WIND TURBINE AM REVIEW

PHASE 2 REPORT

CONFIDENTIAL

AUGUST 2016

WIND TURBINE AM REVIEW

PHASE 2 REPORT

Department of Energy & Climate Change

Issue 3 – Issued

Project no: 3514482A
Date: August 2016

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QUALITY MANAGEMENT

ISSUE/REVISION	DRAFT ISSUE	FIRST ISSUE	SECOND ISSUE	THIRD ISSUE
Remarks	Issued for external peer review	Issued for DECC review	Second Issue	Third Issue
Date	27.01.16	14.03.16	31.03.16	10.08.16
Prepared by	M. Lotinga	M. Lotinga	M. Lotinga	M. Lotinga
Signature				
Checked by	R. Perkins	R. Perkins	R. Perkins	R. Perkins
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Authorised by	R. Perkins	R. Perkins	R. Perkins	R. Perkins
Signature				
Project number	3514482A	3514482A	3514482A	3514482A
Report number	2	2	2	2
File reference	3514482A	3514482A	3514482A	3514482A

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PREAMBLE

The project has been undertaken by a research team lead by WSP | Parsons Brinckerhoff (the Internal Research Team), who are responsible for the overall editorial content of the report. During the project, help was sought from three Independent External Reviewers (IER), who undertook a number of paper reviews, providing commentary on the robustness and conclusions for those papers. They also provided a review of the entire document. Comments attributed to the IER are clearly signposted in the report.

An OAM Review Steering Group, chaired by DECC, was set up to agree the detail of the proposed approach to this work and to monitor progress. The Group provided a scrutiny and challenge function but it did not seek to influence the conclusions or recommendations, in order to maintain the independence of the research. The other Steering Group members were Public Health England (PHE); Department for Environment, Food and Rural Affairs (Defra); Department for Communities and Local Government (DCLG); Welsh Government; Scottish Government and Northern Ireland Executive. The [WSP | Parsons Brinckerhoff] project team were also invited to attend the Steering Group meetings.

A draft report was provided to three peer reviewers commissioned separately by DECC. This final report addresses the comments raised by the peer reviewers, and a spreadsheet detailing their comments and how they have been addressed in the report has been produced.

The authors would like to take this opportunity to thank all those who have assisted in gathering data, making papers available, and raising awareness with Stakeholders of this research.

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BACKGROUND

Current planning policy for the assessment and rating of wind turbine noise in England, Scotland, Wales and Northern Ireland refers to the ETSU-R-97[1] document. Wind turbines are known for their distinctive acoustic character often described as a 'swish', which is also referred to as amplitude modulation (AM). Recent evidence suggests that at times this 'swish' can become more of a pronounced 'thump', leading to complaints from wind farm neighbours.

In response to growing concerns about the impact of excessive AM on residents, WSP | Parsons Brinckerhoff was commissioned by the Department of Energy and Climate Change to undertake a review of research into the effects of and response to AM and, if considered necessary, to recommend a control method suitable for use as part of the planning regime.

AIMS

The aims of the study are to review the evidence on the effects of AM in relation to wind turbines, the robustness of relevant research into AM, and to recommend how excessive AM might be controlled through the use of a planning condition, taking into account the current policy context of wind turbine noise. The work included working closely with the Institute of Acoustics' AM Working Group, who have proposed a robust metric and methodology for quantifying and assessing the level of AM in a sample of wind turbine noise data.

METHOD

The study has involved the collation and critical review of relevant literature on the subject of AM, which included published papers on dose response studies, case studies, existing planning conditions, and current planning guidance. Key points from the reviewed evidence have been extracted and summarised upon which to draw the reports' conclusions.

CONCLUSIONS

The review has concluded that there is sufficient robust evidence that excessive AM leads to increased annoyance from wind turbine noise, and that it should be controlled using suitable planning conditions. Key elements required to formulate such a condition have been recommended.

RECOMMENDATION

It is recommended that excessive AM is controlled through a suitably worded planning condition which will control it during periods of complaint. Those periods should be identified by measurement using the metric proposed by work undertaken by the Institute of Acoustics, and enforcement action judged by Local Authority Environmental Health Officers based on the duration and frequency of occurrence.

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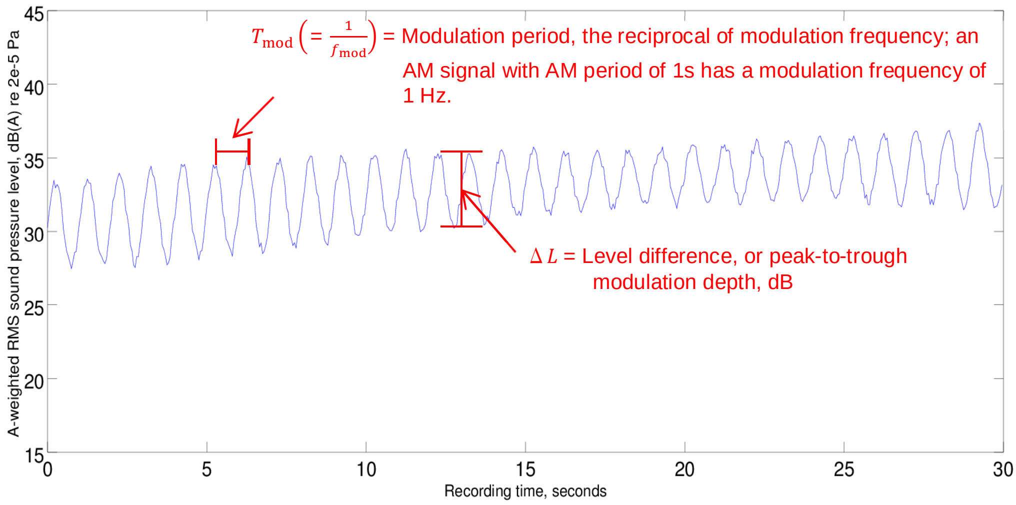
[1] *ETSU-R-97 The assessment and rating of noise from wind farms,* The Working Group on Noise from Wind Turbines Final Report September 1996

EXECUTIVE SUMMARY

WSP | Parsons Brinckerhoff has been commissioned by the Department of Energy and Climate Change (DECC) to undertake a review of research into the effects of and response to the acoustic character of wind turbine noise (WTN) known as Amplitude Modulation (AM).

The diagram below illustrates an example of a signal exhibiting amplitude modulation, and how the terms of modulation frequency and depth are defined.



In WTN, these fluctuating AM characteristics are commonly perceived as sounds that could be described as 'swish', or less frequently as 'thump'. Further definitions of amplitude modulation, fluctuation sensation and relevant acoustical concepts are described in an Appendix to this report.

At the time of writing, planning policy in England, Scotland, Wales and Northern Ireland refers to the ETSU-R-97[2] document for the assessment and rating of wind turbine noise. This planning guidance document is supplemented by a Good Practice Guide[3] (GPG) which is currently endorsed by all four Governments.

The ETSU-R-97 and GPG documents set out how noise assessments should be undertaken at the planning stage in the United Kingdom. It should be noted that the acoustic descriptor $L_{A90,\ 10min}$ is used for both the background noise and the wind turbine noise, and that the noise levels recommended in ETSU-R-97 *"take into account the character of noise described as blade swish."* That is to say that a certain level of amplitude modulation is included within the recommended noise limits.

The objective of this project has been to review the current evidence on the human response to WTN AM, evaluate the factors that contribute to human response (such as level, intermittency, frequency of occurrence, time of day, etc.), and recommend how excessive AM might be controlled through the use of a planning condition. The work has been undertaken in two Phases. This report relates to Phase 2, and should be read in conjunction with the Phase 1 report.

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[2] *ETSU-R-97 The assessment and rating of noise from wind farms,* The Working Group on Noise from Wind Turbines Final Report September 1996

[3] *A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise*, Institute of Acoustics, May 2013

The project work for Phase 2 has involved the collation and critical review of relevant papers, existing planning conditions, and existing planning policies where they relate to AM from wind turbines. Based on a combination of the evidence found and professional experience, a recommendation has been made on the potential make up of a planning condition to control AM. It should be noted that the condition has been designed only for new planning applications, and applicability for use in Statutory Nuisance investigations (where methodologies and acceptability criteria are different to those used for planning enforcement) on existing wind turbine sites has not been considered as part of this review.

The collated research was split into two categories. 'Category 1' papers comprised only those studies specifically investigating a scaled response to quantified AM WTN exposure, while 'Category 2' papers covered any other papers considered relevant to AM, such as complaints-triggered case-studies, broader epidemiological studies, and research into the psychoacoustics of WTN sound characteristics.

The main conclusions from the Category 1 studies reviewed in Section 3.2 can be summarised as follows:

- Within both laboratory and field test environments there is a strong association between increasing overall time-average levels of AM WTN-like sounds with increasing ratings of annoyance.
- Within a laboratory test environment:
  - subjects rated noticeable modulating WTN-like sounds as more annoying than similar noise without significant modulation;
  - the onset of fluctuation sensation for a modulating WTN-like sound appeared to be in the region of around 2 dB modulation depth;
  - increasing modulation depth above the onset of fluctuation sensation showed a broadly increasing trend in mean ratings of annoyance, but changes in mean annoyance rating tended to be relatively small and in some cases inconsistent;
  - equivalent annoyance ratings of AM and steady WTN-like sounds derived by level adjustment did not show a strong increasing trend with increasing depth of modulation; and
  - equivalent 'noisiness perception' of WTN-like AM sounds compared with a steady sound showed a gradually increasing trend with modulation depth.

It was also concluded that the results from both the laboratory and field studies should be approached with caution, since they may not readily translate to how people respond to WTN exposure in their homes[4].

The Category 2 papers reviewed in section 3.3 provide supporting evidence that:

- Perception of amplitude modulation in WTN and other environmental sounds affects subjective annoyance;
- There is a potential association between WTN-related annoyance and increased risks of sleep disturbance and stress;
- There are non-acoustic factors that play an important role in influencing the subjective annoyance attributed to noise from wind turbines, including sensitivity, attitude, situation,

[4] The field studies typically quantify noise exposure externally to the properties, but exposure (especially at night) could often be indoors.

aesthetic perception and economic benefits (this is common to many other industrial noise sources as well); and

- Annoyance due to AM WTN seems to be increased during normal resting periods, i.e. late evening / night-time / early morning. This could be due to increased sensitivity, greater AM prevalence or magnitude (e.g. due to diurnal variations in atmospheric conditions) or a combination of these factors.

It is noted that none of the Category 1 or 2 papers have been designed to answer the main aim of the current review in its entirety. The Category 1 studies have limited representativeness due to sample constraints and the artificiality of laboratory environments, whereas the Category 2 studies generally do not directly address the issue of AM WTN exposure-response. A meta-analysis of the identified studies was not possible due to the incompatibility of the various methodologies employed. Notwithstanding the limitations in the evidence, it was agreed with DECC that the factors to be included in a planning condition should be recommended based on the available evidence, and supplemented with professional experience.

The prevalence of unacceptable AM has not been evaluated as part of this study, and current state of the art is that the likely occurrence cannot be predicted at the planning stage. That does not preclude future research to determine the likelihood of AM occurring coming forward, and the development of a risk based evaluation, or similar. Due to the lack of ability to predict AM occurring on a site, and the reported difficulties in applying Statutory Nuisance provisions to control AM on existing sites, it is likely that the default position for a decision maker would be to apply the condition on all sites unless evidence is presented to the contrary.

The review concludes that where there are high levels of AM[5], the adverse effects could be significant. On this basis a control for AM is required, and this could be achieved via a suitably-worded planning condition imposing action on the operator of the turbine(s) to reduce the impacts identified. The condition must accord with existing planning guidance, and should be subject to legal advice on a case by case basis.

The few existing planning conditions or suggested methods in existence to control AM have been reviewed as part of the project. The methods include the well documented condition for the Den Brook[6] wind farm, a sample condition from Renewable UK[7] and proposals to use the method in British Standard BS 4142:2014.

Following the review, the elements required for a suitable planning condition to control AM have been recommended. It is noted that the AM control has only been designed for use with new planning applications; applicability for use in Statutory Nuisance investigations on existing wind turbine sites, where the legal regime is different (and outside the project scope), has not been considered as part of this review.

Any condition developed using the elements proposed in this study should be subject to a period of testing and review. The period should cover a number of sites where the condition has been implemented, and would be typically in the order of 2-5 years from planning approval being granted.

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[5] At present it is not possible to predict whether AM will or will not be prevalent on a site.
[6] http://www.den-brook.co.uk/
[7] http://www.renewableuk.com/en/publications/index.cfm/template-planning-condition-am-guidance-notes

PROPOSAL FOR PENALTY SCHEME

The review found that the planning condition should include the following elements:

- ✓ The AM condition should cover periods of complaints (due to unacceptable AM);
- ✓ The IOA-recommended metric[8] should be used to quantify AM (being the most robust available objective metric);
- ✓ Analysis should be made using individual 10-minute periods, applying the appropriate decibel 'penalty' to each period (using Figure 12), with subsequent bin- analysis;
- ✓ The AM decibel penalty should be additional to any decibel penalty for tonality;
- ✓ An additional decibel penalty is proposed during the night time period to account for the current difference between the night and day limits on many sites to ensure the control method works during the most sensitive period of the day, i.e. the night-time period (this addition would not apply to situations in which other planning conditions dictate the limits to be set as lower for night-time than for daytime).;
- ✓ Professional judgement should be used for planning enforcement of the AM condition in terms of frequency and duration of breaches identified; and
- ✓ The condition is only designed for upwind, 3-bladed turbines with rotational speeds up to approximately 32 RPM[9]. Further research is needed for turbines with higher rotational speeds or greater numbers of blades[10].

Further research has been recommended to supplement the limitations of the available research which underpins the above recommendation, although if the proposed penalty system, when implemented in a suitable planning condition, achieves the aim of reducing the impact from AM, then this research may not be required.

[8] *A Method Rating Amplitude Modulation in Wind Turbine Noise,* Institute of Acoustics Noise Working Group (Wind Turbine Noise), 2016

[9] Specifically, the IOA metric is limited to a working upper modulation frequency of around 1.6 Hz, and the exposure-response research underpinning the proposed penalty system addresses modulation frequencies within the 0-1.5 Hz range.

[10] Both of these factors affect the AM character due to the 'blade passing frequency', as explained in Appendix A Glossary & Concepts.

1 INTRODUCTION

1.1 GENERAL

1.1.1 WSP | Parsons Brinckerhoff has been commissioned by the Department of Energy and Climate Change (DECC) to undertake a review of research into the effects of and response to the acoustic character of wind turbine noise (WTN) known as Amplitude Modulation (AM), or more specifically an increased level of modulation of aerodynamic noise as perceived at neighbouring residential dwellings. A glossary of acoustical terminology and concepts relevant to WTN and AM is included in Appendix A.

1.1.2 At the time of writing, planning policy in England, Scotland, Wales and Northern Ireland refers to the ETSU-R-97 (Energy Technology Support Unit Working Group on Noise from Wind Turbines, 1996) document for the assessment and rating of wind turbine noise. This planning guidance document is supplemented by a Good Practice Guide (GPG) which is currently endorsed by all four Governments, published by the Institute of Acoustics (IOA, 2013).

