern three-bladed machines. AM is therefore a potential explanation of complaints in this case, but this does not cause concern about the future.

of noise complaints and nuisances throughout England and Wales. A summary of some of the results from 2004/2005 is given in Table 3.

The number of households complaining to local authorities about noise from windfarm sites throughout the UK since 1991 has been calculated in the preceding section as 81, which corresponds to an average of approximately 5 per year. The number of complaints was projected as 230, an average of about 14 per year, although we have less confidence in this figure than that for the number of complainants. From Table 3 the number of complaints about industrial noise (probably the most comparable category with windfarms at least in terms of the character of the noise) was 7,522 in a year. The total number of complaints about noise was 286,872. It should be noted that the figures from Table 3 are based on returns from 69% of local authorities in England and Wales, whereas the figures for windfarms are from 100% of local authorities throughout the UK (i.e. also including Scotland and Northern Ireland), so that the comparison will tend to overstate the significance of windfarm noise in relative terms.

	Industrial	Commercial/ leisure	Domestic	Construction/ demolition	Vehicles machinery and equipment in streets	Miscellaneous	Total
Noise incidents complained of	7.5	35.8	206.1	11.7	11.3	14.5	286.9
Nuisances	1.4	6.0	27.6	1.8	1.7	1.0	39.5

Table 3 Summary of CIEH statistics on noise complaints and confirmed nuisances (thousands) from 2004/2005 for 69% of local authorities in England and Wales.

It is clear that complaints about noise from windfarms make up an extremely small proportion of the total noise complaints: complaints about industrial noise exceed those from windfarms by around three orders of magnitude, and complaints about noise in general exceed those from windfarms by between four and five orders of magnitude. We would stress that this does not imply that individual complaints about windfarms are less important than about other noise sources, but rather that the scale of the problem in absolute terms is significantly smaller than for other categories of noise.

Clearly a major factor in the small number of complaints relating to windfarms is the relatively small number of sites compared to, say, industrial sites in general. It would be interesting to make a comparison in terms of the proportion of sites of a particular type that attract complaints. However, whilst we know from this study that about one in five windfarms attracts complaints at some point, we do not have comparable figures for other types of site and we are not therefore able to compare in relative terms.

We can gain further insight into the significance of windfarm noise by looking at nuisance statistics. We note from Table 2 that for 16 windfarm sites the local authority considered the noise from the windfarm not to be causing a nuisance, four cases were pending at the time of the survey, i.e. the local authority had not yet reached a formal decision, and in only one case was the noise judged to be causing a statutory nuisance. There are several categories of nuisance in law, and in order for a noise to be actionable by a noise abatement notice it must be categorised as a ‘statutory nuisance’ a formal definition of which is given in the Environmental Protection Act 1990. We confirmed that the one ‘Yes’ site had been categorised by the local authority as a ‘statutory nuisance’. For the 16 sites not considered to be causing a ‘nuisance’ it can be taken that there was also no ‘statutory nuisance’. Therefore, there is only one confirmed case of statutory nuisance from the 17 sites for which data is available. Note again that these figures cover a 16 year period. In comparison, Table 3 shows that there were a total 39,508 confirmed noise nuisances in 2004/2005, of which 1,401 related to industrial noise. Again, it is clear that windfarm noise is an extremely small-scale problem compared with other types of noise, particularly since the figures for other sources are an underestimate for the UK as a whole as remarked earlier.

One further observation from the nuisance statistics is that the proportion of complaints which were subsequently confirmed as causing a nuisance is smaller for windfarms than for any of the other categories of noise as used by the CIEH and given in Table 3. The proportion for industrial noise was about 19% in 2004/2005, and for noise complaints in general it was about 14%. The comparable figure for windfarms is about 6% based on one nuisance per 17 cases for which we have firm data from Table 2. These figures could be interpreted in several ways, although one should be aware that the number of results is too small to draw firm conclusions, and also that the picture could change if some of the four pending cases is eventually judged a nuisance. One possible interpretation is that expectations are higher for windfarm noise than for other categories of noise. If so, we might speculate that the newness of windfarms as a noise source might be a relevant factor. Another possible interpretation might be that local authorities are somehow more lenient for windfarms than for other categories of noise sources, although this seems unlikely since the role of an Environmental Health Officers is to act as an independent judge. We might also speculate that Environmental Health Officers may not have the expertise or confidence in their experience to challenge an ETSU report and are therefore more reluctant to declare a nuisance compared with less complex and better understood noise sources. Again, the fact that windfarm noise is relatively recent phenomenon could be a factor here. Several other factors might influence the decision of the investigating officer, but these are not particular to windfarms so will not be discussed here as they would not explain differences in the proportion of nuisances between categories.

Comments on the use of complaint statistics

One should, of course, be cautious about placing too much reliance on data derived purely from reported complaints. The first reason is that not everyone who is adversely affected by a noise goes to the trouble of making a formal complaint. Thus, complaint statistics tend to underestimate the number of people adversely affected. This is a recognised effect, and applies to all noise sources, but to different extents. For example there is evidence that people tend to complain less about traffic noise than other noise sources for the same degree of annoyance because they do not feel that it will have any effect. It seems likely that, if anything, people might be more inclined to complain about windfarms than about other noise sources because of the high level of publicity surrounding the issue, but we have no definitive information on this question. Therefore, we have no basis for assuming that windfarm noise is any different to, say, industrial noise in this respect.

The second reason for caution is that there is no control on complaints: anyone may make a complaint whether or not they have reasonable cause for dissatisfaction. People can, and frequently do, use noise as a proxy for some other grievance, and thus a proportion of noise complaints may be motivated by some other factor entirely. Thus, the fact that a site receives complaints does not imply that the noise situation is unsatisfactory. Conversely, a lack of complaints is no guarantee of a satisfactory situation. Although we did not ask specifically about other motivations in the questionnaire, some local authorities volunteered the view that ulterior motives were a factor, although not necessarily the only factor, in the complaints they had received. This was the case for three sites, and in one of these it was felt to be a strong factor. The same conclusion may apply to other sites but we have no definitive information.

The third reason for caution is that some complaints may go direct to windfarm operators without being recorded by local authorities. Many local authorities now require, as part of planning permission, the operators to undertake noise monitoring and will forward details of complaints to the operator for further investigation. If complainants were to go directly to the operator rather than via the local authority then some complaints may not have been recorded by the local authorities. There is no legal requirement on the part of the operator to report noise complaints that are made directly to them to the local authority.

In order to try to estimate the scale of this effect we carried out a telephone follow-up to the detailed survey, in which we asked four local authorities, between them responsible for 10 of the 27 complained-about windfarms, if they thought it likely that they had missed many complaints. The answers were consistent. Firstly, none of the local authorities had formal procedures by which the operator was required to forward details of any complaints to them, and therefore they could not guarantee that they had records of all complaints. However, all four local authorities also felt it unlikely that many, if any, complainants had escaped their records entirely. In some cases they felt that local residents would not know who the operator was, so would complain first to the local environmental health department. Some felt that since they were in close and open contact with developers to try to resolve known problems that they would have become aware of additional complaints. Others commented that they specifically requested complainants to contact them again if the problem was not resolved to their satisfaction.