1.1.3 The ETSU-R-97 and GPG documents set out how noise assessments should be undertaken at the planning stage in the United Kingdom, The following aspects of the assessment process are particularly drawn out for later reference:

- The acoustic descriptor $L_{A90,\ 10min}$ is used for both the background noise and the wind turbine noise. In the case of wind turbine noise, the $L_{A90,\ 10min}$ is expected to be about 1.5-2.5dB(A) less than the L_{Aeq} measured over the same period. The reason stated for the use of the $L_{A90,\ 10min}$ descriptor for wind turbine noise is *"to allow reliable measurements to be made without corruption from relatively loud, transitory noise events from other sources."*
- The noise levels recommended in ETSU-R-97 *"take into account the character of noise described as blade swish."* That is to say that amplitude modulation is included within the recommended noise limits.
- ETSU-R-97 contains a separate assessment method for the identification of tonality in wind turbine noise, and a prescribed 'penalty'[11] system is stated which adds a decibel penalty to the overall noise level to be compared to the noise limits.

1.1.4 Concern about AM has been growing over recent years. The issue is routinely brought up at planning meetings and Public Inquiries for new wind turbine schemes, and it is alleged that complaints to Local Authorities relating to AM from wind turbines are increasing[12]. The extent of the problem is unclear, due in part to a lack of agreement on the definition of the type and degree of AM in wind turbine noise that could lead to complaints, and suggestions from residents groups that some complaints are not being reported through Local Authorities. While a national survey of noise attitudes (SoNA) and annoyance has recently been published (AECOM, 2015), wind turbine noise does not feature in the key findings, a fact that may reflect the relatively small proportion of the UK population exposed to WTN.

1.1.5 A recent study of wind farm impacts in Scotland indicated that AM could be perceived by residents in around two thirds of the ten case study sites, however specifics about the AM (such

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[11] Throughout this report, unless otherwise stated, 'penalty' refers to a numerical decibel penalty, as contrast with other forms, for example financial or legal penalties.

[12] See later reviews in Section 3 for more details.

as the magnitude affecting the descriptions) were less clear (SLR & Hoare Lea, 2015). The study also noted that a large majority of the surveyed residents were not affected by noise from the wind farms.

1.1.6 The Institute of Acoustics (IOA) formed an AM working group (AMWG) in the summer of 2014. The work of the group has been to undertake a review of the current knowledge of AM, to agree a definition of AM which is consistent with the likelihood of complaints, and to define a robust metric and methodology to quantify AM when it is present within wind turbine noise. A proposal for three metrics was consulted upon in 2015, and a preferred metric has been proposed as providing the most robust method to quantify AM in field measurements of wind turbine noise.

1.1.7 The objective of this project is to review the current evidence on the human response to AM, evaluate the factors that contribute to human response (such as level, intermittency, frequency of occurrence, time of day, etc.), and recommend how excessive AM might be controlled through the use of a planning condition. Where possible, a method to assess the likely impacts of the decision on the level of AM control in relation to current Government planning policy, and potential health effects will be set out.

1.1.8 The work has been undertaken in two Phases. This report relates to Phase 2, and should be read in conjunction with the Phase 1 report.

1.2 STUDY AIMS

In order to achieve the project objectives, the aims of this study are:

- → To review the evidence on the effects of, and response to, AM in relation to wind turbines, focussing on any peer reviewed literature, and including but not limited to the research commissioned and published by RenewableUK (RUK) in December 2013;
- → To work closely with the Institute of Acoustics' AM Working Group, who are expected to recommend a preferred metric and methodology for quantifying and assessing the level of AM in a sample of wind turbine noise data;
- → To review the robustness of relevant dose-response relationships, including the one developed by the University of Salford as part of the RUK study;
- → To consider how, in a policy context, the level(s) of AM in a sample of noise data should be interpreted;
- → To recommend how excessive AM might be controlled through the use of an appropriate planning condition; and
- → To consider the engineering/cost trade-offs of possible mitigation measures.

2 METHODOLOGY

2.1 APPROACH

2.1.1 The project work for Phase 2 has involved the following steps:

Phase 2

1.	Undertake the search for relevant papers; Obtain copies of all relevant evidence, including the RUK work
2.	Critically review the robustness of the relevant studies into the subjective response to AM, and any penalty schemes
3.	Critically review the RUK proposed planning condition in the context of ETSU-R-97[13] and the "six tests" for a planning condition. These tests are listed in the NPPF[14] and other Devolved Authority Planning Guidance
4.	Summarise (for a non-technical audience) main findings of the review
5.	Recommend an appropriate penalty scheme (or alternative) for use in a planning condition, compatible with the IOA AM Working Group's preferred metric
6.	Prepare a draft report summarising the main findings and setting out clear recommendations, in a form suitable for publication by DECC.
7.	Amend the report in light of peer review comments, and produce a final report.
8.	Present the main findings and recommendations to the IOA's AM Working Group and, separately, to DECC's Steering Group.

2.1.2 This report includes the output from steps 1 to 6 inclusive.

2.2 STAKEHOLDER CONTACT

2.2.1 A number of Stakeholders were contacted to raise awareness of the research, and secondly solicit responses on research work in hand, or papers about to be released. These Stakeholders represent a wide range of Local Authorities, Trade Bodies, Residents Groups and Universities

[13] Energy Technology Support Unit Working Group on Noise from Wind Turbines (1996)
[14] National Planning Policy Framework in England (DCLG, 2012), or equivalent documents in Wales, Scotland and Northern Ireland

involved in research in the field. The list of Stakeholders was drawn up in consultation with the OAM Review Steering Group, and the final list of those consulted is shown in Table 1.

Table 1: Stakeholder List

No.	Body
1	Anglesey / Ynys Mon Council
2	Armagh, Banbridge and Craigavon Council
3	Cardiff University Psychology Dept
4	Carmarthenshire County Council
5	Chartered Institute of Environmental Health
6	Friends of the Earth / (Cymru)
7	Harrogate Borough Council
8	Highland Council
9	Huntingdonshire District Council
10	Institute of Acoustics AM Working Group
11	Institute of Acoustics Scottish Branch
12	Local Government Association
13	Midlothian Council
14	Montgomeryshire Against Pylons
15 & 16	Planning Scotland
17	Powys District Council
18	Powys Wind Farm Supporters
19	RenewableUK
20	Scotland Against Spin
21	Scottish Borders Council
22	Scottish Government Inquiry Reports Unit
23	Scottish Industry Policy
24	South Cambridgeshire District Council
25	The Independent Noise Working Group
26	The Planning Inspectorate
27	Waveney District Council
28	Welsh Local Government Association
29	West Lothian Council
	Research Institutions:
30	The University of Salford
31	The University of Tokyo
32	Seoul National University
33	Ghent University

2.2.2 A summary of the responses is included in Section 3.1.

2.3 EVIDENCE REVIEW METHODOLOGY

OVERVIEW

2.3.1 The purpose of the literature review was to establish the current level of knowledge of AM, and the extent to which the human response to AM is understood. In order to undertake the reviews, the papers were initially categorised as follows:

1. Research directly addressing a scaled response to a quantified human exposure to amplitude-modulated wind turbine noise (real or simulated)
2. Other papers (e.g. self-reported complaints, anecdotal evidence, etc.)

2.3.2 Category 1 papers were each reviewed by two of the independent external reviewers. Category 2 papers have been catalogued, reviewed by the internal research team, and where deemed to be important, also reviewed by an independent external reviewer. A summary of the review outcomes for Category 1 and 2 papers are contained in sections 3.2 and 3.3 respectively.

PROCESS

2.3.3 The following databases were searched for ‘black’ literature (i.e. independently peer-reviewed and published in recognised and reputable journals, and searchable in research databases):

- Web of Science
- PubMed

2.3.4 The search terms used were those identified and agreed at Phase 1, as summarised in Table 2.

Table 2: Keywords for Literature Search

a)	**Wind Turbine Noise**	
	NOISE	QUALITY OF LIFE
	WT	SOUND QUALITY
	WIND TURBINE	JUDGEMENT
	AMPLITUDE	FLUCTUATION
	MODULATION	FLUCTUATING
	WIND FARM	FLUCTUATE
	WTG	WIND TURBINE GENERATOR
	DOSE	NUISANCE
	RESPONSE	COMPLAINTS
	DOSE-RESPONSE	EXPOSURE
	ANNOYANCE	ACCEPTABILITY RATING
	ANNOYING	THRESHOLD
	SLEEP	PENALTY
	HEALTH	SWISH
	WELLBEING	THUMP
	AM	MENTAL HEALTH
	RHYTHMIC	NOISE SENSITIVITY
	FLUTTER	EXPERIENCE
	SWOOSH	EXPERIENTIAL
	WHOOSH	LOW FREQUENCY

Table 2: Keywords for Literature Search		
b)	**Other Areas**	
	NOISE	QUALITY OF LIFE
	AMPLITUDE	SOUND QUALITY
	MODULATION	PRODUCT SOUND QUALITY
	AM	JUDGEMENT
	DOSE	FLUCTUATION
	RESPONSE	FLUCTUATING
	DOSE-RESPONSE	FLUCTUATE
	ANNOYANCE	NUISANCE
	ANNOYING	COMPLAINTS
	SLEEP	EXPOSURE
	HEALTH	ACCEPTABILITY RATING
	WELLBEING	HELICOPTER BLADE SLAP
	THRESHOLD	HELICOPTER NOISE
	PENALTY	SWISH
	FLUTTER	MENTAL HEALTH
	RHYTHMIC	NOISE SENSITIVITY
	THUMP	LOW FREQUENCY

2.3.5 These terms were combined where possible using Boolean operators to narrow the results. The date range was generally limited to 2000-present. Example combinations are given in Table 3 (other combinations were also employed):

Table 3: Example Combinations of Keywords for Literature Search

Database	Search terms	Results
Web of Science	TS=((nois* OR sound) AND ((wind NEAR (farm* OR turbine* OR generator)) OR WTG OR WT) AND (AM OR amplitude OR modulation OR rhythmic OR flutter OR swoosh OR whoosh OR fluctuat* OR swish OR thump OR "low frequency") AND (dose OR response OR dose-response OR exposure OR exposure-response OR annoy* OR sleep OR health OR (well NEAR/5 being) OR "quality of life" OR "sound quality" OR judgement OR nuisance OR complaints OR "acceptability rating" OR threshold OR penalty OR (mental NEAR health) OR sensitiv* OR experien*))	146 results on 30/10/2015
PubMed	((((((((nois*[Title/Abstract] OR sound[Title/Abstract])) AND ("wind farm"[Title/Abstract] OR "wind turbine"[Title/Abstract] OR "wind farms"[Title/Abstract] OR "wind turbines"[Title/Abstract] OR WTG[Title/Abstract] OR WT[Title/Abstract]))) AND (amplitude[Title/Abstract] OR modulation[Title/Abstract] OR AM[Title/Abstract] OR exposure[Title/Abstract] OR dose[Title/Abstract] OR response[Title/Abstract])))))	115 results on 03/11/2015

2.3.6 The titles and abstracts of the search results were examined to identify relevant literature. In addition to the searchable databases, conference proceedings were searched for further 'grey' literature (i.e. non-independently peer reviewed, or where peer review status is uncertain), including from the following sources:

- International Commission on the Biological Effects of Noise (ICBEN) Congress
- International Meeting/Conference on Wind Turbine Noise
- International Meeting on Low Frequency Noise and Vibration
- International Congress on Sound and Vibration (ICSV)
- International/European Congress and Exposition on Noise Control Engineering (Inter-noise/EuroNoise)

2.3.7 Finally, any other additional literature made known to the research group or identified from reference lists was added to the database. A total of 134 publications were identified using this process. The full list of identified papers is included in Appendix B.

2.3.8 The titles and abstracts of the list were reviewed to classify the papers in terms of relevance to the study aims. On this basis, papers addressing only physical source mechanisms and measurement techniques for AM WTN were specifically excluded. At the end of this process, 69 separate publications were shortlisted for more detailed review.

2.3.9 The detailed reviews were carried out using a standard process framework to extract specific details about each paper, including the quality, conclusions and risks of bias (see Appendix C for included categories). At the inception of the review process it was hoped that a recognised research quality rating scale could be applied to allow direct comparison, and the Newcastle-Ottawa Scale (Wells, et al.) was initially considered as a potentially useful candidate (Zeng, et al., 2014). It swiftly became clear that the design of the most relevant studies, which were primarily laboratory-based, uncontrolled and cross-sectional in nature, did not lend themselves well to this type of rating scale and the results would therefore not yield useful comparative information. As a result it was decided that weighted consideration would be determined by reviewers based on their judgement of the importance of the study relative to the aims of this research. For the key publications, i.e. those within the first category described above, two external reviewers independently reviewed each paper, and the results were compared. Conclusions and applications to be drawn from the studies were agreed by discussion.

2.3.10 Prior to the first draft of this review report, a final check was made (16th March 2016) in the database sources referred to above, to ensure no relevant new research had been published in the interim.

STUDY LIMITATIONS

2.3.11 It is noted that applying the search terms and filtering the papers as stated could introduce selection and publication bias into the process. The risk of bias in any review cannot be eliminated, but steps were taken to minimise this risk as described above, i.e. by searching more than one database, including searches of grey literature, by defining the categorisation criteria and by defining a protocol for reviewers to complete the reviews.

2.3.12 For studies falling into Category 1, the risks of selection bias are extremely low, given the relatively small body of existing literature.

2.3.13 Selection bias in Category 2 is more probable due to the wider range and volume of studies identified, and it has been acknowledged in section 3.3 that some studies have been specifically excluded. This is most relevant to the epidemiological papers addressing the potential health effects relating to general WTN exposure, in which the AM component has not been specifically quantified or rated. This body of literature is relatively large, and represents a wide range of different theories, results, views and opinions. The current review of this work has focussed on recent, existing systematic reviews, and recent large-scale field studies only. The conclusions drawn from this work may therefore be questioned on the basis of selection bias, but it should be noted that these conclusions do not impose significant practical influence on the outputs of this research, i.e. a recommendation for an AM planning control.

2.3.14 Wind turbine acoustics is a swiftly-developing field of knowledge, and new research is published on a regular basis. The drafting and review process of this report took place over a period of months, and consequently new study material inevitably came to light after the review period had been completed. In particular, two papers appeared in the peer-reviewed literature prior to the final draft that would have met the Category 1 criteria in the review. These papers have not been reviewed by the independent external reviewers, but the main findings and possible implications have been briefly outlined by the internal research team in the Annexes to this report (Annex 1 and Annex 2). To summarise the findings, both studies are believed to broadly support the recommendations made for a proposed planning control.

3 REVIEW SUMMARY

3.1 STAKEHOLDER RESPONSES

3.1.1 A number of Stakeholders identified during the Phase 1 work were contacted by email firstly to raise awareness of the research, and secondly solicit responses on research work in hand, or papers about to be released. A number of the Stakeholders responded to the email, the key points of which are summarised below:

- ✓ No new WTN AM research was identified that the team were not able to find through the searches undertaken, or from previous knowledge that was considered to be relevant to the study. Other non-AM research was noted by two Stakeholders, but was also not relevant to the study;
- ✓ Some of the Local Authorities contacted are currently investigating noise complaints from wind farms sites with suspected AM aspects. None of these investigations had been concluded at the time of writing (Jan 2016); and
- ✓ The papers produced by the Independent Noise Working Group (INWG)[15] were referenced a number of times. These have been included in the Category 2 review in section 3.3.