Therefore, whilst it is possible that there have been some noise problems that are not reflected in the results of the detailed survey, we consider it unlikely that significant numbers of complainants have escaped local authority records. In any case, windfarm noise is no different to other types of noise in this respect: for example, a complaint about industrial noise may be directed to the operator of the site and may never feature on local authority records, particularly if the problem is resolved. Therefore, the comparisons with other noise sources in the previous section should be reliable.

Other factors arising from the survey

Some other possible causes of noise complaints emerged as part of this exercise. ‘Unrealistic expectations’ was thought to be a factor in at least one case, i.e. the complainant believed that the noise would be less noticeable than it actually proved to be. In this case the local authority considered that the complaint could possibly have been avoided by more accurate information from the developer at the planning stage. Another possible cause is that complaints are being prompted by planning applications to build other sites nearby. This was mentioned as a factor in two or three cases. In one further case the sheltered location of the complainant’s property was identified as contributing to the complaint, i.e. the background noise at the property, which normally helps to mask noise from the windfarm, does not increase when conditions are windy at the wind farm.

Finally, for five of the sites having received complaints EHOs commented that the site met planning conditions. In one of these cases AM was a factor, in three it was not, and in the fifth it was possible. We do not know whether these comments indicate that complaints were unjustified, or alternatively that planning conditions were too lenient.

4. Further investigation of sites with AM

In the previous section the prevalence of AM in terms of the number of sites affected was determined. In this section we evaluate in more detail the four sites for which AM is thought to contribute to complaints, with the aim of obtaining an estimate of the proportion of time for which AM might occur. This estimate has to be based on complaint data, since it is beyond the scope of this project to take measurements. Using the complaint data we can carry out the following steps:

a. obtain complaint logs;
b. determine the range of wind speed and direction prevailing at times when complaints occur;
c. obtain continuous records of wind speed and direction occurring at the site;
d. calculate, by comparing b. and c., the proportion of the time for which the wind conditions associated with complaints prevail.

A second aim of this section is to determine whether complaints at these sites are historic or ongoing.

4.1. First site

For the first site, a complaints log was available giving date and time of complaints, together with wind speed and direction. Within this five month period complaints were registered for 61 hours out of 2510. Hourly averaged wind data from the MIDAS Weather Station nearby were also obtained. Both the complaints and MIDAS data are plotted on Figure 2. The high degree of agreement between the MIDAS and complaint log data gives confidence that the data from the Weather Station are representative for the wind farm site. Figure 3 gives the same wind direction data, plotted in a different format: the distance from the centre of the plot indicates the proportion of the time for which the wind was from the given direction. The purple line is from the weather station data and shows that over the whole period the prevailing winds were fairly evenly distributed between 150º and 340º. The blue line relates to the complaints and indicates that most complaints occur for directions around 200º.

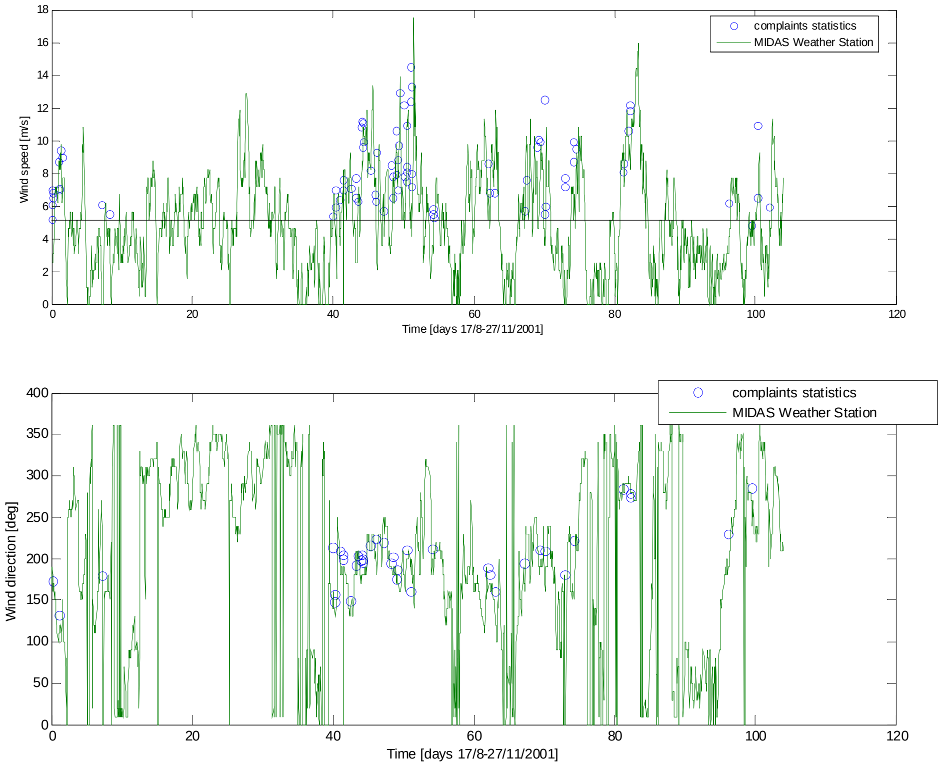

Figure 2 Time series of wind speed (top) and direction (bottom) for MIDAS data (green line) and data from the complaints log (blue circles) at first site.

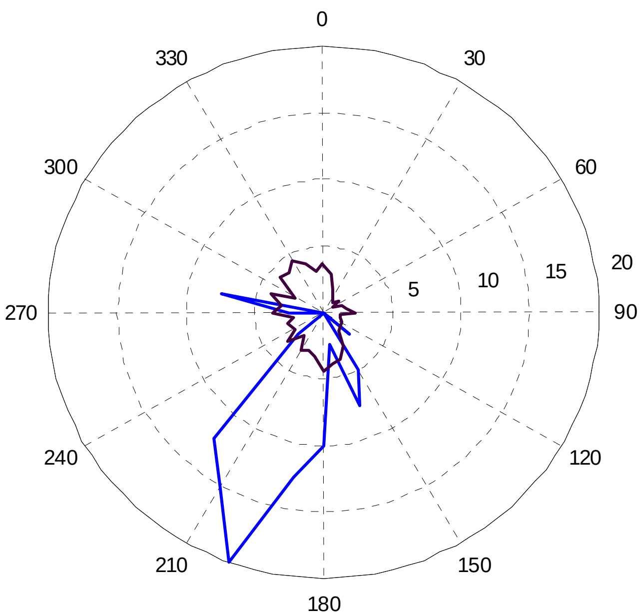

Figure 3 Distribution of hourly wind direction averages at first site: % for complaints (blue solid line); % for weather station data during the whole analysis period from Figure 2 (black dotted line).

From the data in Figure 2 and Figure 3 we can now try to give a figure for the proportion of time for which wind conditions associated with complaints are likely to arise. First, we note that complaints only occurred for wind speeds exceeding 5m/s, which is the cut-in speed of the turbines. Second, all complaints occurred for wind directions in the range 140º to 270º, i.e. for a 130º arc encompassing southerly and westerly directions. However, looking further at Figure 2 and Figure 3 we see that all parts of this range are not equally important, with the majority of complaints (73%) occurring within a narrower 40º arc between 180º and 220º (as shown by prominent lobe in Figure 3). Wind directions within this 40º arc were consistently associated with complaints whereas angles of between 220º and 270º were sometimes, but not always, associated with complaints. Furthermore, when complaints occurred at the higher values of wind direction the descriptions from the complaint logs are generally less suggestive of AM as a cause. Thus, the 130º arc is probably conservative because it includes conditions which do not consistently yield complaints and the complaints do not tend to suggest AM. On the other hand, the 40º arc includes most but not all complaints so might be slightly unconservative.