3.1.2 There was also general feedback that there is a need for an AM control through the planning system.

3.2 CATEGORY 1 PAPERS

INTRODUCTION

3.2.1 The literature search yielded five studies directly investigating a scaled response to quantified AM WTN exposure: 3 laboratory-based and 3 field-based (one study was composed of both field and laboratory components).

3.2.2 The identification details of these studies are summarised below, including the nature of the publication (in square brackets; black = independently peer-reviewed paper; grey = not independently peer-reviewed, or peer review status uncertain).

[15] http://www.heatonharris.com/reports-publications

Table 4: Category 1 Research Papers

Study	Lead research group	Relevant key publications	Study type
A	Seoul National University, Korea	*An estimation method of the amplitude modulation in wind turbine noise for community response assessment* (Lee, Kim, Lee, Kim, & Lee, 2009) [grey] *Annoyance caused by amplitude modulation of wind turbine noise* (Lee, Kim, Choi, & Lee, 2011) [black] *An experimental study on annoyance scale for assessment of wind turbine noise* (Seong, Lee, Gwak, Cho, Hong, & Lee, 2013a) [black] *An experimental study on rating scale for annoyance due to wind turbine noise* (Seong, Lee, Gwak, Cho, Hong, & Lee, 2013b) [grey]	Lab
B	The University of Tokyo, Japan	*Study on the amplitude modulation of wind turbine noise: part 2 – auditory experiments* (Yokoyama, Sakamoto, & Tachibana, 2013) [grey] *Audibility of low frequency components in wind turbine noise* (Yokoyama, Sakamoto, & Tachibana, 2014a) [grey] *Perception of low frequency components in wind turbine noise* (Yokoyama, Sakamoto, & Tachibana, 2014b) [black] *Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise* (Yokoyama, Koboyashi, Sakamoto, & Tachibana, 2015) [grey] *Nationwide field measurements of wind turbine noise in Japan* (Tachibana, Yano, Fukushima, & Sueoka, 2014) [black] *Outcome of systematic research on wind turbine noise in Japan* (Tachibana, 2014) [grey]	Lab/field
C	The University of Salford, UK	*Wind turbine amplitude modulation: research to improve understanding as to its cause & effect. Work package B(2): development of an AM dose-response relationship* (von Hünerbein, King, Piper, & Cand, 2013) [grey] *Affective response to amplitude modulated wind turbine noise* (von Hünerbein & Piper, 2015) [grey]	Lab
D	Ghent University, Belgium	*Wind turbine noise: annoyance and alternative exposure indicators* (Bockstael, Dekoninck, de Coensel, Oldoni, Can, & Botteldooren, 2011) [grey] *Reduction of wind turbine noise annoyance: an operational approach* (Bockstael, Dekoninck, Can, Oldoni, de Coensel, & Botteldooren, 2012) [black]	Field
E	The University of Adelaide, Australia	*Characterisation of noise in homes affected by wind turbine noise* (Nobbs, Doolan, & and Moreau, 2012) [grey]	Field

REVIEW

3.2.3 The research papers discussed in this section were reviewed by the independent external reviewers.

STUDY A

SUMMARY I

3.2.4 A group at Seoul National University conducted a state-funded laboratory study aimed at developing a scale for rating annoyance from AM WTN.

3.2.5 There were two distinct stages to this work: the first (I) is described by Lee et al. (2009), (2011). This experiment used modified turbine sound recordings as stimuli and subjects rated 'annoyance' on an 11-point scale according to ISO 15666:2003 (ISO, 2003). The results indicated a strong and statistically significant association between the annoyance and the overall A-weighted time-averaged level of the noise, as shown in the reproduced Figure 1. The direct relationship between the modulation and the mean annoyance ratings was not presented graphically, but reanalysis of the results produces the charts shown in Figure 2, with overall average level as a parameter. This indicates a broadly increasing trend, but with relatively small changes in mean annoyance over the range of modulation depths[16]; almost all of the samples showed a change in the mean annoyance of less than 1 scale interval across the entire range of modulation depths (compared with 4-5 intervals for changes in level).

3.2.6 The spread in the data was also not presented and the statistical analysis produced a range of results: analysis of variance (ANOVA) indicated a significant relationship between annoyance and modulation depth at the 5% level, but statistically significant differences were not consistent across the stimuli set; only the samples featuring the two maximum and the minimum AM depths[16] could be distinguished in paired comparisons (also at the 5% level).

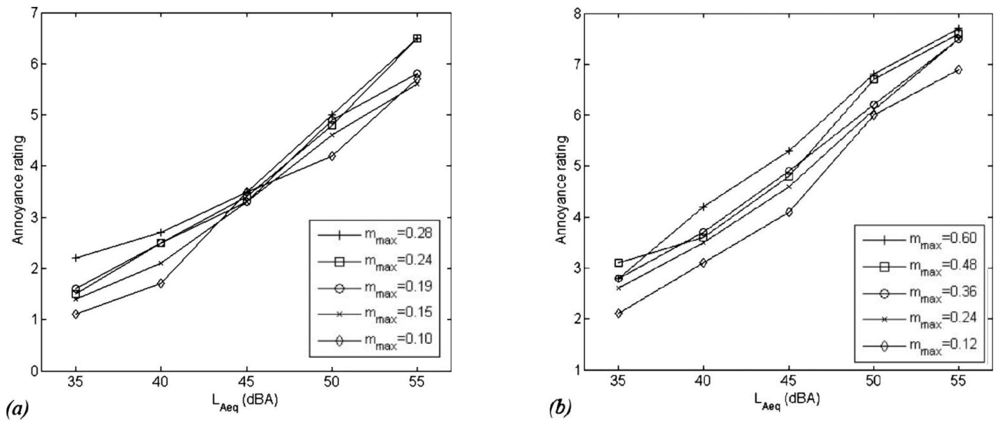

Figure 1: Association of amplitude-modulated wind turbine noise level with mean annoyance ratings over a range of modulation depths (as parameter) for two sample sets, one with higher low-frequency spectral content (left) and one with higher mid and high-frequency content (right), from (Lee, Kim, Lee, Kim, & Lee, 2009)

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[16] In terms of $\Delta L = 20\log_{10}(1+m/1-m)$ as defined by Fastl and Zwicker (2007), but replacing the general modulation factor m with the spectral maximum m_{max} obtained using a Fourier Transform method.

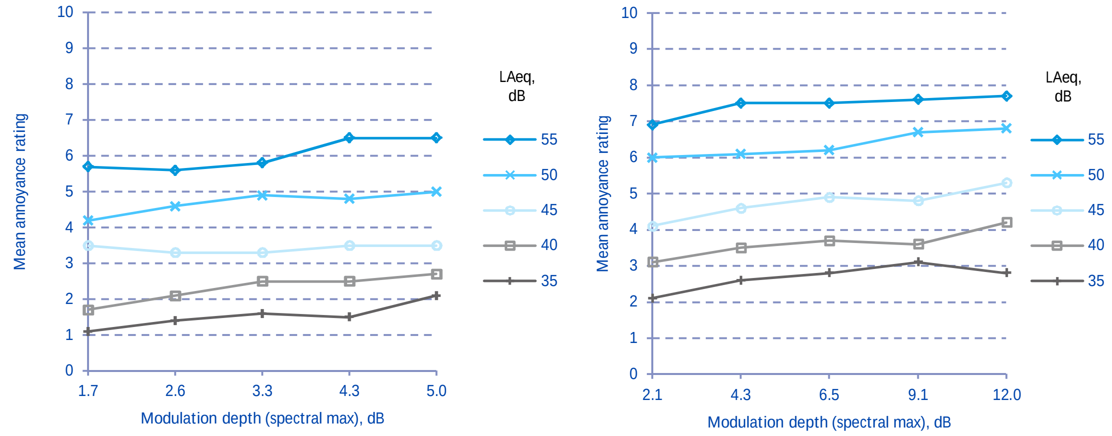

Figure 2: Estimated relationship between wind turbine noise amplitude modulation (maximum spectral modulation depth) and mean annoyance ratings corresponding with the results in Figure 1 with overall average level (L_{Aeq}[17]) as parameter, reanalysed from (Lee, Kim, Lee, Kim, & Lee, 2009)

DISCUSSION I

3.2.7 Great care and attention was applied to the stimuli used in this study to ensure that that the parametric changes were closely controlled. However, the method for obtaining subjective responses is questionable: the application of a social survey technique to a laboratory environment could have an uncertain influence on the results. For example, the briefing of the subjects is likely to affect their interpretation of how to rate ‘annoyance’, and any contextual information provided to subjects is not detailed. Furthermore, the scale used introduces the idea that the subject is likely to find the noise annoying, when this is not necessarily certain. Although having subjects rate ‘annoyance’ responses in a laboratory setting is not unusual, it does present potential problems: the responses assigned by subjects to their perception of the noise may not necessarily really reflect ‘annoyance’ given that people in a ‘safe’ and artificial environment would presumably feel little, if any, of the emotive experience that feeling real annoyance often entails.

3.2.8 The sample size used in the experiment is small (30 subjects, although again, not unusual for this type of study), and unlikely to be widely representative of a typical population of wind turbine noise-exposed communities (all subjects were aged 20-30 years). It is also noted that the delivery method used employed headphones, which, even with binaural processing, would not give a natural representation of WTN exposure within its typical context.

SUMMARY II

3.2.9 The second phase (II) is reported in two similar papers by Seong et al. (2013a) (2013b). The stimulus used was changed to the output from a simulation turbine noise model and a similar sample recruited (32 subjects aged 20-34) for further laboratory listening tests. A slightly different 7-point response scale was used to record annoyance. Good correlations were shown using linear regression for mean annoyance with equivalent level (L_{Aeq}), fluctuation strength[18], and maximum level (L_{AFmax}), with the correlation value increasing for each respective metric. However, only the maximum level correlation was shown to have equal-variance by residuals testing (i.e. that the regression can be said to be a good model for the relationship between the variables).

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[17] A-weighted equivalent continuous sound pressure level.
[18] Defined in (Fastl & Zwicker, 2007). NB: Includes overall broadband noise level as a parameter.

3.2.10 An association was also indicated between annoyance and the simulated direction of incidence relative to the turbine. Examination of the associated model description (Lee, Lee, & Lee, 2013) shows that the position of highest annoyance corresponds to the direction in which both the level (L_{Aeq}) and modulation depth (defined as L_{AFmax}-L_{AFmin}) have high magnitudes; the position of lowest annoyance corresponds to the direction in which modulation depth is at its highest magnitude, but the overall time-average level is at its minimum (due to simulated interference effects in the crosswind direction).

DISCUSSION II

3.2.11 This study shows some interesting results and could indicate an avenue of further research; the authors were contacted to enquire about more recent research developments but no response was received prior to completing this review.

3.2.12 The results again indicate that modulation and level affect subjective laboratory ratings of annoyance, and that the level seems to have stronger influence.

OVERALL

3.2.13 The main conclusion drawn from these studies is that changes in the overall time-average level have a stronger influence on how perception of AM WTN is subjectively assessed than changes in the modulation depth, although the latter is shown to have an observable affect (as might be expected). Application of these lab results to a real situation should be approached cautiously in view of the limitations of the experimental approach and the subject sample.

STUDY B

SUMMARY

3.2.14 These studies formed part of a large-scale investigation into wind turbine noise in Japan, incorporating field measurements and social surveys along with the laboratory exposure-response studies into AM, low-frequency noise (LFN) and infrasound components.

3.2.15 Two papers by Yokoyama et al. (2014a) (2014b) report the results from tests designed to detect thresholds for perception of amplitude modulated LFN and infrasound in WTN. The six stimuli included three samples of recorded AM WTN with depths between 2.1 and 3.7 dB, measured as D_{AM}[19] (roughly equivalent to around 3-5 dB ΔL). The experiment was designed to detect the onset of sensation across the frequency range; it was found that low-frequency spectral components of the WTN below the 31.5Hz third-octave band were inaudible for the majority of subjects.

3.2.16 Another set of experiments continued the work by examining the thresholds of fluctuation sensation using AM WTN recordings; the experiment used filtering to modify the samples in a similar way to the LFN audibility threshold experiments, and it was found that spectral content below around 100 Hz did not contribute significantly to fluctuation sensation for the majority of subjects (Yokoyama, Sakamoto, & Tachibana, 2013) (Yokoyama, Koboyashi, Sakamoto, & Tachibana, 2015).

3.2.17 Further experiments reported by Yokoyama et al. (2013), (2015) directly examined the effect of varying the modulation depth of synthesised AM broadband noise (filtered to simulate WTN) on

[19] Defined as the width in dB between the 5th and 95th percentiles of the difference between fast and slow weighted sound pressure levels in a WTN sample (3-minute samples used).

the perceived fluctuation and 'noisiness' sensation by a method of paired comparison adjustment: 10s samples were compared with and without AM content at two overall time-averaged levels (35 and 45 dB $L_{Aeq,10s}$), and subjects adjusted the level of the AM sound until 'noisiness' was deemed equal with the unmodulated sample. The results broadly indicated a general increase in perceived 'noisiness' with AM depth, although the spread of the responses widened considerably as AM depth was increased, indicating greater uncertainty in the mean result. For AM depths less than 4 dB, the mean changes in the adjusted levels were no greater than 1dB, as shown in Figure 3. It can also be seen that when the signals were effectively identical (i.e. at 0 dB modulation depth), some respondents still made small adjustments of up to 2 dB, indicating the residual uncertainties involved in the perceptual comparison.

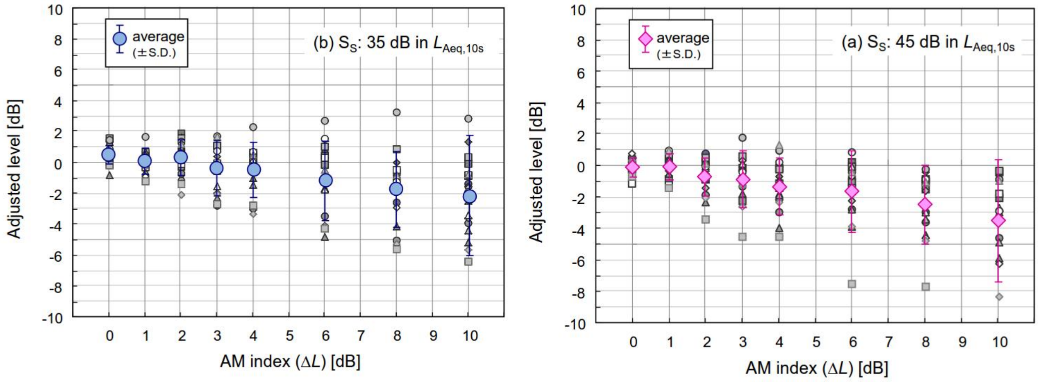
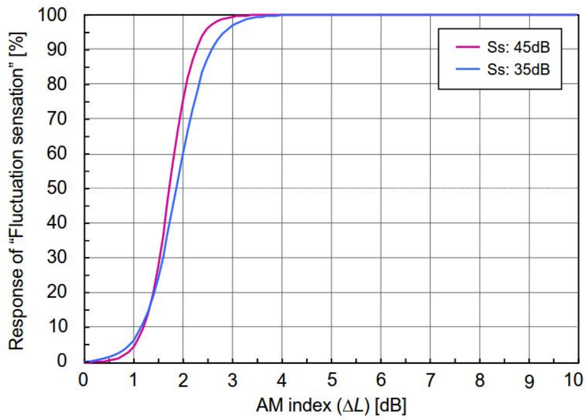


Figure 3: Level adjustments of amplitude-modulated noise to achieve equivalent perceived noisiness with a steady-state noise, from (Yokoyama, Koboyashi, Sakamoto, & Tachibana, 2015)

3.2.18 It is also noted that the mean differences tended to be slightly larger for the 45 dB L_{Aeq} stimuli compared with the 35 dB L_{Aeq} stimuli. Examination of the individual results indicates that one particular subject (represented with circular data points) consistently gave responses for the 35 dB stimuli that were opposite to the general trend, indicating their perception of the steady noise as 'noisier'. This would have influenced the mean differences somewhat, and this result is not replicated in the 45 dB stimuli set. Consequently it appears uncertain whether the results indicate a genuine perceptual difference between the two stimuli sets, or whether this result may reflect some uncertainty in the experimental design and, potentially, differing interpretations of the intended responses.