The weather station data has been analysed taking the wind conditions characteristic of complaints to be: speed above 5m/s and direction 140º to 270º i.e. the 130º arc. These meteorological conditions were met in 580 hours out of the 2510 hours of monitoring, which corresponds to 23 % of the time. Taking the smaller 40º arc as characteristic of complaints, the corresponding figure is 5.3%. As weather conditions change with the seasons and sometimes even from year to year a period of several years (1/1/2000-1/1/2007), was analysed for the Weather Station. The wind direction data for this period are shown in Figure 4 and Figure 5. The identified meteorological conditions during this period were met for 25% of the time taking the 130º arc, and 9% taking the 40º arc. If we assume that the complaints were caused exclusively by AM then we can conclude that meteorological conditions likely to cause AM occur for more than 9% and less than 25% of the time at this site, with the true value probably towards the lower end of this range, say about 15% as an overall figure. We can therefore say that the conditions associated with AM would occur on average about one day in seven. However, it should be noted that these are average figures and that in reality the characteristic conditions might occur quite irregularly. This is shown in Figure 5 which plots the wind speed for periods when the wind direction was within the 130º arc as mentioned above. It is seen that the characteristic conditions might occur for several days running followed by a longer period with no such conditions.

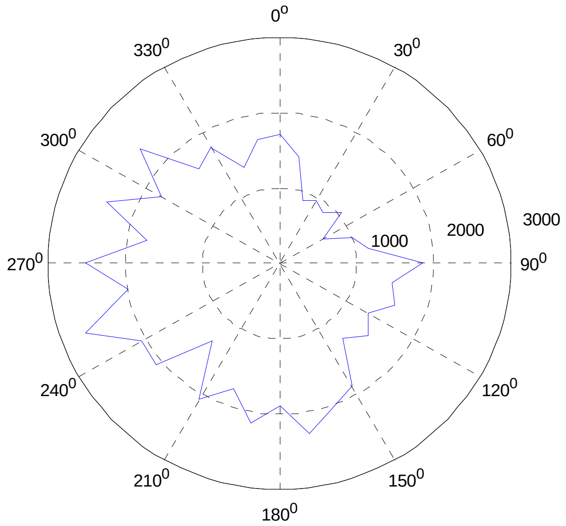

Figure 4 Distribution of hourly wind direction averages averaged over a seven year period for first site.

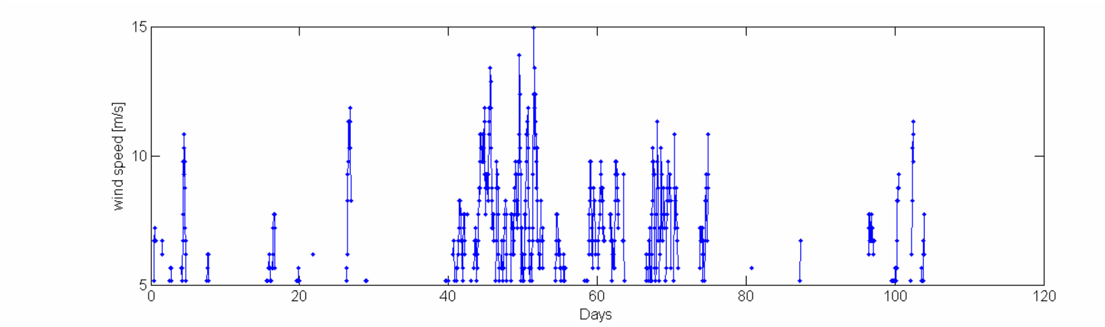

Figure 5. Wind speed for the periods when AM might occur at first site, i.e. wind speed >5m/s and direction between 140° and 270°.

The final question about this site concerns whether AM is historical or ongoing. The Local Authority for this site has reported that there have been no complaints since 2004, suggesting either that the problem has been alleviated, or that people have become accustomed to it, or a combination of both.

4.2. Second Site

For the second site a complaints log was available prior to 2003. This site was the subject of complaints associated with a number of wind directions, however, it was generally agreed that AM occurred specifically for Easterly winds and for speeds from the cut-in speed, of around 5m/s, up to 10 m/s measured at a height of 10m above ground level. Above 10m/s (which corresponds to about 13m/s at hub height) the noise of wind in the trees would start to mask the sound of the wind farm. No wind data was available for this site; generally in the UK easterly winds are relatively uncommon suggesting that the conditions for AM would not be present most days of the year, although there could be periods of continuous easterly winds for several days at a time.

AM on this site was associated with three specific wind turbines. To alleviate the problem, a turbine control system was programmed to shut down these three machines for wind directions between 55° and 130°, and for wind speeds from the cut-in speed to a hub height wind speed of 13 m/s. The benefits of this system may be seen in the reduction of complaints which reduced from 50 – 52 per year for 2002 – 2003 to 7 – 10 per year between 2004 and 2006. The residual complaints may be associated with westerly winds rather than the easterly wind which resulted in the audible AM. We might cautiously conclude that the AM problem on this site has been solved, or at least substantially alleviated by these measures.

4.3. Third Site

For the third site a complaints log was available for the period when the wind farm commenced operation to date. The log details a number of sounds that are audible at the property. The complainant describes periods of operation when amplitude modulation of the aerodynamic noise (AM) is clearly audible inside and outside the building. When the AM is described, the common factor between different days is the wind direction, which falls into a narrow range between 140° and 170°, i.e. a SSE wind tending to a Southerly wind direction.

Analysis of the historical wind rose (Figure 6), which was supplied by the wind farm operator and which is based upon the 10 year average data supplied by the Meteorological Office for a nearby reference site and the on-site wind speed measurements undertaken by the developer for a one year period, indicate that this range of wind directions would be expected to occur for 7 – 9% of the year. This does not account for the range of wind speed likely to cause AM, i.e. at very low wind speeds the turbines would not be operating and at very high wind speeds the natural background noise would tend to mask wind turbine noise. With periods of very high and low wind speed removed, the average year will see the wind from this direction for 7% of the time. We therefore conclude that the conditions likely to cause AM on this site will be present for approximately 7% of the time. It should be mentioned that other noise issues are also reported at this site, but these are not considered in this report which focuses on the issue of AM.