3.2.19 A subjective assessment of fluctuation sensation was made for each sample using descriptive onomatopoeic words (such as "*zah, zah*", "*guon, guon*"). This allowed an assessment of the AM depth onset of fluctuation sensation, which was analysed as around 2 dB Δ*L*; this is in agreement with the earlier findings of Vos et al. (2010a) [grey], as reported by van den Berg et al. (2011) [grey].



ΔL derived from $L_{Ap,F}$

Figure 4: Perception of Fluctuation in synthesised amplitude-modulated wind turbine noise, from (Yokoyama, Koboyashi, Sakamoto, & Tachibana, 2015)

3.2.20 The field study component of the research included measurements of WTN at 34 wind farms around Japan, from which useful data for 29 sites were analysed (Tachibana, Yano, Fukushima, & Sueoka, 2014). The social survey aspect of the work, reported by Kuwano et al (2014), did not specifically investigate the influence of AM in the responses received from the 1076 participants (including 332 respondents from 16 non-wind farm sites, used as a control group). The developed D_{AM} metric was applied to the measurements made at 18 of the wind farm sites, which was used to produce a distribution of occurrence of measured modulation depth in the field data, reproduced in Figure 5. The researchers suggested that the distribution indicated that AM might be above the threshold of perception in about 75% of the measured WTN data, at the measurement points. The noise measurement points at each site were uniformly distributed within a distance of 100-1000m from the turbines. The study does not clarify which measurement points were used (i.e. at what proximity to the turbines) to analyse the data to produce the D_{AM} distribution, so the applicability of the 75% AM perception statistic to the experience of residents cannot be ascertained.

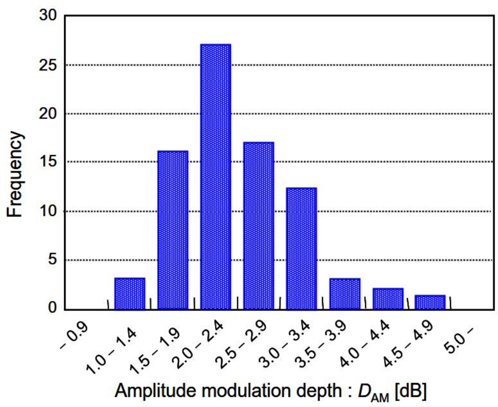


Figure 5: Distribution of D_{AM} in the field data from 18 Japanese wind farm sites, from (Tachibana, Yano, Fukushima, & Sueoka, 2014)

DISCUSSION

3.2.21 The approach of this study had some useful qualities. The laboratory components focussed on perception by i) identifying the onset of fluctuation sensation for subjects, and ii) rating their perception in terms of a subjective assessment of 'noisiness'. It avoided a requirement for subjects to rate 'annoyance', which is a potentially complex, emotional response to perception. Nonetheless, it is not clear how the subjects might have interpreted the request for evaluation of 'noisiness'; the spread in the results may reflect different interpretations, and the variation between individual responses would be exacerbated by the small sample size: results from 15 subjects were reported in the 2013 paper, with 17 reported in the 2015 version (the paper is not explicitly clear as to whether the latter was a fresh attempt at the experiment or simply added more subjects to the existing dataset, but the results presented are very similar). The limitations of the lab study in terms of the sample size and representativeness, as well as the stimuli used and the lab setting should be borne in mind when considering wider application.

3.2.22 The development of the D_{AM} metric was intended to provide a "*simple and practical*" method for measuring AM in WTN. Some shortcomings in applying this method to real long-term field data have been highlighted in later work by Large et al (2015) and by the IOA AMWG (2015a), due to its susceptibility to influence by extraneous non-WT noise. It is unclear whether this issue was detected by the original research team and to what extent the results reported by Tachibana et al (2014) may have been affected by extraneous noise, or what mitigating controls were put in place to protect against this possibility.

3.2.23 The conclusions that can be drawn from this study include i) the onset of fluctuation sensation for the sounds is somewhere around 2 dB modulation depth, using the AM index adopted by the Tokyo group; ii) there appeared to be relatively small perceptual differences (i.e. in terms of 'noisiness', which might be considered as the distinctiveness between the sounds used) for changes in modulation of less than 4 dB depth; and iii) for changes in modulation depth of 4 dB and above, perceived differences in 'distinctiveness' of the AM stimuli increasingly varied; a small number of the subjects perceived a relatively large difference, while the majority perceived differences in a smaller range, averaging to around 1.5-3.5 dB.

STUDY C

SUMMARY

3.2.24 Research was carried out by the Acoustics Research Centre at the University of Salford on behalf of RenewableUK (RUK) and reported by von Hünerbein et al (2013), (2015). A staged approach to the study investigated sensitivity to a range of possible parameters with a potential influence on perception of AM WTN. The noise exposure employed synthesised WTN samples that allowed the parameters to be systematically varied, including level, modulation depth, envelope shape, spectral character and modulation frequency. The results of the preliminary tests were used to identify which parameters would be carried forward for final testing, which included level and modulation depth; other parameters were either fixed at a representative setting or considered of negligible influence. In the final test subjects were asked to imagine the exposure as if they were at home relaxing in the garden, and some additional measures were taken to reinforce the contextualisation. The subjects rated their 'annoyance' using a modified scale based on ISO 15666:2003 (ISO, 2003).

3.2.25 As reproduced in Figure 6 and Figure 7, the results bear similarity to those obtained by Lee et al. (2009) (2011) (i.e. compare with Figure 1 and Figure 2, however, it should be noted that the 'modulation depths' used are derived using quite different methods in each study). Increases in average level corresponded with relatively large increases in the annoyance rating; increases in modulation depth (keeping average level constant) resulted in smaller changes in rated annoyance, which were not found to be statistically significant at the 5% level (although a relational trend can be observed). It was concluded that average level dominated the annoyance response (von Hünerbein & Piper, 2015).

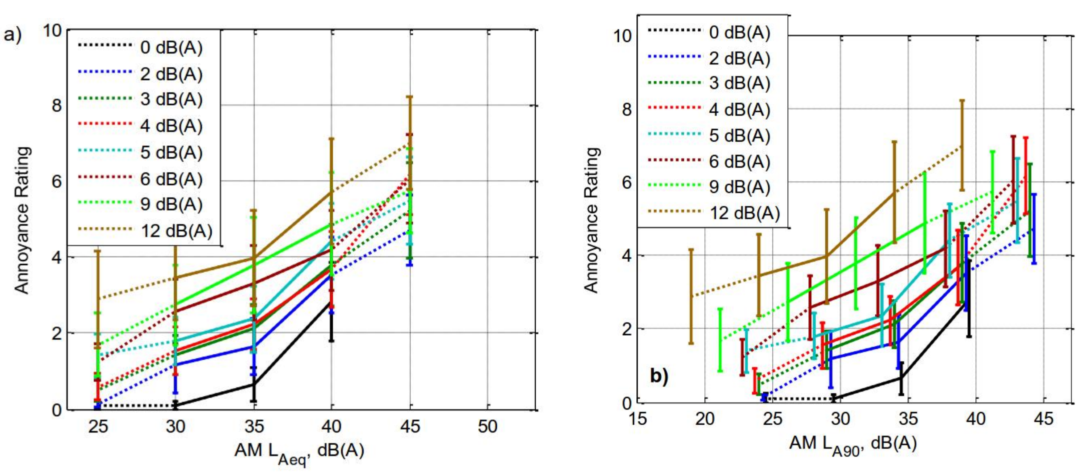


Figure 6: Association of amplitude-modulated wind turbine noise level measured as L_{Aeq} (left) and L_{A90}[20] (right) with annoyance ratings, with modulation depth as parameter, from (von Hünerbein, King, Piper, & Cand, 2013) – dotted lines indicate results from reduced sample, error bars: 95% confidence intervals (CI)

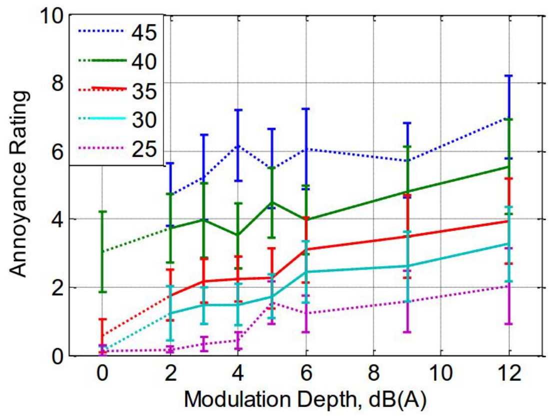


Figure 7: Relationship between modulation depth and annoyance rating with overall average level (L_{Aeq}) as parameter, from (von Hünerbein & Piper, 2015) – dotted lines indicate results from reduced sample, error bars 95% CI

3.2.26 The tests also examined the 'equivalent annoyance' using a method of paired comparison adjustment in a similar way to Yokoyama et al. (2013). The experiment compared an 'Adaptive Broadband Stimulus' (ABBS) signal (a noise signal of steady starting amplitude, that could be modified, or adapted, by the participant to achieve equivalence of annoyance with the paired AM signal). The results of this experiment broadly indicated that most subjects perceived relatively small or inconsistent differences for changes in modulation depths > 2 dB, even up to 12 dB depth, as reproduced in Figure 8. An anomalous result was obtained for 0 dB depth (comparison of identical stimuli), attributed to possible expectation bias amongst participants (i.e. they may have assumed that every stimuli pair presented must be different).

[20] A-weighted sound pressure level exceeded for 90% of the measurement interval.

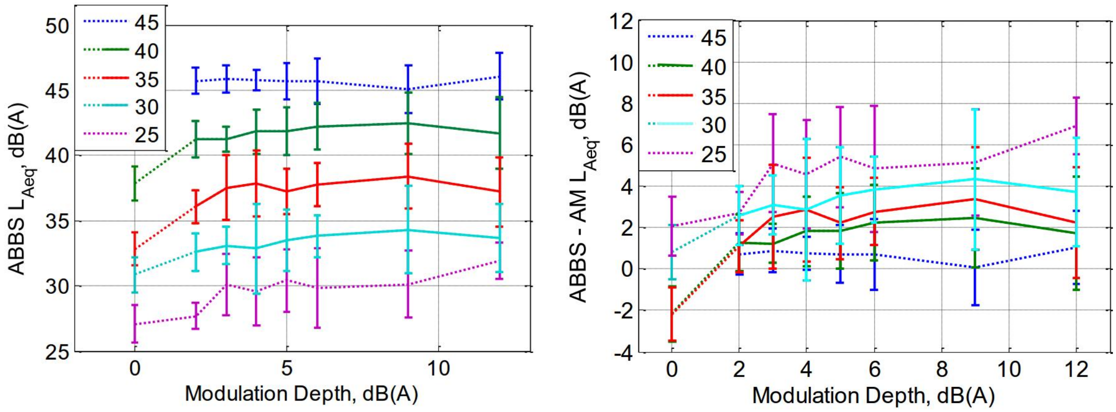


Figure 8: Level adjustments of broadband noise to achieve equivalent annoyance compared with amplitude-modulated noise of a fixed average level (as parameter), as adjusted levels (left), and normalised to adjustment level differences by subtracting the average level (L_{Aeq}) of the amplitude-modulated noise (right), reproduced from (von Hünerbein, King, Piper, & Cand, 2013) – dotted lines indicate results from reduced sample, error bars 95% CI

3.2.27 The analysis produced average adjustments of 1.7 dB at 40 dB L_{Aeq} and 3.5 dB at 30 dB L_{Aeq}; this trend (i.e. smaller adjustment differences with increasing level) was confirmed across the level range, with an overall average adjustment value of 2.3 dB. This scale of level adjustments is similar to those obtained by Yokoyama et al. (2015), despite differences in the experimental design: i) in the Salford study, subjects adjusted the levels to give equivalent 'annoyance' responses, whereas in the Tokyo study, subjects adjusted the levels to give equivalent perception of noisiness; ii) the modulation depth metrics used were derived using different approaches; iii) the adjustment method employed was the reverse in each study, i.e. one approach (Salford) adjusted the steady broadband noise to be subjectively equivalent to the AM, while the other (Tokyo) adjusted the AM to be equivalent to the steady broadband; and iv) the stimuli used and the delivery systems were slightly different.

3.2.28 The RUK study also analysed the same adjustments against the L_{A90} of the AM signal. The results of this analysis are shown in Figure 9.

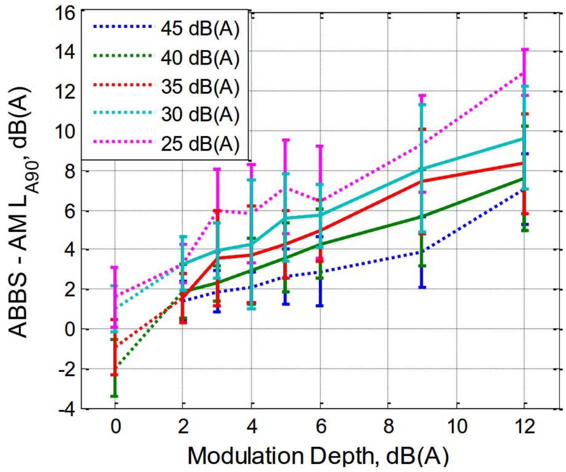


Figure 9: Level adjustments of broadband noise to achieve equivalent annoyance compared with amplitude-modulated noise of a fixed average level (L_{Aeq} as parameter), as normalised by subtracting the 90% exceeded level (L_{A90}) of the amplitude-modulated noise (right), from (von Hünerbein, King, Piper, & Cand, 2013) – dotted lines indicate results from reduced sample, error bars 95% CI

3.2.29 The results in Figure 9 appear to show a more linear relationship for L_{A90}-normalised equivalent annoyance with modulation depth than using the L_{Aeq} normalisation (for example, compare with the right side of Figure 8). In analysing these results, the study authors note that "*in summary L_{A90} might be a suitable parameter to express annoyance ratings in the psychoacoustic context and should be investigated more closely in future studies*". This is discussed further below.

3.2.30 In 'sensitivity tests' conducted using smaller sample sets, the authors examined a number of other parameters that were thought to have potential to influence the results, including modulation frequency. The results indicated that the AM signal with a 1.5 Hz modulation frequency was rated more annoying than a signal with a 0.8 Hz modulation frequency. This is also discussed further below.