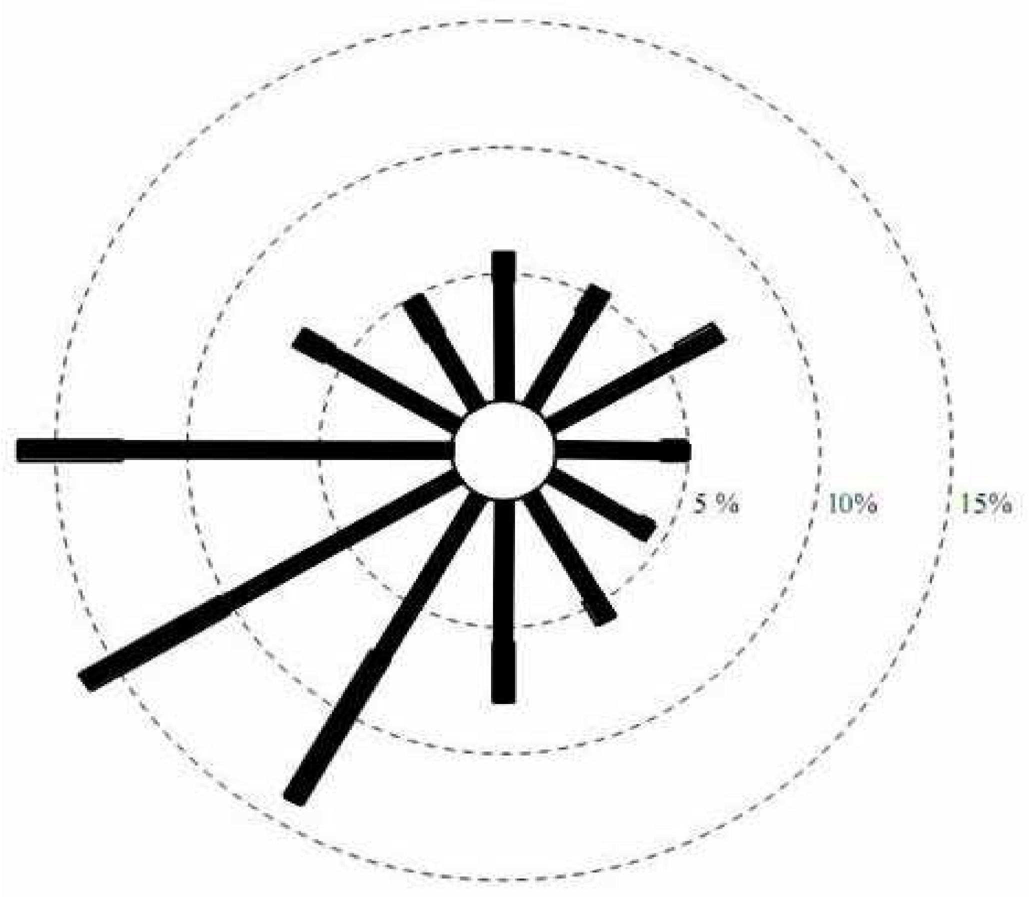

Figure 6 Wind farm rose for third site

4.4. Fourth Site

No complaints logs were available from the fourth site from which to ascertain the characteristic meteorological conditions, and therefore the prevalence of AM could not be determined. Regarding the question of whether the problem has been solved, complaint history suggests that the problem is not a continuing one since the last complaint relating to AM was in 1998. There have been other complaints since then, but relating to specific fault conditions (not associated with AM) which were rectified. According to the Local Authority, AM probably does occur at this site, i.e. there is significant modulation of the aerodynamic noise from the windfarm, but the noise levels are not sufficient at nearby properties to cause a significant problem. Furthermore, the site is operating within its planning conditions, and in this respect the Local Authority does not consider the site to be a continuing problem. Other than regular noise monitoring the operator has not made any remedial works to the site that would have caused the complaints to subside. Therefore, it is possible that the initial complaints, which occurred when the site was still new, were due to the unfamiliarity of the noise.

To conclude, whilst it appears that AM does occur at this site, it also appears to be at most a marginal problem.

4.5. Conclusions from AM sites

To summarise, the meteorological conditions associated with AM have been assessed for two sites, and are likely to occur between 7% and 25% of the time, although the latter figure is on the conservative side. Of the four sites where AM was judged by the Local Authority to be present in only one case, which is a recent installation, is there an ongoing investigation. In two cases complaints have largely or completely subsided, in the final case a turbine control system has been installed and, although there are some ongoing complaints, AM is probably not the cause.

5. Worldwide literature survey

The aim of the literature survey is to summarise the current scientific knowledge about AM and immediately related subjects. Our main information sources were peer-reviewed documents, that is reliable, independently checked sources, such as books, government reports and journals. Where necessary, proceedings from scientific conferences are also considered. Under the References headline we list all the publications we have found and read but not necessarily explicitly cited in the text.

The subjects in the literature review cover how AM is accounted for in government guidelines and regulations, how noise in general and AM in particular are generated by wind turbines, how the immission of noise is influenced by propagation and why psychoacoustics is important to interpret measurements and complaints correctly.

5.1. Search terms

Some thought was given to search terms since AM is not a widely recognised phenomenon and might be reported under different names. The following English search terms were used:

Amplitude Modulation
Aerodynamic Modulation
Modulated Noise
Wind Noise
Turbine Noise
Wind Farm Noise
Aero(-)acoustic Noise
Rotor Noise
Tonal Turbine
Fluctuating Noise
Swish.

5.2. Information sources

The following journals were searched with the above terms.

Journals searched

1. Journal of the Acoustical Society of America
2. Journal of Sound and Vibration
3. Journal of Low Frequency Noise, Vibration and Active Control
4. Applied Acoustics
5. Technical Acoustics
6. Acoustical Science and Technology (Formerly Acoustical Society of Japan)
7. Journal of Vibration and Acoustics
8. Noise and Vibration Worldwide
9. Renewable Energy
10. Wind Energy
11. Renewable and Sustainable Energy Reviews
12. Energy
13. Journal of wind engineering and industrial aerodynamics
14. Journal of solar energy engineering
15. Applied energy
16. All relevant IEEE Journals
17. Some papers which appear as abstracts only in JASA
18. International Journal of Energy Research,
19. American Institute of Aeronautics and Astronautics Journal
20. Transactions of the ASME: Journal of Dynamic Systems Measurement and Control and Renewable Energy.

Conference proceedings search

1. Wind Turbine Noise 2005
2. Internoise 1996
3. Euronoise 2003 & 2006
4. BWEA Wind Energy Conferences 1997 - 2005

5. Forum Acusticum 2003-2006

Other Sources Found

1. Government Reports – Scotland, Denmark, Wales, Sweden etc
2. Books
3. General public reports

Because there have been major wind energy developments in Germany in the recent past, articles in German – using German search terms – were also searched. There are no likely journal sources in German, and the only likely conference (DAGA) only publishes abstracts rather than full papers. Therefore the German language search focussed on the internet. Only two papers have been found in this way which were from the mid 1990s and in English.

5.3. Government reports and regulations

The current British guidelines and regulations are detailed in PPS2 (2004) for England, PAN45 (2002) for Scotland and TAN8 (2005) for Wales which can all be traced back to ETSU-R-97 (1997). The general role of these is to define acceptable noise levels for the protection of the population, to introduce consistent procedures for establishing and rating noise levels and to minimise noise levels from wind turbines. These documents were thoroughly reviewed in Hayes (2006).

Separate noise limits are applied for daytime and night-time. ETSU-R-97 indicates that the purpose of these different noise limits is that for night-time periods, the emphasis is on the prevention of sleep disturbance, whereas, the daytime noise limits are to protect the amenity value of the area and of a property in particular.

The noise limits take the form of a fixed level for periods when background L_{A90} noise levels are very low and a margin above the background once background noise levels increased due to wind effects. The daytime noise criterion is defined as “the greater of 35-40 dB L_{A90} or background + 5 dB” and for the night-time period “the greater of 43 dB L_{A90} or background + 5 dB”.