DISCUSSION

3.2.31 The similarity of these results with those from Lee et al. (2011) is especially notable given that there were differences in the exposure method used: in particular the Salford approach (in the final test) delivered the stimuli over an ambisonic loudspeaker array rather than headphones. The scales used in the studies to measure response were also similar but had differences: the Salford approach allowed subjects to input their rating on a continuous scale, whereas the Seoul rating used a discrete numerical input. These factors might be expected to somewhat affect the outcome of the results, but there is a remarkable consistency between the study outcomes.

3.2.32 The L_{A90}-based analysis of the equivalent annoyance test results partly illustrate a feature of the synthetic stimuli employed; as the modulation depth increases and the average level (L_{Aeq}) is held constant, the L_{A90} is reduced. As a result, the normalisation of the adjusted broadband noise level by subtracting the amplitude-modulated L_{A90} results in a larger difference (between ABBS L_{Aeq} and AM L_{A90}), which increases in magnitude with increasing modulation depth. In field signals, this would not necessarily be the case, as the average level of a real modulating WTN signal is not constant, and could increase with increasing modulation depth, whereas the non-WT background noise may be relatively steady in level.

3.2.33 The sample size used for the final tests in the Salford study was again small, with 20 subjects, across an age range of 20-50 (average approx. 30). The recruitment process detailed suggests a risk of selection bias, in that it was clear that the study would be looking at the response to wind turbine noise, although it is acknowledged that it may have proved difficult to find willing participants for vaguer, masked study intent. Again, the representativeness of the sample to the wider population of WTN-exposed people must be questioned.

3.2.34 The aforementioned issues of briefing and applicability of lab-rated annoyance results are also relevant to this study: one external reviewer suggested that the context of 'relaxing in the garden' may not necessarily be compatible with the scenario in which AM WTN could be most problematic. For example, an alternative or augmenting scenario may have included 'trying to get to sleep on a summer night with the window open'. Similar types of laboratory tests conducted to specifically investigate LFN (not generated by wind turbines) have used a sleep/night-time scenario (Moorhouse, Waddington, & Adams, 2009) [black], which enables a comparison of sensitivity to be made; given the comparability with WTN this suggests a possible further avenue of investigation.

3.2.35 It was noted on review that the reported tests conducted to examine the influence of the stimulus envelope shape on the annoyance rating were carried out using a constant modulation depth close to the bottom of the range employed (1.7 dB). The results of this study and other works already discussed indicate that a depth of this magnitude would be very much on the edge of fluctuation perception, and so it is a fair assumption that varying skew and width of AM signals with such a small AM depth would be very difficult for subjects to perceive and distinguish. This also indicates another avenue of investigation that does not appear to have been fully explored in the literature, and may be of some value given the subjective descriptions (e.g. 'thumping') sometimes attributed to AM WTN, and often highlighted as the most disturbing to those affected.

3.2.36 The main exposure-response results were obtained using AM WTN stimuli with a modulation frequency of 0.8 Hz. The sensitivity test results indicated that increasing the modulation frequency to 1.5 Hz could result in increased absolute annoyance ratings. This suggests that the equivalent annoyance decibel ratings might also be expected to be slightly greater than those shown above. However, results from the sensitivity tests must be considered with caution: the sample sizes were considerably smaller than the main tests and consisted only of subjects that would normally be considered 'expert listeners', i.e. staff and students of the University Acoustics Research Centre.

3.2.37 The main conclusions drawn from this study tend to reinforce those obtained from the similar Seoul and Tokyo experiments: overall average level was the dominant factor in perception of the AM noise; once the sound was established as clearly modulating, further increases in modulation depth did not greatly affect the perception.

3.2.38 Consideration only of averages in the response results masks the extremities, in which some subjects noticed a larger perceptual change with much finer distinctions in modulation depth, while conversely some subjects actually indicated a lower annoyance with an increase in modulation depth. These observations illustrates the difficulty some subjects had in distinguishing the changes – this is reflected in the appended participant observations: "*sounds were perceived by a number of participants to be very similar*" (von Hünerbein, King, Piper, & Cand, 2013).

STUDY D

SUMMARY

3.2.39 This field study, reported by Bockstael et al. (2011) (2012), was aimed at investigating the connection between operational parameters recorded from a set of wind turbines, WTN exposure and annoyance self-reported by residents neighbouring the installation. It should be noted that the study followed complaints about WTN from the neighbours and a consequent mitigation strategy implemented by the operator. Self-reporting was enabled over a 6-month study period via an online application based on a simple question on annoyance and a 5-point response scale.

3.2.40 The study examined detailed aspects of turbine operation from the data supplied by the operator, including production yield, blade velocity and hub height wind speed. Meteorological data was also collected. Logistic regression was used to form a model of the statistically significant relationship between reported annoyance and blade velocity, which itself was related to the WTN level extracted from measurements at the properties. A 'fluctuation indicator' was derived using a Fourier transform method from minute-long samples of the noise measurements. This metric was found to broadly increase with increasing annoyance, as indicated in Figure 10. Unfortunately the scaling used for the derivation of this indicator is not fully explained and so direct comparison with other AM measures discussed is not possible. The extent of the error bars are probably a reflection of the very small sample size (3 regular respondent households from a sample of 8); in some cases the results indicate that a fluctuation of a relatively low level (measured by the indicator) could produce a 'not at all' annoyed report from some subjects, and an 'extremely' annoyed report from others.

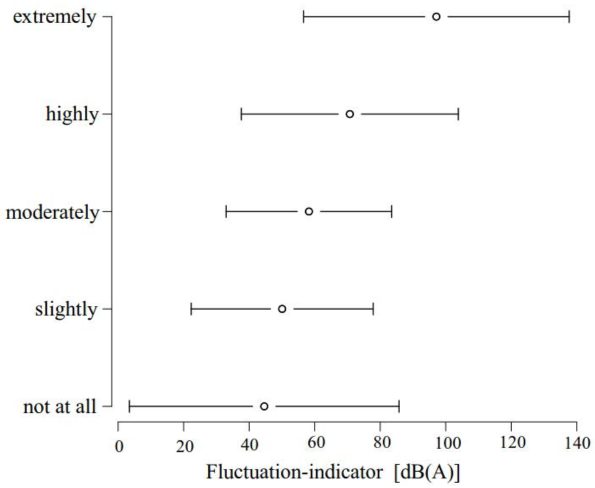


Figure 10: Relationship between fluctuation indicator and reported annoyance (error bars show +/-σ), from (Bockstael, Dekoninck, Can, Oldoni, de Coensel, & Botteldooren, 2012)

DISCUSSION

3.2.41 Given the context of existing noise issues at the site, the representativeness of the results for wider application is open to question. Nonetheless, this is the only study in which the perceptual response could be expected to be a strong representation of that felt by the subject within a suitable residential amenity context, i.e. their own home.

3.2.42 This study shows a good example of careful design and analysis of data for a field experiment. The considerable limitations due to the sample size and situational background (together with the difficulty in cross-comparison of the results due to the lack of clarity in the AM metric employed) restrict its wider application, but it might be regarded as a promising pilot study.

3.2.43 One suggestion made by a reviewer to improve the reliability of this type of response data collection in the field was for self-reports of perception to be prompted at irregular intervals, e.g. by SMS[21], perhaps reverting to self-prompted reporting during periods used for sleeping. This could improve the rate of responses from otherwise low-rate responders and widen the dataset for analysis. More importantly, it would help to reduce any bias potentially introduced by the natural tendency for some subjects to report when most annoyed and not at other times (as documented in this example).

3.2.44 One serious and inevitable drawback on this study is the lack of controls on confounding factors such as personal attitude etc., and this could be significant in a situation where respondents may already have a negative view of the noise source. Research discussed under the Category 2 studies highlight some of the factors shown to influence subjective responses in field survey work relating to WTN.

[21] Short message service (text messaging)

STUDY E

SUMMARY & DISCUSSION

3.2.45 Researchers at the University of Adelaide carried out a preliminary field study designed to test a wind turbine noise measurement and subjective response recording system (Nobbs, Doolan, & and Moreau, 2012). Automated measurements were conducted inside a resident's home near to an operational wind farm, triggered by the occupant and including a 10-point annoyance scale rating and optional notes. The recordings were analysed to produce a measure of AM depth and plotted against recorded annoyance rating, with no apparent association. The results of this study (apparently designed as a simple pilot test for the proposed AM measurement and rating system) are deemed to be of no meaning or use for this research, due to the smallest possible sample size (1), and the lack of any controls or analysis of confounding factors that may have influenced the results.

CATEGORY 1 CONCLUSIONS

3.2.46 The main conclusions from the Category 1 studies are summarised as follows:

- Within laboratory and field test environments, increasing overall time-averaged levels of AM WTN-like sounds showed a strong and significant association with increasing ratings of annoyance.
- Within a laboratory test environment:
  - subjects rated modulating WTN-like sound as more annoying than similar noise without significant modulation;
  - the onset of fluctuation sensation for a modulating WTN-like sound appeared to be in the region of around 2 dB modulation depth (the peak-to-trough level difference in the Fast-weighted sound pressure $L_{pA,F}$ time-series);
  - increasing modulation depth above the onset of fluctuation sensation showed a broadly increasing trend in mean ratings of annoyance, but changes in mean annoyance rating tended to be relatively small, sometimes inconsistent, and typically not statistically significant[22];
  - equivalent annoyance ratings of AM and steady WTN-like sounds derived by level adjustment did not show a very strong increasing trend with increasing depth of modulation; average differences were in the region of around 1.7-3.5 dB; and
  - equivalent 'noisiness perception' of WTN-like AM sounds compared with a steady sound showed a gradually increasing trend with modulation depth, but with a tendency for the spread in perceptual results to also increase. On average the differences were in the region of around 1.5-3.5 dB.
- Wider representativeness of both the laboratory and field results should be approached with caution: sample sizes are very small and may not be fully representative of the wider population of WTN-exposed people; stimuli employed in the laboratory often are very carefully controlled to allow fine adjustment of specific parameters – this kind of regularity in the signal will not be closely reflective of temporal variations experienced in the field, which may further affect subjective responses.

[22] Subsequent research summarised in Annex 1 indicates a more consistent relationship between modulation depth and annoyance.

3.3 CATEGORY 2 PAPERS

INTRODUCTION

3.3.1 During the literature search, category 2 studies were broadly separated into the following sub-categories:

a. Primary study or review of elements of the human exposure-response relationship with AM WTN that did not meet the category 1 criteria

b. Case study examining un-scaled responses (e.g. complaints) to AM WTN exposure

c. Primary study or review of the human exposure-response relationship with non-wind-turbine amplitude-modulated noise (e.g. HVAC[23] plant)

d. Primary study or review of the human exposure-response relationship with WTN, without specifically addressing responses to quantified AM characteristics (priority given to studies investigating potential adverse health effects other than subjective annoyance, as the association of environmental noise, including WTN, with subjective annoyance has been well-established for some time)

e. Study examining further aspects of AM WTN with potential or partial relevance (excluding source generation theory / testing and AM measurement / quantification techniques)

f. Study examining the application of a planning control or penalty scheme for AM WTN

3.3.2 In addition, relevant publications from an "Independent Noise Working Group" made available on the website of Christopher Heaton-Harris MP (Conservative, Daventry) were also included in the review.

3.3.3 Unless otherwise indicated, the research papers discussed in this section were reviewed by the internal research team. The status of each paper is indicated in square brackets at first reference.

ASPECTS OF THE HUMAN RESPONSE TO AMPLITUDE-MODULATED WIND TURBINE NOISE EXPOSURE

Review Papers 1 & 2

3.3.4 A useful review of relevant literature is given by van den Berg (2009) [grey] and later by van den Berg (2011) [grey], including the following studies.

Psycho-acoustic characters of relevance for annoyance of wind turbine noise (Persson Waye & Öhrström, 2002) [black]

3.3.5 Five different WTN recordings were played to 25 subjects in a laboratory setting. In general, the sounds rated as more annoying were also given higher ratings on descriptors of "*lapping*" and "*swishing*". Derived psychoacoustic metrics such as 'fluctuation strength' and 'modulation %' could not explain the variation in annoyance.

[23] Heating, ventilation and air-conditioning

Perception and annoyance due to wind turbine noise – a dose-response relationship (Pedersen & Persson Waye, 2004) [black]

3.3.6 A cross-sectional field study incorporating social survey questionnaire results from 351 respondents in Sweden, over an area covering $30km^2$ and containing 16 turbines. Of those within the sample who reported noticing WTN (64%), around a third also reported being annoyed by a “swishing” character (a feature that was significantly correlated with noise annoyance), while annoyance due to “pulsating / throbbing” characteristics was also reported by around 1 in 5. Noise annoyance was also significantly correlated with further subjective factors including “attitude to visual impact”, “attitude to wind turbines” and “sensitivity to noise”.

The beat is getting stronger: the effect of atmospheric stability on low frequency modulated sound of wind turbines (van den Berg G. P., 2005) [black]

3.3.7 This paper provides a broad view of the issues surrounding AM WTN and potential effects on people. Measurement results from three sites are analysed to indicate typical fluctuation level variations (i.e. AM), focussing on the influence of the atmospheric conditions. The reported fluctuations in terms of the difference between the maximum and minimum sound pressure levels (L_{Amax} – L_{Amin}) are 4 to 6 dB for single turbines and 5 to 9 dB for multiple (i.e. a wind farm). However, the author acknowledges this measure can easily be influenced by incidental extreme values, and also results for the difference between the L_{A5} and L_{A95} measures, yielding somewhat lower values of 3 to 4 dB.

3.3.8 It is reported from the author’s experience of the Rhede wind farm (Germany/The Netherlands) that operations on a clear night at times produced a beating sound likened to “*distant pile driving*”, and that the sound character during the daytime (with low atmospheric stability) could be very different (i.e. less intrusive).

3.3.9 An analysis of the fluctuation strength metric is presented, indicating that a change in modulation depth ΔL from 3 to 6 dB for a broadband noise corresponded to an increase in fluctuation strength from negligible to 0.18 vacil. The conclusion is drawn that the fluctuations of modern wind turbines are likely to be readily perceivable under stable atmospheric conditions. Any possible links from the measured data with site-specific resident responses are not reported.

Auralization and assessments of annoyance from wind turbines (Legarth, 2007) [grey]

3.3.10 Five different WTN binaural recordings were made and auralised for different distances using a computer propagation model. Twenty subjects were played the recordings using headphones and simultaneously presented with a visual image of a turbine at an appropriate distance. AM was quantified using fluctuation strength applied to specific frequency bands relevant to the “swishing sound” (350-700 Hz) where fluctuation was stronger. A logistic regression model for annoyance was presented based on the relationship with L_{den}[24]. It was stated that the annoyance model could be “improved by including the metrics for prominent tones and for the swishing noise”, although the supporting results were not provided.

Response to noise from modern wind farms in The Netherlands (Pedersen, van den Berg, Bakker, & Bouma, 2009) [black]

3.3.11 Another cross-sectional field study, this time conducted in The Netherlands, analysed data collected from 725 respondents living within 2.5km of a wind turbine installation. Of those who

[24] ‘Day evening night’ equivalent noise level, i.e. a period-weighted L_{Aeq} measure commonly used for EU Directive noise mapping

noticed WTN at their dwellings (46%), 3 in 4 reported a “swishing / lashing” sound, while “thumping / throbbing” was reported by less than 10%, and few of the respondents described the WTN as low frequency. The results showed a strong correlation between noise annoyance and negative opinion of visual impact. Economic benefit from wind turbines was also significantly associated with the likelihood of a respondent reporting ‘no annoyance’, despite detection of the WTN being the same between benefit/no benefit comparison groups. A large proportion (40%) of respondents reported hearing WTN more clearly at night.