ETSU-R-97 has summarised the issue of blade swish/AM as follows: "*The noise levels recommended in this report take into account the character of noise described as blade swish. Given that all wind turbines exhibit blade swish to a certain extent we feel this is a common-sense approach given the current level of knowledge.*" The character of blade swish is described as "*irregular enough to attract attention*"," *to a degree, turbine-dependent*" and "*dependent upon the position of the observer*".

Since the publication of ETSU-R-97 a further review of European policies regarding wind turbine noise has been carried out by Pedersen (2003). Of particular interest are German legislation from 1999 and Dutch Legislation from 2001 as these were not reviewed in ETSU-R-97. In German legislation different noise limits are applied to different areas. The areas are industrial, mixed, residential and sensitive (for example, hospitals or health resorts). In Dutch legislation wind turbine noise limits are based upon a wind speed dependent curve which starts at 40dB (A) at night time, 50 dB (A) during the day and 45 dB (A) during the evening. None of these regulations makes any special allowances for AM.

5.4. Generation of wind turbine noise

There is a large body of literature relevant to noise generation by wind turbines. For example, there are many publications concerning noise from aerofoils, propellers, fans and helicopters which may be relevant. Fortunately, the fundamental issues for windturbines have been summarised in two text books, and most of the following few paragraphs are a distillation from these references.

Noise sources on wind turbines fall into two main categories: aerodynamic and mechanical. Mechanical noise sources are primarily connected with the electrical generation parts of the turbine, the gear box and the generator. These sources are generally located in the nacelle. The character of the noise generated is similar to that from other types of rotating machinery, and often includes an audible tone or note that might be described as a 'whine' or 'hum'. Noise with a pronounced tonal feature is generally recognised to be more annoying than noise of a comparable level but with neutral character. This subjective effect is recognised in the ETSU guidelines where a penalty is added which is related to the audibility of the tone. Mechanical noise was audible from early turbine designs. On modern designs the problem has been almost completely eliminated, although it may arise temporarily if there is a mechanical fault, such as worn bearings within the gear box/generator, worn teeth within the gear box, or misalignment of the generator drive shaft. This discussion of mechanical noise does not shed light on the causes of AM noise, but it does help to interpret some of the complaint statistics, many of which were from early turbine designs or due to a fault condition.

Apart from occasional fault conditions creating mechanical noise, the dominant noise generating mechanisms on modern turbines are aerodynamic. Aerodynamic sound is generated by pressure variations within the air which fluctuate at acoustic frequencies, i.e. between about 20 and 20,000 times per second. In wind turbines such fluctuating pressure is caused by flow turbulence. If hypothetically the flow of air into, and over the blades could be made completely smooth the major noise sources would disappear. In practice, the flow is generally turbulent and so some noise generation is inevitable.

First, air flowing into the blades due to wind is not completely smooth, but contains turbulent eddies of a range of sizes. These eddies are ‘ingested’ into the blade region and generate *inflow turbulence noise* as the blades chop through them. Second, as air flows over the surface of the blades, turbulence is generated close to the surface in the so called boundary layer. This boundary layer turbulence generates noise, particularly when it interacts with the trailing edge of the blade, which is therefore known as *trailing edge noise*. This is often the principal noise generating mechanism on wind turbines. Other types of turbulence are the vortices shed from the tip which generates *‘tip noise’* or from the trailing edge of the blade. Trailing edge vortices are stronger for blunt trailing edges and the associated noise is therefore called *blunt trailing edge noise*. The above four mechanisms, inflow turbulence, trailing edge noise, tip noise and blunt trailing edge noise, account for the majority of the noise from wind turbines, and on modern design blunt trailing edge noise is not a significant effect.

Other types of turbulence may also generate noise, but can be avoided. A condition known as 'stall' may occur and indeed is used to regulate rotational speed and power generation for some designs. This can generate noise up to 10dB higher than without stall. However, manufacturers are increasingly tending to move away from stall-regulated machines, particularly for machines of higher power, one of the main reasons being the higher noise levels they generate. Another possible cause of noise is flow over imperfections in the blade surface, for example damage due to holes in blades has been known to cause strongly noticeable tones. For large wind turbines with good manufacturing quality control, such imperfections would be considered a fault condition.

The frequency of the noise generated depends on the size of the turbulent eddies; broadly speaking large eddies produce low frequency noise and small eddies generate higher frequencies. Mostly, the character of aerodynamic noise is broad band, i.e. it does not contain a distinguishable note or tone, but is of more random character such as noise from rustling leaves, waterfalls, rain etc. The dominant character of the combined aerodynamic noise as described above is therefore a 'swish', which is familiar to most people who have stood near to a large wind turbine. Blade swish is not completely steady, but is modulated (fluctuates) at the rate at which the blades pass a fixed point, i.e. there is a cycle of increased and then reduced level which typically at the blade passing frequency of around once per second. In the majority of installations the modulation depth is a few dB which is subjectively acceptable. It is not clear why in some situations the modulation depth increases to the point where it becomes subjectively unacceptable, and therefore potentially annoying. In early wind turbine designs, where the rotor was positioned downwind of the tower, a pronounced 'thump' was caused as each blade passed through the wake shed from the tower. However, this effect is eliminated completely for the upwind rotor designs found on all new windfarm developments since the large scale uptake of wind energy development in the UK, and does not therefore explain the occurrence of AM.

It seems likely that AM is due to fluctuation in the strength of some of the above mechanisms rather than to some completely new mechanism. 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. Van den Berg has investigated this possibility and has postulated that in stable atmospheric conditions the difference in wind speed between the top and bottom of the rotor is relatively high. Therefore, the wind speed seen by a blade varies cyclically, which in turn may cause the noise level to vary once per revolution. This work is discussed in more detail in the next section.

Sound generation by turbulence is a highly complicated phenomenon that is still not completely understood despite a great deal of research into noise from fans, aircraft, and propellers, and great advances since the 1950s. Mathematical models for turbulence and turbulence generated noise have been developed but not to the stage where reliable prediction is possible from the drawing board. The occurrence of AM implies that fluctuations are occurring in the generating mechanisms, and the causes of such variations are still less well understood. There are no existing models by which AM can be predicted.

5.5. Propagation of wind turbine noise

In general noise propagation from wind turbines is determined by source directivity, geometric spreading and atmospheric absorption, ground reflections and absorption, meteorological effects and terrain complexity. The audibility of noise from wind turbines is then determined by the ratio between turbine and background noise, the so-called masking effect.

According to Oerlemans and Lopez (2005) AM noise from wind turbines is not equally loud in all directions but is radiated primarily from the outer part of the downward moving blade in the downward direction. This is the reason that AM noise can often be heard underneath the turbine but not further away because at a considerable distance the recipient is more in line with the horizontally propagated – weaker – noise.

This directional sound is then spreading as it travels away from the turbine**.** The so called geometric spreading decreases sound levels with increasing distance from any source. Atmospheric absorption also reduces the sound level with distance but is more effective at high frequencies with the consequence that low frequency sound travels further**.**

The main influence of meteorology is the change in sound speed profile due to wind shear and temperature profiles which is well described in Wagner et al. (1996). Most pronounced is the "shadow zone" upwind of the noise source and the increased noise levels in the down wind direction. In extreme inversion conditions sound rays from elevated sources can be bent back down to the ground downwind and create focussing effects at considerable distances from the sound source resulting in slightly enhanced noise immission relative to no-wind, no-inversion conditions (e.g. ISVR, 1991)..