Effects of sound on people (van den Berg F. , 2011) [grey]

3.3.12 In reviewing the issue, the author proposes that the modulation component in WTN, when perceived, could be the most important factor influencing subjective disturbance, due to the unpredictability and perceived lack of control for those exposed.

Review Paper 3

Wind turbine noise: an overview of acoustical performance and effects on residents (van den Berg F. , 2013) [grey]

3.3.13 Includes a review of factors contributing to AM, and suggests that AM is reported to occur more often at night.

Review Paper 4

3.3.14 Another review of relevant literature is found in the report by the Council of Canadian Academies (2015) [grey], prepared for the Canadian Government, including (amongst reviews of the category 1 studies summarised in section 3.2) the following paper.

Psychoacoustic aspects of noise from wind turbines (Fastl & Menzel, 2013) [grey]

3.3.15 A laboratory study was conducted by exposing 13 subjects to a single recording of AM WTN at a range of levels; one of the samples had been modified to remove the AM component of the sound. Subjects rated annoyance using a ‘free magnitude estimation’ technique by stating a number for each sample but without any defined scale; these were then converted to relative annoyance ratings. A statistically significant relationship between the sound level or loudness and annoyance was shown, but there was no significant difference in rated annoyance between the modulated and un-modulated versions of the signal at equivalent loudness. No data to indicate a relationship for annoyance with modulation / fluctuation was presented, and the results did not include any quantification of AM signal content.

DISCUSSION

3.3.16 The papers reviewed in this section appear to reinforce the suggestions that periodic AM increases annoyance due to WTN, as does increasing level. A number of non-acoustic factors are also identified as influencing the annoyance attributed to noise.

CASE-STUDIES INVESTIGATING UN-SCALED HUMAN RESPONSE TO AMPLITUDE-MODULATED WIND TURBINE NOISE EXPOSURE

Acoustic noise associated with the MOD-1 wind turbine: its source, impact and control (Kelley, McKenna, Hemphill, Etter, Garrelts, & Linn, 1985) [grey]

3.3.17 A very early investigation into the disturbing 'thumping' noise, infrasound pulses and vibration experienced by neighbours of an experimental downwind[25] turbine installation. The study examined the source generation mechanisms and possible remedial measures. The source was identified as complex interactions between the rotating blades and the tower structure, exacerbated by local stall conditions and the design of the aerofoil. A number of possible design solutions were proposed, including a modified aerofoil shape and operational angle of attack.

3.3.18 This paper presents a technical and high quality investigation of a specific WTN problem. Increased (or 'enhanced'/'excessive' etc.) AM WTN associated with upwind turbines is most likely due to fundamentally different mechanisms than the blade-tower interaction case studied here, as shown in recent research developed by Makarewicz et al. (2015) [black], Oerlemans (2015) [black] Cand et al. (2015a) [grey] and Smith (2013) [grey]. Nonetheless, the information on the acoustical characteristics within residents' rooms and the influence of meteorology provide some background information that may help to explain why the annoyance reported in some cases can be more intensive than might be expected from outdoor measurements or perception of AM WTN near to the turbines.

Wind turbine noise assessment in a small and quiet community in Finland (Di Napoli, 2011) [black] & ***Case study: wind turbine noise in a small and quiet community in Finland (Di Napoli, 2009) [grey]***

3.3.19 A field study carried out in response to complaints made to a local authority about noise from a single turbine installation.

3.3.20 Measurements were made over a day and night period primarily to quantify the sound power of the turbine. In addition the author analysed the data and recordings to examine spectral and AM content.

3.3.21 A number of relevant sound characteristics are noted: an apparent increase in low frequency noise around 40 Hz when hub height wind speeds increased above a particular value, modulating at the blade passing frequency (NB. this was noted from measurements made at close range to the turbine only; at further distances different sounds were noted, including a "rumbling", "clapping" and "swish"); greatest modulation depths when the WTN aggregate level was steady, rather than in transition (i.e. the measured AM depth reduced when the overall turbine sound was increasing or decreasing due to changes in wind speed); evidence of 'double peaks' in the AM noise level, i.e. peaks occurring more often than the blade passing frequency.

3.3.22 It was noted that the maximum recorded AM depth in the measurement was around 5 dB, but no statistical analysis of the AM results is reported.

3.3.23 There is very little information provided on the complaints that triggered the study, and the measurements were necessarily carried out at closer range to the turbine than the locations of residential dwellings, due to very low audibility of the WTN during the survey.

[25] A downwind design places the blades downwind of the supporting tower; most modern turbines employ the opposite configuration, i.e. upwind.

3.3.24 The study makes some interesting observations and suggestions as to possible causes of the observed sound characteristics, such as blade-structure interactions, and blade phase interference.

Wind turbine amplitude modulation: research to improve understanding as to its cause & effect (Bullmore, Jiggins, Cand, Smith, von Hünerbein, & Davis, 2011) [grey]

3.3.25 This summary of AM WTN case-related measurements and complaint reports is provided by Bullmore et al. (2011), also reviewed by Bullmore et al. (2013) [grey], including the following study.

3.3.26 The results of an investigation by van den Berg, G.P. (2004) [black] indicated measured AM depths (in the A-weighted levels) at one site of up to 5 dB, and sounds that were described as 'pulse-like' and 'thumping', a character considered by the author likely to have contributed to annoyance reported by the residents. It is also noted that complaints were focussed in late evening and night-time periods.

Amplitude modulation and complaints about wind turbine noise (Gabriel, Vogl, Neumann, Hübner, & Pohl, 2013) [grey]

3.3.27 A medium-scale field study carried out to record complaints about WTN from neighbours of a wind farm in Germany. A questionnaire and complaints form were issued together with audio recorder to 212 residents. Sampled noise measurements were taken at specific outdoor locations, and meteorology was also recorded.

3.3.28 Around 45% of the sample returned complaint sheets. Analysis of the complaints sheets showed that around 32% of the sample made complaints about noise that were clearly related (by the complainant) to a subjective description fitting with AM. Compared with the total number of complaint sheets reported (95), this proportion was around 72%.

3.3.29 The authors note that the results show a distinct increase in complaints immediately after a public presentation of the project, which could be due to a) distinct operational or meteorological conditions that increased annoying noise from the site; b) increased noise sensitisation among residents (i.e. respondents becoming more conscious of the noise as a response to awareness of the investigation), c) a decrease in the possible perception of futility in complaining, or d) complainants seeking to maximise any subsequent action taken to reduce the operational capabilities of the wind farm. It is not possible from the presented information to understand which factors could have influenced the results.

3.3.30 Some of the audio recordings of noise made by the residents were analysed, and modulation metrics derived; the results presented show a relatively large sound pressure level difference of over 14 dB ΔL in and around the 160 Hz 1/3 octave band, although it must be presumed that this is a maximum difference as the sample durations and variation are not detailed. It is also noted that this sample represented the only AM WTN recording lasting longer than 1 minute from any of the 28 samples analysed; in all other cases any perceptible AM WTN lasted less than 10s.

3.3.31 The study was launched in response to concerns raised about WTN, and respondents were fully aware of the nature and intent of the investigation. As such there is a strong risk of selection bias in the results, which makes interpretation of the prevalence of AM annoyance from the complaints data potentially problematic. There is no detailed analysis presented of the complaints distribution, but it is noted that 95 complaints had been documented from 10 residents. Of these, 80% were reported in relation to the night-time or early morning. This suggests that, for those making complaints, these periods are especially critical.

3.3.32 There is interesting speculation in the paper on the possibility of short periods of AM being an 'attention trigger' that provides a pathway towards increased noise disturbance, rather than being highly disturbing in and of itself. This suggests a possible avenue of further research.

Noise characteristics of 'compliant' wind farms that adversely affect its neighbours (Large & Stigwood, 2014) [grey]

3.3.33 This is a discussion paper incorporating field data from 4 wind farm sites where complaints about noise have been recorded or made known to the authors. Details of the complaints themselves (e.g. status, frequency, distribution, time of day etc.) are not presented.

3.3.34 The study examines relatively short sampled periods of measurement data recorded at each site, and analyses the samples using a range of AM assessment metrics to compare the results.

3.3.35 A speculative discussion on nuances of AM WTN perception, based on an analogy with musical dynamics and expression, is presented as a set of possible psychoacoustic explanations for subjective responses.

3.3.36 All of the response evidence presented is anecdotal and un-scaled, and wider representativeness would not be reliable: non-acoustic factors contributing to complaints at the sites cannot be ruled out or the potential effects isolated (for example, attitude of the complainants, attitude of the site operators, history of planning and development of the sites, visual impacts, sensitisation due to the investigative work etc.). No causal relationship between the noise characteristics and complaints (as suggested by the authors) could be robustly established from the data.

3.3.37 The objective of the paper is really to raise a wide range of discussion points and questions about character assessment, rather than to derive an exposure-response relationship (while numerical AM values are quoted for the samples analysed, this is primarily with the aim of comparing demonstrable efficacy of different measures in quantifying AM, and showing high ratings, despite apparent compliance with national guidelines).

3.3.38 This study provides an interesting discussion with lots of pertinent questions raised but few answers given. It does raise the important point as to the likely success or otherwise of a penalty system aimed solely at controlling AM in isolation, rather than looking more broadly at combinations of characteristics, as well as the cumulative effects of intermittency, duration and changes in character.

Initial findings of the UK Cotton Farm Wind Farm long term community noise monitoring project (Stigwood, Stigwood, & Large, 2014) [grey]

3.3.39 This paper reports analysis of 10 months' field data measured near to a UK wind farm, with the intent of establishing prevalence of occurrence of AM, investigating the relationship with wind behaviour, and examination of different AM assessment metrics.

3.3.40 In reviewing the earlier work published by RUK (von Hünerbein, King, Piper, & Cand, 2013), the authors point out the potential problems with translating laboratory annoyance rating methods to the annoyance experienced by WTN-exposed populations, due to the contextual and stimulus differences (these issues have also been discussed in section 3.2).

3.3.41 There is very little analysis of subjective responses, although the authors note that the community have made complaints to the local planning authority concerning noise. A section of the paper is also dedicated to a description of an online software platform devised by the authors to allow members of the public to subjectively rate recordings made at the monitoring location.

Perception and effect of wind farm noise at two Victorian wind farms (Thorne, 2014) [grey]

3.3.42 This report was prepared at the request of residents living in the vicinity of a wind farm subject to complaints about WTN. The version reviewed comprises an update to the original 2012 publication.

3.3.43 The study investigated the possible relationship between adverse health effects and WTN exposure in the local population at two sites. Questionnaires were issued to 25 participants to enable self-reporting of a range of possible factors, including sleep disturbance, annoyance and sensitivity. The questionnaires included use of some recognised health / quality of life metrics.

3.3.44 The results show a very high proportion of self-reported sleep disturbance (over 90%), and annoyance (over 80%) attributed to WTN exposure. The report argues that adverse health effects due to WTN are marked by a range of acoustical thresholds, including:

- 32 dB $L_{Aeq,10min}$ outside a dwelling
- 22 dB $L_{Aeq,10min}$ inside a dwelling
- "*Unreasonable or excessive modulation*" in audible, regularly varying[26], WTN[27]: 4 dB AM depth (peak-trough) is 'unreasonable'; 6 dB AM depth is 'excessive'

3.3.45 The results reported suggest the participants feel strongly that their quality of life has worsened due to the presence of the wind farms. However, the suggestion that specific health effects are attributable directly to the wind farm noise exposure (and AM in particular) are not supported by the evidence presented.

3.3.46 There are details provided in the paper to demonstrate how the apparent health effects reported have been linked to the specific acoustic thresholds identified. The author notes that the report is in summary form, which may explain the lack of supporting analysis; it is also stated that cause and effect information was submitted during related planning hearings and a 2011 Australian Senate Inquiry, but is not presented in the paper. The Senate Inquiry concluded that there was insufficient rigorous research to establish whether adverse health effects were caused by WTN exposure (The Senate Community Affairs Reference Committee, 2011).

3.3.47 Despite the presence of a range of non-specific questions about noise within the questionnaire, which would in other situations typically be used to mask the intent of the survey, the context of the study (within planning hearing / inquiries) means that the respondents would be likely to have already been fully aware of the study objectives and hypotheses.

3.3.48 This is a cross-sectional field study conducted with a small sample size (25), no equivalent control group and within the context of a planning inquiry; wider applicability of the results is therefore limited.

Quantifying the character of wind farm noise (Hansen, Zajamšek, & Hansen, 2015) ***[grey]***

3.3.49 This paper analysed data obtained during a monitoring program carried out by the South Australia Environmental Protection Agency in response to noise complaints relating to Waterloo Wind Farm, the results and data from which are freely available online (South Australia Environmental Protection Agency, 2015).

3.3.50 Hansen et al. (2015) selected a sample of the diary entries completed by neighbouring residents and corresponding periods of the noise monitored at locations nearby. The diary entries, which included an unclearly-scaled subjective rating of "*strength of noise event*" (rated 1-4) together with descriptive words to qualify the nature of the sound (e.g. "*rumbling, thumping*") and confirmation of whether the turbines were turning at the time of the entry, were compared with a wide range of

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26 The criterion is defined as applying to WTN that exceeds the numerical AM thresholds for a total of 1 minute or more in a 10-minute period.

27 Measured in terms of short-term L_{Aeq} or L_{pAF} using 100 to 125ms averaging.

possible AM assessment metrics to detect any relationship. There is no description of the briefing that residents may have received to gain an understanding of the intention of the noise strength rating. No agreement was observed for the subjective rating with the AM metrics, but better agreement was obtained by comparison with loudness[28]. A-weighted, C-weighted and G-weighted sound pressure levels were also presented but not mentioned in the analysis discussion.

3.3.51 The representativeness of this study is limited due to the likely selection bias, the relatively small sample (four respondents' diaries), and the very short duration of audio data analysed (a total of 50 minutes).

Measurements demonstrating mitigation of far-field AM from wind turbines (Cand & Bullmore, 2015b) [grey]

3.3.52 This study presents results from an investigation into remedial measures designed to reduce the occurrence of transient blade stall, believed to be the primary source mechanism in generating a high degree of AM.

3.3.53 Data from two different sites are included, both of which are reported as having been subject to AM WTN-related complaints, and a different mitigation strategy is examined at each, i) physical treatments directly on the blades, and ii) software modifications to reduce the angle of attack during the conditions (i.e. specific wind speed ranges) in which high AM had been associated with complaints. Measurements were conducted at multiple synchronous positions at both sites, including near and far field locations, over a period of months, although the datasets were reduced in both cases: at the blade-treated site to consider only data obtained during shutdown of un-treated turbines; at the modified-software site only periods known to have generated prominent AM were analysed, with matched post-mitigation measurement periods.

3.3.54 The results are presented in a different form for each site: at the blade-modified site, the prevalence of AM periods in which the measured modulation (quantified in terms of AM magnitude rating[29]) was above a defined threshold (set to ≥ 3 dB) were recorded as proportions of the total measurement dataset (10 hours pre-treatment, 23 hours post-treatment). It was shown that, over a similar wind speed range, the prevalence of AM with a magnitude above the threshold for more than 30s in a 10-minute period was around 50% prior to the treatment, reducing to slightly over 3% following the blade modifications.