To predict noise levels from wind turbines the wind speed is measured at 10 m height. Using a typical wind profile for neutral atmospheric conditions the wind speed is then extrapolated to hub height. In situations with large wind shear – low wind speed near the ground and high wind speed at hub height – the background noise created for example by vegetation noise close to the ground is small. The turbine blades experience a higher wind speed resulting in unexpectedly high aerodynamic noise levels. The lack of background noise then leaves the turbine noise more audible. Several authors report this reduction of the masking effect (Harders and Albrecht, 2005, Sloth, 2005, Golec and Golec, 2005, van den Berg 2003, 2004, 2005a). Both Klug (2005) and van den Berg (2003, 2004, 2005, 2005a, 2005b) find that high wind shear situations occur frequently during the night time in so called stable atmospheric conditions.

Because of its complex nature, the most debated meteorological influence on outdoor sound propagation is that from atmospheric turbulence. In the noise shadow, turbulence can lead to enhanced noise levels (Wilson 2000) compared to the high levels of attenuation normally found upwind of a noise source. It also spreads the sound more widely leading to a net-attenuation of highly directional noise (Salomons, 1994).

Many wind farms in countries like The Netherlands and Germany are situated in very flat terrain with no obstacles to influence sound propagation between the turbines and the immission sites. In the UK many sites are a lot more complex than that; partly in hilly or even mountainous terrain or in the middle of a forest. For these sites the sound propagation becomes a lot more complicated too. Bolin (2005) dedicates an entire publication to the systematic deployment of vegetation noise to mask turbine noise. Apart from absorption and reflections from obstacles which attenuate and enhance noise respectively, complex terrain also provides obstacles that act as a “noise screen” (Jacobsen, 2005, Prospathopoulos and Voutsinas, 2006). This effect is frequency dependent. If the size of the obstacle is a lot bigger than the wavelength it is an effective screen. For very low frequencies and small objects this is not always the case (Jacobsen, 2005).

One propagation phenomenon relating to AM noise is not yet well understood: In some situations AM noise seems to travel and can be heard at a considerable distance from the turbines. First explanation attempts have been published by van den Berg (2003, 2004, 2005) and it appears likely that a combination of generation and propagation mechanisms is responsible for this effect. Further studies are needed to explain and predict the observed noise levels.

5.6. Amplitude Modulation of Wind Turbine Aerodynamic Noise

Amplitude modulation of the noise associated with the operation of wind turbines was identified within the Report “*The measurement of low frequency noise at three UK wind farms: URN No: 06/1412*” issued by the DTI in July 2006. Within the conclusions of this report, the following were identified:

- Infrasound associated with modern wind turbines is not a source which will result in noise levels which may injurious to the health of a wind farm neighbour;
- Low frequency noise was measurable on a few occasions, but below the existing permitted Night Time Noise Criterion;

- That the common cause of complaint was not associated with LFN, but the occasional audible modulation of aerodynamic noise, especially at night.

The measurements undertaken and reported within the DTI Report identified periods during wind turbine operation when noise associated with the operation of the wind turbines varied in level at the blade passage frequency[2] of the wind turbines. When this variation in the noise associated with the operation of the wind turbines was noted by neighbouring residents, it was described as "*a distant train*" or "*distant piling*".

Measurements of the internal noise levels during these periods of wind farm operation indicate that A-weighted noise levels are subject to amplitude modulation levels of between 3 – 5 dB(A). Analysis of these periods using third octave band analysis indicates that between 200 – 800 Hz, noise levels in specific frequency bands may change between 8 – 10 dB. External measurements indicate that, for external A-weighted changes in level of 3 – 4 dB(A), third octave band levels may change by between 7 – 9 dB. Measurements reported for Wind Farm D (Table 1) have indicated that third octave band levels when complaints were received before the implementation of wind turbine control features, indicated level changes of 12–15dB. (All the above figures are ranges from peak to trough).

The finding that this modulation is concentrated between the frequency bands of 200 – 800 Hz is significant in that this is generally generated by the trailing edge of a wind turbine blade. This has been identified as one of the main sources of aerodynamic noise associated with the operation of wind turbines (Oerlemans and Lopez, 2005).

Trailing edge noise was identified by van den Berg (2006) as the most likely source of the modulation which he observed at a wind farm on the Dutch/Germany border. However, van den Berg postulates that the increased levels of modulation which he observed were associated with the change in the aerodynamic environment seen by a wind turbine blade as it passes in front of the wind turbine tower. He postulates that when the turbine is at this point, a decrease in the wind speed associated with the

[2] Blade passage frequency is the frequency at which the wind turbine blades pass a fixed point on the wind turbine rotor, typically assumed to be the wind turbine support tower. For a wind turbine operating at 30 rpm, with a three bladed rotor, this would equate to 90 blade passes a minute, or a blade passage frequency of 1.5 Hz.

presence of the tower will result in a change in the aerodynamic properties and therefore the noise generated by the wind turbine. Van den Berg considers that this is exacerbated by the increased atmospheric stability which occurs for his test site during the night hours. With increased atmospheric stability, the wind speed seen at the hub height of the wind turbine may be appreciably higher than that found at the lowest part of the rotor path, which is also where the effect of flow disturbance around the support tower is felt. Van den Berg's analysis indicated that the maximum change in noise levels based upon these conditions was from 2 ± 1 dB for neutral conditions increasing to 4.8 ± 1.7 dB for very stable atmospheric conditions. To achieve the levels of modulation that van den Berg measured on the façade of neighbouring dwellings, he suggests that multiple sources have added together to obtain increased levels of modulation which "phase" in and out to give increased periods of modulation of the aerodynamic noise.

However, measurement of the aerodynamic noise sources within Oerlemans and Lopez (2005) indicate that the tower/blade interaction is a source which is at least 12 dB below that associated with the downward sweep of the turbine blade. It is recognised that these measurements were undertaken in neutral atmospheric conditions for a location relatively close to the wind turbine, however, there is almost no indication of the presence of the wind turbine tower within the data. Therefore, the effect of the tower on an upwind wind turbine noise emission character as postulated by van den Berg is not borne out by measurements in the field.

Measurements of wind farm noise at sites in the UK indicate that where a wind farm has periods of increased AM, these are not necessarily related to periods of high wind shear. Wind Farm Site D, for example (see Table 1 above), is subject to periods of increased amplitude modulation when the wind is blowing from the east. An easterly wind does not increase the stability of the atmosphere seen by the wind turbines as this noise is associated with day and night-time operations, however, topographical effects result in some wind turbines being 'unsure' as to the wind direction. This is caused by the wind turbine wind vane being influenced by the wind direction at the hub height of the rotor but the wind direction at the lower arc of the rotor may be from a different direction. When specific wind turbines are stopped from operating the modulation all but disappears. Wind speed measurements from tall free-standing anemometer masts located atop hills indicate that there is little change in atmospheric stability between the day and night-time periods. However, locations in flat landscapes do indicate an increase in the wind shear which is associated with stable atmospheric conditions but not to the level described by van den Berg (2006).

On the basis of the above discussion, it is clear that the observed effects of amplitude modulation which is sufficient in level to initiate complaints associated with this acoustic feature is still not understood in sufficient detail to provide design guidelines to minimise the potential for such a feature and is also still subject to debate.