3.3.55 For the modified-software site, the results are presented in terms of the AM magnitudes measured over the wind speed range for each condition. The analysis indicates a reduction in AM magnitude at the worst-case wind speed of around 0.5 dB on average, and 1 dB for the upper 68% confidence interval (CI). Further statistical analysis of these results to examine the results could lend greater support to the conclusions and establish the significance of the pre- and post-treatment differences.

3.3.56 In terms of changes in the subjective response, very little information is given beyond noting that for the modified-software site, complaints were understood to have subsided following implementation of the strategy. Another dimension to the study might have looked more closely at the subjective element, to establish the efficacy of the treatment from an exposure-response perspective. It is clear however that the focus of the experiment was aimed towards validating the suspected cause of increased AM severity at the same time as testing effective mitigation measures. The results suggest that relatively small reductions in AM of the order of a few dB (in terms of the magnitude metric used) may have an effect in reducing complaints (and by

[28] Evaluated according to the model proposed by Fastl and Zwicker (2007)
[29] The metric developed by the IOA AMWG specifically to quantify the AM component of WTN.

extension, annoyance), although further testing and analysis would be needed to investigate this fully.

DISCUSSION

3.3.57 The case-study research has value in highlighting the issue of AM in WTN, and provides persuasive supporting evidence, in the form of complaints or descriptions, that is an important factor in determining or exacerbating subjective annoyance responses. The research also points towards increased sensitivity to AM during quiet periods typically used for rest and relaxation, i.e. evening and night-time.

3.3.58 Case-study research has the drawback of limited wider applicability; in some cases the studies are carried out in response to complaints about WTN, and as such it is impossible to isolate effects caused by acoustic phenomena from the influence of non-acoustic factors that modify responses.

3.3.59 Recent work has highlighted the typical causes of increased AM from wind turbines, and the potential for methods of mitigation.

HUMAN RESPONSE TO NON-WIND-TURBINE AMPLITUDE-MODULATED NOISE EXPOSURE

The identification and subjective effect of amplitude modulation in diesel engine exhaust noise (Kantarelis & Walker, 1988) [black]

3.3.60 This study presented simulated diesel engine noise modulating at around 8 Hz with two different AM depths (5 and 13 dB) and was rated for subjective annoyance on a 10-point scale.

3.3.61 The authors suggest the results indicate an association between AM and annoyance for this type of noise, although information on the exposure and subject group is not reported, and there is no statistical analysis included to support the finding. The presented results appear to show a slight increase in rated annoyance for the greater modulation depth, but there is no unmodulated ‘control’ sound, and without an indication of the number of subjects and associated spread in the results it is difficult to have confidence in the conclusion. There is a clearly-observable relationship between increasing maximum level (L_{Amax}) and rated annoyance for both modulation depths.

Review Paper

3.3.62 A useful review of further material is provided by van den Berg (2011), covering the following papers.

Annoyance caused by constant-amplitude and amplitude-modulated sounds containing rumble (Bradley, 1994) [black]

3.3.63 A laboratory experiment examining subjective response to synthesised fluctuating noises designed to resemble HVAC[30] sources. A total of 9 subjects (age range 16-50) were asked to compare both modulated and un-modulated test sounds ‘containing rumble’ (i.e. with greater energy in the low frequencies) with a reference steady noise and adjust the test signals to be equally annoying with the reference. Two modulation depths and five modulation frequencies (in steps between 0.25 and 4 Hz) were used to modulate the low frequency content of the test signal;

[30] Heating, ventilation and air conditioning

although the overall AM depths of the final signals are not given, the L_{10}-L_{90} parameter[31] was shown to be around 3-5 dB over the 31.5 – 250 Hz octave bands.

3.3.64 On average, for the particular case of a 2 Hz modulation frequency, subjects attenuated the modulated test signal by an extra 4 dB when compared with the equivalent un-modulated test signal, both paired against the reference. Unfortunately there is virtually no information presented on the recruitment and briefing of the subjects, so their understanding and any contextualisation of equalising 'annoyance' is unknown.

The effect of fluctuations on the perception of low frequency sound (Moorhouse, Waddington, & Adams, 2007) [black]

3.3.65 This study, also later documented by Moorhouse et al. (2009) and Moorhouse et al. (2013) [black], was part of a Defra[32]-funded investigation into low frequency noise (LFN) disturbance and methods for assessing complaints.

3.3.66 A total of 18 subjects were recruited for the laboratory experiment, with an average age range of 32-62 (overall average 50), intentionally including 3 subjects self-reportedly highly sensitive to LFN. The results from the subjects were analysed both combined and separately in 3 groups divided according to both sensitivity and age. The briefing given to the subjects is detailed, and was based around the subject determining whether they felt they would find a presented sound acceptable if they heard it within their own home. This study also presented a night-time condition, switching the lights off and asking the subject to evaluate the sounds as if they were trying to get to sleep.

3.3.67 The stimuli presented included both real recordings and artificially-generated low frequency tonal signals. Subjects adjusted the level of the presented signal until deemed acceptable within the scenario context. The fluctuation in each signal was quantified using the percentile level difference L_{10}-L_{90}. The results indicated that the average acceptability thresholds were around 5 dB lower for fluctuating sounds with L_{10}-L_{90} values above 5 dB, when compared with those for steady sounds. Fluctuating sounds with L_{10}-L_{90} of around 4 dB had average thresholds of 1-4 dB lower than the steady sounds. The results were interpreted as evidence to support an assessment scheme for fluctuating LFN based on a 5 dB penalty value applied to sounds incorporating modulation exceeding 4 dB L_{10}-L_{90} (Moorhouse, Waddington, & Adams, 2013)[33]. A second criterion also required the noise under assessment to have a rate of change in fast-weighted[34] sound pressure level exceeding 10 dB/s.

3.3.68 The results are presented as averages without error bars, and there is limited statistical analysis presented to lend additional weight to the conclusions (this may be due the small sample size, which would limit the usefulness of significance testing). Nonetheless, it is informative to see a difference in sensitivity (i.e. in terms of mean acceptability thresholds) expressed by subjects for a simulated night-time situation, a contextual factor was not addressed in the category 1 laboratory studies reviewed in section 3.2. In this case the average threshold differences (i.e. between stimuli with or without modulation) for the tonal signals between day and night-time were shown to be in the region of 3-4 dB.

[31] The difference between the 10th and 90th percentiles of the signal sound pressure level

[32] Department for Environment, Food and Rural Affairs (UK)

[33] This publication comprised an erratum slightly modifying the original conclusion stated in the related paper.

[34] Time-weighting used to evaluate root-mean-square sound pressure, fast = 0.125s.

A comparison of the temporal weighting of annoyance and loudness (Dittrich & Oberfeld, 2009) ***[black]***

3.3.69 This laboratory study presented 12 subjects (mostly students, aged 20-31 years) with artificial randomly fluctuating broadband noise. It was shown that the variation of the stimuli in terms of standard deviation σ had a significant effect on rated annoyance but not on estimation of loudness; paired stimuli with σ = 4 dB were judged more annoying than those with σ = 2 dB, despite having equal L_{eq}.

Annoyance caused by low frequency sounds: spectral and temporal effects (Vos, Houben, van der Ploeg, & Buikema, 2010b)

3.3.70 In this laboratory study, 32 subjects (half with mean age 26, and half with mean age 53) were presented with a range of AM stimuli, including a 31.5 Hz tone, 31.5 Hz 1/3-octave bandpass filtered pink noise and road traffic-like filtered broadband noise, all modulated at 1 Hz frequency. AM depths of 6 and 12 dB were used for the broadband noise, with an additional depth of 18 dB used for the tones and 1/3-octave band noise.

3.3.71 The results for the tone signals showed a significant effect of both loudness and AM depth on rated annoyance. The stimuli were presented at 10, 25 and 40 phon loudness; for the 25 and 40 phon tones, the modulated versions were given significantly higher mean annoyance ratings compared with the unmodulated, with rated annoyance apparently increasing up to 12dB depth; at 18 dB AM depth there was no significant increase, suggesting subjects could not distinguish between 12 and 18 dB AM depth.

3.3.72 The results for 1/3-octave band noise showed no relationship with AM.

3.3.73 The results for the AM broadband noise again showed a significant increase in rated annoyance for modulated versus unmodulated, but there was no significant difference between the 6 and 12 dB AM depths used, again suggesting subjects had difficulty making a distinction once AM was detected in the signal.

3.3.74 In another experiment the subjects were played sound recordings of fluctuating aircraft and road traffic noise, which were compared with steady noise modified to have equal spectral content to the modulating sounds. The results for the sound recordings showed no significant effect due to fluctuation, but a strong relationship between overall time-average level and rated annoyance.

3.3.75 The author suggests that the results may indicate an equivalent annoyance steady noise level difference in the region of around 10 dB for the AM depths tested (i.e. ≥ 6 dB ΔL). This value appears to have been obtained by comparing the results from the artificial signal tests with those from the sound recordings.

Effects of sound on people (van den Berg F. , 2011) [grey]

3.3.76 In summarising the above studies, van den Berg concludes that the laboratory work indicates an association of increasing annoyance with AM broadband noises compared with the steady equivalent, but that the effect on annoyance may not continue to increase with greater modulation depth. The equivalent annoyance level difference (i.e. steady vs. modulating noise) is suggested as at least 3 dB.

Other Papers

3.3.77 Further studies identified in the literature search include the following publications.

Sound characteristics in low frequency noise and their relevance for the perception of pleasantness (Bengtsson, Persson Waye, & Kjellberg, 2004) [black]

3.3.78 This study was aimed at investigating subjective response to HVAC-like noise within the context of an occupational environment. 30 subjects were presented with an artificial stimulus combining recorded HVAC sound with filtered noise and modulating tones.

3.3.79 The subjects generally showed a preference for noise modulating at frequencies as far from the 2-6 Hz interval as possible within the 0.1-10 Hz range used, essentially confirming findings from earlier studies, including those reported by Fastl & Zwicker (2007). There was no investigation of the effect of altering modulation depth.

Annoyance of time-varying road traffic noise (Kaczmarek & Preis, 2010) [black]

3.3.80 This laboratory experiment prepared four auditory scenarios by arranging recorded road traffic passes into different temporal configurations, controlling the total number and type of vehicles within each structure. Nineteen subjects (aged 19-24) rated annoyance for 3 variations of each of the scenarios using an 11-point scale, and psychoacoustic parameters for each stimulus were also calculated.

3.3.81 The results showed that rated annoyance was significantly correlated with fluctuation strength, loudness and roughness. There were significant differences in the rated annoyance between the different temporal structures / scenarios. However, the differences were relatively small, in total (highest to lowest) spanning around 1 interval on the annoyance scale, based on averaged results. The scenario with highest annoyance ratings was composed from regularly spaced car passes at around 0.2 Hz (i.e. 5 second gaps between events), whereas the least annoying comprised discrete groups of 24 passes at around 2 Hz.

Spectral and modulation indices for annoyance-relevant features of urban road single-vehicle pass-by noises (Klein, Marquis-Favre, & Weber, 2015) [black]

3.3.82 This study used experimental results from a listening test with 14 subjects to derive proposed new measures for subjective characteristics, including the temporal description ‘sputtering’. Sputtering was found to have a correlation with the fluctuation strength metric, however this type of character is typically found in engine-like noises and unlikely to have wider applicability to WTN. There was no separate examination of modulation depths or frequency.

DISCUSSION

3.3.83 Most of the research in this section appears to support the idea that modulated noises are generally considered less pleasant than a steady equivalent at the same energy-average level. The metrics used to quantify modulation and the stimuli types vary considerably between studies, but broadly-speaking this difference in perception might be translatable to a level difference somewhere in the region of around 3-4 dB on average. It is noted that the stimuli used in the studies varied and was not necessarily WTN-like; in one study using broadband noises, a greater difference of up to 10 dB was proposed, though this conjecture was based on a comparison between different stimulus types.

3.3.84 There is some evidence to indicate that sensitivity to a modulating noise is greater in the context of a ‘getting to sleep’ situation than in a general ‘relaxation’ setting.

HUMAN RESPONSE TO WIND TURBINE NOISE EXPOSURE (HEALTH EFFECTS)

3.3.85 The literature search highlighted at least 30 separate papers that could be included in this category using the relatively specific search criteria defined in section 2. Since the vast majority of these studies were not deemed directly relevant to the aims of the project (as they did not attempt to quantify the AM component in the exposure), only a relatively small proportion have been reviewed, with the emphasis firmly on recent systematic reviews of the existing literature and large-scale epidemiological field studies aimed at establishing the likelihood of relationships between WTN and a range of possible health effects. Although somewhat relevant (since WTN inherently involves a degree of AM), this section is not intended to be an exhaustive review of individual studies into general WTN (i.e. where AM is not quantified) and health effects. Instead, a summary set of conclusions are presented based on interpretation of the main study outcomes and the weight of the evidence.

3.3.86 The following studies have been considered:

- ***Health impact of wind farms*** (Kurpas, Mroczek, Karakiewicz, Kassolik, & Andrzejewski, 2013) [black]
- ***Systematic review of the human health effects of wind farms*** (Merlin, Newton, Ellery, Milverton, & Farah, 2013) [grey]
- ***Wind turbine noise and health study – summary of results*** (Health Canada, 2014a) [grey], including supporting information from[35]:
  - ***Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: social survey and sound level modelling methodology*** (Michaud, et al., 2013) [grey]
  - ***Health impacts and exposure to sound from wind turbines: updated research design and sound exposure assessment*** (Health Canada, 2014b) [grey]
- ***Wind turbines and health: a critical review of the scientific literature*** (McCunney, Mundt, Colby, Dobie, Kaliski, & Blais, 2014) [black]
- ***Health effects related to wind turbine noise exposure: a systematic review*** (Schmidt & Klokker, 2014) [black]
- ***Wind turbines and human health*** (Knopper, et al., 2014) [black]
- ***Social survey on wind turbine noise in Japan*** (Kuwano, Yano, Kageyama, Sueoka, & Tachibana, 2014) [black]
- ***Wind turbine amplitude modulation & planning control study – Work Package 3.2: Excessive amplitude modulation, wind turbine noise, sleep and health*** (Hanning, 2015) [grey]
- ***Understanding the evidence: wind turbine noise*** (Council of Canadian Academies, 2015) [grey]
- ***The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies*** (Onakpoya, O'Sullivan, Thompson, & Heneghan, 2015) [black]

3.3.87 On review of these publications, it is clear that the study of human health effects (such as stress, anxiety, sleep disturbance, tinnitus, psychological and mental health) potentially caused by WTN exposure is a developing area of research, and there remain differences of opinion in the

[35] Subsequent to completion of the literature review component of this research, the final results of this study have been published in peer reviewed literature, listed in Annex 3. The published results confirm the earlier preliminary findings, i.e. the study found no significant association between the reported WTN levels (up to 46 dB(A) outdoors) and self-reported or objective measures of sleep disturbance.

literature. The following conclusions are considered by the internal research team to represent the current state of knowledge:

- There is strong evidence to show that exposure to WTN can cause increased annoyance amongst exposed populations.
- There is evidence to suggest that exposure to WTN is associated with increased risk of sleep disturbance for external WTN levels exceeding 40 dB(A). Much of the research indicates that where sleep disturbance is identified, this is more closely associated with annoyance than with levels of WTN exposure. For many people within exposed populations, it therefore seems likely that sleep disturbance may occur as a result of increased annoyance due to the presence of wind turbines, and at least part of this annoyance can be explained by the noise component (other factors are also important as discussed below). In other words, sleep disturbance could be an indirect effect of WTN exposure in cases when an individual feels increased annoyance, but direct causality cannot currently be robustly and consistently demonstrated.
- Similarly to sleep disturbance, there is limited evidence to indicate that increased stress or anxiety are associated with WTN exposure, and any effect may also be indirectly due to heightened annoyance responses rather than as a direct result of exposure.
- There is a body of evidence, generally anecdotal, suggesting a range of other possible (adverse) health effects and quality of life impacts that some people attribute to WTN exposure. These cases are not currently supported by the weight of the epidemiological evidence. It is acknowledged that prolonged exposure to levels of environmental noise has been linked with long-term health issues (WHO, 2011), but such effects have so far not been consistently or robustly demonstrated in the case of wind farm noise. Again, this could be explained by the small numbers of exposed persons and the relatively low levels of noise emitted, as well as further subjective modifying factors discussed below.
- A range of non-acoustic factors have been identified as potentially contributing to or modifying the annoyance that some people feel and attribute specifically to noise from wind farms. These include:
  - Specific visual impacts (shadow flicker, lights, rotation);
  - General attitude to wind farm appearance in the landscape;
  - Direct economic benefits from wind energy generation or specific wind turbine installations;
  - General attitudes to wind energy generation;
  - Type of area (urban / rural);
  - Exposure to positive / negative media coverage of wind energy and wind farm noise, and the activities of campaign groups; and
  - Sensitivity to noise and possible sensitisation due to awareness of wind farm noise research.