5.7. Psychoacoustics

There are two sets of psychoacoustic related literature which are of interest when considering the problem of AM noise emissions from wind farms; those which examine the effect of modulated noise on listeners and those which examine psychoacoustic phenomena directly caused by wind farms.

The perception of loudness is described in Moore (2004). The perceived loudness of a sound is found to be dependent upon intensity and frequency content. It is also different for different listeners. For wideband noise the smallest detectable amplitude change amounts to 0.5-1 dB depending upon the sensitivity of the listener.

The effect of amplitude modulation within diesel locomotive noise with respect to the annoyance it causes for humans is examined in Kanteralis and Walker (1988). It was found through subjective tests that the noise from a diesel locomotive type was rated as being annoying compared to an electric type locomotive despite both having similar low frequency content. The testing was carried out in a situation which replicates the listening conditions of a typical living room. The difference in annoyance was found to be related to a pulsing effect or amplitude modulation in the diesel engine case that occurred at the firing frequency of the diesel engine. The authors comment that if the modulation frequency is increased above 12 Hz the annoyance is decreased. However, as typical wind turbine blade passing frequencies are of the order of 1Hz this does not give much insight into the situation for wind turbine noise.

In a paper on the annoyance and known psychoacoustic effects for wind turbine noise Persson-Waye and Ohstrom (2002) report how the character of the noise from wind turbines built by five different companies is perceived by a small number of listeners. They conclude that levels of annoyance cannot be explained by the psychoacoustic parameters loudness, sharpness, fluctuation strength and modulation. Several studies, including Pedersen (2003), mention that although there is correlation between annoyance levels and sound levels, the annoyance is also influenced by visual factors and attitude to wind turbines.

Three publications by Pedersen and Persson-Waye (2004, 2005, 2006) report a significant relationship between A-weighted sound pressure level and annoyance and unexpectedly high annoyance levels. Apart from the given explanation of visual factors their methodology of using prediction models to determine the sound pressure levels could have been responsible for these results.

In summary, every psychoacoustic factor mentioned does not seem to be able to predict annoyance levels for wind turbines. The images used in descriptions of wind turbine noise and the fact that tonal and impact noise are perceived as more annoying than broadband noise suggests that information content in noise might be a key to understanding annoyance levels.

6. Survey of manufacturers worldwide

A survey of manufacturers of wind turbines was undertaken to determine whether AM has been identified by wind farm manufacturers as a potential source of annoyance, whether they have any understanding of its causes or possible mitigation measures.

A list of turbine manufacturers was obtained from the BWEA. The definition of a turbine manufacturer was a supplier of wind turbines with a minimum generating capacity of 250 kW. This rules out domestic scale wind turbines which are less likely to exhibit the type of noise under investigation due to the increased rotor speeds (higher blade passage frequencies) and potentially increased number of turbine blades.

Each wind turbine manufacturer listed in Table 2 below was contacted to obtain a relevant contact within the companies. The manufacturers with which contact was made are identified within Table 2 below.

Mkt Share	*Company*
12.9%	Gamesa Energy UK
17.7%	GE Energy
2.6%	Nordex UK Ltd
3.2%	REpower UK Ltd
5.5%	Siemens Wind Power
27.9%	Vestas Wind Systems a/s, Denmark
13.2%	Enercon GmbH, Germany
6.1%	Suzlon energy india
2.1%	Ecotechnia, Spain
2.0%	Mitsubishi, Japan
	Acciona, Spain
	Clipper Windpower USA
	EU Energy Germany
	Harokasan BV Netherlands
	Leitner AG Italy
	M. Torres, Spain
	Multibrid germany
	ScanWind Norway
	Vensys GmbH, Germany
	WinWinD, Finland

Table 4 Manufacturers of large turbines: World-wide market share

Of the manufacturers which were contacted through an e-mail request which outlined the scope of the study and which provided relevant background information, five manufacturers offered comments with respect to their experience. The majority of the other responses indicated that the contact, although being responsible for noise emissions testing for the turbines, had little or no knowledge of the issue of aerodynamic noise generation from a turbine.

It was commented upon by manufacturers that there is no need to assess the potential for high levels of modulation associated with the aerodynamic noise emissions of a wind turbine within IEC61400-11.

However, a German manufacturer indicated that analysis of the impulsivity of the emitted noise is undertaken for some wind turbine tests following the guidance used in Germany[3]. These measurements have been used for the reporting of impulsivity of the noise emitted by wind turbines and which are for installation within the German market. The method determines the Rating Level, L_r, of a single noise source or of an installation of similar sources or all sources from a noise source having an impact at a specified location. The Rating Level is determined from the following equation:

$$L_r = L_{eq} + K_I + K_T + K_R + K_S$$

where

L_{eq} is the equivalent continuous sound pressure level, as in DIN 45641, for the rating time, T_r;

K_I is the impulse adjustment;

K_T is the tone adjustment;

K_R is the adjustment for rest periods;

K_S is the adjustment allowing for special conditions.

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[3] DIN 45645-1 Ermittlung von Beurteilungspegeln aus Messungen, Teil1: Geräuschimmissionen in der Nachbarschaft: July 1996: DIN 45646-1 Determining noise rating levels from measured data: Part 1: Environmental Noise

Of particular interest when assessing the potential for modulation of the aerodynamic noise is the impulse adjustment which is defined within the Standard as follows:

$K_I = L_{FTeq} – L_{eq}$

where

L_{FTeq} is defined as the "Time-averaged maximum A-weighted level which is the maximum A-weighted level averaged over the measurement time interval, T";

The interpretation of this statement used in practice is to measure the difference between the maximum and average sound pressure level over 5 seconds and then to average all the 5 second values obtained during one minute. In formal terms this means that the 5 second value of $L_{FT(t)} – L_{eq(t)}$ is measured (where $L_{FT(t)}$ is the maximum A-weighted sound pressure level using a Fast time weighting) and the average of 20 subsequent values is then obtained. The one minute period is used because this accords with the time averaging period to determine the source noise levels of the wind turbine.

The Impulse adjustment K_I is equal to the level difference between L_{FTeq} and L_{eq}. If K_I is no greater than 2 dB, then no adjustment is made. When the difference is greater than 2dB, then the calculated value is applied as the appropriate correction.

The results of such measurements indicate that wind turbines rarely attract an acoustic feature correction associated with impulsivity as the rise time for the sound source is not sufficiently short, i.e. the onset of the sound is not sufficiently rapid. However, it should be noted that measurements are usually undertaken close to the wind turbine; if AM is caused by interaction between turbines, or is an effect concerned with sound propagation rather than with noise generation then measurements close to a turbine might not pick up an AM problem as perceived at a receiver location. Therefore, analysis of noise at receptor locations may lead to a different assessment as to the need for an adjustment for impulsivity.

A final comment is that the German impulsive correction as described above is intended as a rating method for an existing noise, rather than as a prediction method. It is not clear whether it could be used as a rating method suitable for AM, but this would warrant further investigation.

A Danish wind turbine manufacturer indicated that extreme wind shear may lead to local stall phenomena when the blade is in the top azimuth position. This might lead temporarily to increased levels of aerodynamic noise at the top of the rotor arc which would give modulated noise output consistent with AM. It was also indicated that assuming a neutral atmospheric condition may underestimate the source noise level of a wind turbine in actual conditions. In these circumstances, wind turbine noise immission levels would be higher than predicted and might lead to a greater audibility of wind turbine noise than might normally be expected. This relates to the findings and description of the overall sound pressure level measurements undertaken by van den Berg (2006).

One manufacturer indicated that from 30 turbine installations of their wind turbines, they have one turbine which exhibits high levels of modulation of the aerodynamic noise. This was thought to relate to high inflow turbulence associated with steep sided hills and dense forestry surrounding the turbine.

In summary, from the responses received, it is clear that few wind turbine manufacturers have any practical experience of this phenomenon and even fewer have any potential suggestions as to the cause.

7. Conclusions

1. A comprehensive survey has been conducted of all local authorities with windfarms in their district, or within a closely bordering district. The aim was to ascertain the prevalence of AM. (AM refers to amplitude modulation of aerodynamic noise, i.e. wind turbine noise with a greater than normal degree of fluctuation at about once per second which makes it more noticeable).

2. The survey achieved a 100% response rate. Results indicate that 27 out of the 133 windfarms operational at the time of the survey had received formal complaints about noise at some point in their history.

3. A more detailed survey was conducted among those authorities having received noise complaints. The results revealed that an estimated 230 complaints had been received since 1991, 152 of which were from a single site. The total number of complainants was 81 which is probably a more reliable figure than that for actual complaints.

4. Just under half of the complaints were about mechanical noise and therefore clearly not related to AM. There are four cases where AM appears to be a factor in the complaints, fourteen where it is not, and eight that are marginal.

5. The number of noise complaints about windfarms has been compared with complaint statistics for other types of noise. The total number of complaints about noise generally exceeds those from windfarms by between four and five orders of magnitude indicating that windfarm noise is a small scale problem in absolute terms. In relative terms about 20% of windfarm installations have been subject to complaints, but no data is available to compare this figure with that for other types of noise such as industrial noise.

6. In 16 out of 17 cases for which data is available the windfarm was not considered to be causing a statutory nuisance. In only one case was a statutory nuisance confirmed.

7. A further investigation of the four sites identified by the Local Authority with AM has shown that the conditions associated with AM might occur between about 7% and 15% of the time. It also emerged that for three out of the four sites the complaints have subsided, in one case due to the introduction of a turbine control system.

8. A survey of literature has shown that the causes of windfarm noise have been extensively researched. The general principles are well understood on the whole, although the complexity of turbulent flows means that prediction models are not yet completely reliable.

9. There is little published information on AM, only two peer-reviewed publications are available. The causes of AM are still open to debate, and the theories put forward to date do not apply to some UK sites where the phenomenon has occurred. We conclude that the causes of AM are not fully understood and that AM cannot be fully predicted at current state of the art.

10. A survey of wind turbine manufacturers has showed that some are aware of AM, but that few have practical experience of the issue. It seems unlikely that manufacturers have more advanced knowledge than is available in the literature. This confirms the conclusion in the previous paragraph that AM is not fully understood and cannot be fully predicted at present.

11. Considering the need for further research, 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. On the other hand, since AM cannot be fully predicted at present, and its causes are not understood we consider that it might be prudent to carry out further research to improve understanding in this area.

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9. Appendix: Detailed survey questionnaire

The following was sent to all LAs who responded 'Yes' to the scoping survey questionnaire. Note that the third question asking about the number of complainants was added to the last 7 questionnaires but not to the first 16. It was added because early responses indicated it would provide useful additional information.

Government Survey into Noise from Wind Turbines
(REF: NANR233)

We are most grateful for your response to Phase I of this survey which is intended to lead to improvements in guidance for assessing planning applications for wind turbines. This is the second phase of the survey. You are receiving this questionnaire because in the first phase you responded that you have had noise complaints about one or more of the wind farms in your area or about a wind farm in a bordering authority.

The aim of this phase is to establish the levels and nature of the reported noise complaints received across the UK relating to noise and vibration issues from wind turbines / wind farms, both historic and current. The Government is hoping for as close to a 100% response as possible in this phase.

You told us that you had received noise complaints about **X** wind farms

We would appreciate you taking the time to complete this questionnaire and emailing it back to us at EMAIL ADDRESS PROVIDED.

Please fill in a questionnaire table for each wind farm for which you have had complaints. We have helped you by listing all the windfarms you mentioned in Phase I of this survey.

Please would you return the questionnaire by email to EMAIL ADDRESS PROVIDED by xxxxxxxx.

Your response will be treated confidentially. The data will only be used for the purposes of this study. We will not identify any individuals. We may quote anonymously from the responses received. If we use the names of Local Authorities and/ or windfarms this will only be to indicate whether or not complaints have been received.
Salford University in conjunction with Hayes McKenzie have been appointed by the UK Government (funded by Defra, DTi, and DCLG) to undertake research into noise from windfarms. For details of why this work was commissioned please see http://www.dti.gov.uk/files/file35043.pdf . The aim of the work is to provide clearer advice to planning authorities about wind turbine planning applications.

Government Survey into Noise from Wind Turbines

(REF: NANR233)

Name of wind farm	
How many complaints were received about this wind farm?	
How many complainants contacted you about this wind farm?	
In what year was each complaint made? (if more than one complaint please list the years)	
Please provide a detailed description of the noise complaint(s): (eg, time of day, wind conditions, description of noise, any other factors that might have contributed to the complaint) THIS INFORMATION IS VERY USEFUL SO PLEASE USE AS MUCH SPACE AS NECESSARY. IF THERE WAS MORE THAN ONE COMPLAINT AND THE COMPLAINTS HAD DIFFERENT CAUSES PLEASE COMPLETE A SEPARATE TABLE FOR THE DIFFERENT TYPES OF COMPLAINT.	

Do any of the following terms describe the noise that was complained about at this wind farm site? (Please delete Yes or No as applies)					
Swish	**YES / NO**	Throbbing	**YES / NO**	‘train that never gets there’	**YES / NO**
Swoosh	**YES / NO**	Thudding	**YES / NO**	‘like motion sickness’	**YES / NO**
Ghostly Noises	**YES / NO**	Thumping	**YES / NO**	Whistling	**YES / NO**
Wooh Wooh	**YES / NO**	Pulsating	**YES / NO**	Rhythmical Beat	**YES / NO**
Beating	**YES / NO**	Whooshing	**YES / NO**	Other (please list):	**YES / NO**
Lapping	**YES / NO**	Distant Helicopter	**YES / NO**		
Grinding	**YES / NO**	Rumbling	**YES / NO**		

Did you visit the home of the complainant?	**YES / NO**
Did you visit the wind farm site?	**YES / NO**
Did you hear the noise that was being complained about?	**YES / NO**
Briefly describe the investigation that took place.	
Was the wind farm judged to be causing a noise nuisance?	**YES / NO**
What action, if any, was taken?	
This project is about Amplitude Modulation of Aerodynamic Noise (AM) which can be described as ‘Wind turbine blade noise which is modulated at blade passage frequency (typically once per second) with a sharper attack and a more clearly defined character than usual blade swoosh. It is sometimes described as being like a distant train or distant piling operations’. **Does the noise from this wind farm conform to this description?**	**YES / NO / DON’T KNOW**