DISCUSSION

3.3.88 On the basis of this review, it is considered that at the current time there is insufficient evidence to indicate that the AM component in WTN at typical exposure levels directly causes any significant adverse effects beyond increased annoyance. However, it is noted that virtually none of the reviews of health effect studies explicitly address quantified AM exposure within the noise, and almost all solely consider time-averaged levels in their findings.

3.3.89 Since it is generally accepted that environmental noise can cause sleep disturbance (WHO, 2009), it seems likely that the apparent difficulty in consistently demonstrating a direct causal relationship between WTN and sleep disturbance in the field might be partly explained by the relatively low levels of WTN compared with other forms of environmental noise to which people are quite often exposed. Nonetheless, it should be noted from the research already discussed that increased distinctiveness of WTN is attributable (in part) to AM, and so it is not an unreasonable assumption that in the cases where people feel annoyed, and AM increases their annoyance, any indirect effects that may be associated with this annoyance, such as sleep disturbance or stress, could be exacerbated. In cases where people are situated in close enough proximity to hear WTN when trying to sleep, it is also possible that greater AM will increase the direct risk of disruption to sleep, in particular to the period of ‘getting to sleep’, due to increased awareness of and focus toward the noise; this suggestion seems to be somewhat supported by anecdotal descriptions, however more research would be needed to investigate this fully.

3.3.90 The publication by Hanning (2015) is notable here mainly as it appears to be somewhat in opposition to the findings of many of the above studies and reviews. The paper has also been reviewed by the independent external reviewers and is discussed below in sections 3.3.136 to 3.3.138. It is noted that the paper highlights supporting evidence from the case-study conducted by Thorne (2014), which has also been reviewed in the relevant section herein; it is considered there is little robust analysis in the case-study that upholds the specific findings claimed and subsequently quoted by Hanning (2015). Two other primary study references used to establish the author’s conclusions stem from research reported by Nissenbaum et al. (2012) [black] and Krogh et al. (2011) [black]. Concerns about the potential for significant risk of bias introduction in the designs of these studies and a questionable approach to the results analyses and subsequent conclusions have been raised by McCunney et al. (2014) and Ollson et al. (2013) [grey].

3.3.91 The great difficulty of isolating potential confounding factors in the field studies is clear: many of the review papers highlight sources of potential bias that are not considered to be adequately controlled in the primary research. There is also a significant drawback in that the studies are cross-sectional, and so it is not possible to assess the existence of health issues prior to exposure to WTN, and consequently causality. Moreover, it is not possible to assess the specific effects, including annoyance, which could be attributed to a change in the local noise environment as opposed to an on-going or ‘steady state’ situation. The ‘change’ situation is arguably more immediately relevant in a ’complaints’ context, since the initial response would be to the introduction of a new wind energy installation or, alternatively, expansion of an existing one. Research based on a steady state situation may under- or overestimate the response to WTN in general, and to AM in particular.

3.3.92 It is debatable as to whether further observational studies of a cross-sectional design will add value to the existing knowledge base, and may serve only to further cloud the issue due to the difficulties in isolating confounding factors. Future field studies should consider the potential for a longitudinal design, with effective masking and control groups in place to minimise some of the risks of bias. Well-designed studies considering quantified AM exposure-response would be valuable. In particular, objective measures of health, such as those used in the Health Canada (2014a) research (including sleep actimetry[36], stress hormone and blood pressure measurements), could serve to verify data obtained from typical self-reporting methods such as questionnaires and interviews.

[36] A non-invasive method of monitoring human rest/activity cycles in medical studies

FURTHER RELEVANT STUDIES

Audible amplitude modulation - results of field measurements and investigations compared to psychoacoustical assessment and theoretical research (Stigwood, Large, & Stigwood, 2013) [grey]

3.3.93 This study is a discussion document providing background, features, possible causes and contributing factors of AM WTN. The discussion draws on examples derived from measurements at 13 wind farm sites in the UK.

3.3.94 The main conclusions are that AM propagation is affected by meteorology and air profiles, WTN AM depth at some sites reaches 6-10 dB under some conditions, measurement of AM WTN is problematic and unlikely to be successfully conducted by regulators, and that psychological aspects relating to specific characteristics of the sound may play an important role in subjective responses.

3.3.95 This paper presents a very thorough analysis of a limited set of measurement data. It makes the useful observation that the atmospheric conditions that may contribute to higher risk of increased AM (such as stable atmospheres, temperature inversions, etc.) are more likely to occur during the evening, night or early morning.

WIND FARM PUBLICATIONS PRODUCED BY AN 'INDEPENDENT NOISE WORKING GROUP'

3.3.96 This section outlines a review of a recently-published portfolio of documents reporting on aspects of AM WTN that are relevant to this research. The aims and objectives of the authors are outlined, followed by reviews of the individual reports. It is understood that these papers have been presented to a number of Government departments, and DECC made a specific request to the research team to ensure that they were included in the formal review.

3.3.97 The documents discussed in this section were examined by the independent external reviewers. NB. All review commentary in this section is directly quoted from the review summaries received, as indicated by text in blue font. Any text added by the internal research team is indicated [in square brackets].

3.3.98 It was not possible within the scope limitations of the review to exhaustively check all source references and analyses made within these publications. Consequently the validity and accuracy of interpretative review and analysis of reference literature contained therein has necessarily been taken at face value.

Wind Turbine Amplitude Modulation & Planning Control Study – Terms of Reference (Independent Noise Working Group, 2015) [grey]

SCOPE

3.3.99 This document defines the Independent Noise Working Group (INWG) terms of reference (TOR), taking a holistic view of the current problem with wind turbine AM noise.

3.3.100 It is in response to real concerns about the strategy being implemented by the wind power industry via the IOA.

3.3.101 It was felt that the IOA AM study and report would be narrowly defined with limited scope to address the real problems of AM noise at both existing and new wind turbine sites.

3.3.102 The Objectives of the INWG were given as:

- To protect communities and wind turbine neighbours from amplitude modulation noise.
- This protection is urgently needed by communities close to existing wind turbines, wind turbines where planning consent has been given but the turbines not yet constructed and wind turbines being proposed through the planning system.

3.3.103 The document sets out the membership of a Steering committee which will define the TOR and a set of four deliverables:

- Report providing a rationale for introducing effective controls
- Workable and tested AM planning control or condition for new turbine schemes
- Effective method to control AM noise from turbines where planning consent has already been given
- Produce evidence to demonstrate the effectiveness or otherwise of the AM planning condition being proposed by the IOA NWG

3.3.104 The document sets out plans for wider consultation.

3.3.105 The TOR notes that the report and recommendations will be subject to a thorough review process plus an EHO panel to test the proposed AM control method.

3.3.106 The TOR set out the various Work packages

- WP1: Define and quantify AM
- WP2: Literature and evidence review
- WP3: Effects of AM
- WP4: Den Brook
- WP5: Draft AM planning condition
- WP6: Control of AM noise from existing wind turbines
- WP7: Test the IOA NWG proposed AM planning condition
- WP8: Review the IOA AM study and methodology
- WP9: The Cotton Farm monitoring experience

QUALITY, ROBUSTNESS, RELEVANCE

3.3.107 The TOR document itself, being reviewed here, talks of the Steering Group developing the TOR, [which raises the question as to whether] the TOR were changed during the course of the project.

3.3.108 The document is particularly relevant to the issue of what constitutes adequate planning conditions and effective control measures.

Wind turbine amplitude modulation & planning control study – Work Package 1: The fundamentals of amplitude modulation of wind turbine noise (Yelland, 2015) [grey]

SCOPE

3.3.109 This paper explores aspects of AM and EAM[37] relating to their definition, causes and measurement.

3.3.110 [The] main chapter headings are:

- *The Characteristics of AM and EAM*
- *Causes of AM – wind shear, transient stall pressure pulses, vortex shedding, blade/tower interaction etc.*
- *The RUK[38] report*
- *Measurement problems*

QUALITY, ROBUSTNESS, RELEVANCE:

3.3.111 Much of the section on Conclusions does not actually relate to the preceding content but includes unrelated comment on such issues as [in the INWG author's view] the increasing inadequacy of the ETSU document and the nocebo[39] effects. There are also alarmist comments on potential health hazards and anecdotal claims about various serious effects on animal life, e.g. aborted mink.

3.3.112 The report is very strong, clear and objective on the technicalities of the characteristics and causes of AM. However, when it comes to comments on the RUK report, the tone changes completely. [The INWG author of the paper] starts by impugning the motives of the authors [of the RUK report], the links with industry, lack of peer review etc. He states that the report is "*technically unsound and highly misleading*".

3.3.113 An example of the tone used:

> "*The claim of 'peer reviews' by an author's colleagues who rely on the same customer base and belong to the same professional institution as the author is worthless and serves only to demean the author and the institution.*"

Wind turbine amplitude modulation & planning control study – Work Package 2.1: Review of reference literature (Cox, 2015) [grey]

SCOPE

3.3.114 This work package presents the results of a review of the literature WTN. Over 160 documents were reviewed by the INWG for this study of AM.

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[37] Excessive/excess/enhanced amplitude modulation
[38] RenewableUK – renewable energy trade association (UK)
[39] Describes a response that is caused by a subject's expectation of adverse effects from a stimulus - in this case, exposure to wind farm noise

3.3.115 The report reviews the literature relevant to WTN AM and consolidates the reference material considered by the INWG in the various work packages (WP) making up the study into AM.

3.3.116 Objectives are given as:

- *Review the evolution of knowledge regarding WTN and AM;*
- *Collate the reference literature relevant to this INWG study of WTN AM and produce a common reference list for the study work packages;*
- *Provide a short description of each reference document*

3.3.117 The main chapter headings (which give an indication of the 'tone' of the report) are:

- *Executive Summary*
- *Introduction*
- *Knowledge Evolution*
- *The Case regarding Low Frequency Noise*
- *The Case Against ETSU*

CONCLUSIONS FROM THE PAPER

3.3.118 This review of evidence spanning over 30 years shows a clear evolution of knowledge relating to the science behind WTN and its effects on people. Starting with the NASA research conducted during the 1980s through to the NIA[40] inquiry report of March 2015 and beyond, many of the key scientific aspects are now well understood and well defined.

3.3.119 The most important conclusion from this evidence is that [in the INWG author's view] the official UK WTN guidance, ETSU, is totally unfit for purpose and is failing to protect against the effects of EAM noise. Despite it being updated and acquiring an IoA-developed Good Practice Guide, it was [in the INWG author's view] developed using evidence relevant only to small turbines far removed from the 80m hub height devices being deployed almost twenty years later, and does not reflect the more recent science.

3.3.120 [Original INWG author's description] *Throughout this period since 1997 the wind industry, aided by its acoustic, political and legal consultants has sought to hide the true science behind EAM in WTN and its effects on people though a concerted strategy of obfuscation and political interference. This has been aided by compliant government officials who have been focused on removing barriers to the deployment of wind power generating capacity and by the wind industry effectively taking control of the Institute of Acoustics (IOA). The IOA Good Practice Guide to the application of ETSU subsequently approved by government is an example of how commercial interests and political lobbying have triumphed against science and wind turbine neighbours. At no point does it tackle any of the issues identified by the research into EAM that we have reviewed above. Complaints regarding wind turbine noise currently classified as AM or EAM or OAM[41] or 'greater than expected AM' by the wind industry is an obfuscation of the true nature of*

[40] Northern Ireland Assembly
[41] 'Other' amplitude modulation, another description for AM outside the expected norm.

the problem. As a result, all efforts to date by third parties to have the ETSU noise guidelines revised or replaced with a science-based alternative have been successfully resisted.

QUALITY, ROBUSTNESS, RELEVANCE

3.3.121 The conclusions listed above are not listed as overall conclusions of the report. They come at the end of section 3 on knowledge evolution, which is a discursive and somewhat rambling account of 30 years of research. AM features highly in this account in a rather unstructured way. There are no helpful conclusions on AM itself. Other main parts deal with 'LFN' and the 'Case against ETSU'.

3.3.122 Much of the rest of the report is taken up with extensive summaries of literature.

Wind turbine amplitude modulation & planning control study – Work Package 2.2: AM Evidence Review (Large, 2015) [grey]

SCOPE

3.3.123 This work package deals only with audible EAM. It looks primarily at measurements of AM in support of its existence and prevalence. It looks secondly at reports of AM, which is a limitation of this review as it relies on anecdotal evidence.

3.3.124 This work package is not intended to be a discursive document but simply as a collation of evidence with a brief resume of the AM noted in the relevant study or research project.

CONCLUSIONS OF THE PAPER

3.3.125 [Original INWG author's description] *There exists an international history of evidence that documents the presence and regular occurrence of AM. Empirical data and subjective reports demonstrate that the manifestation of AM and the presence of AM within wind farm noise are effectively linked to increased annoyance. [This review] of AM research provides only a summary of documents and measurements from a single UK consultancy and open-access papers. Access to papers published in subscription-only journals or to the resources available to larger consultancies can only be expected to increase documented cases of AM and provide further evidence supporting the prevalence of AM.*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.126 The title is misleading in that the evidence is a 'mish-mash' of reported complaints, comments on research papers, plus objective measurement data assessed as constituting AM.

3.3.127 The papers included some of those being considered by [the current study on behalf of DECC] such as Lee et al. (2009). However, no systematic assessment is made.

3.3.128 Appendix A [in the paper] gives a table of more than 70 sites where complaints were noted. This seems unrelated to the main text. No documentary evidence is provided about the form of complaint, e.g. written, telephone etc.

Wind turbine amplitude modulation & planning control study – Work Package 3.1: Study of noise and amplitude modulation complaints received by local planning authorities in England (Sherman, 2015) [grey]

SCOPE

3.3.129 [Original INWG author's description] *This study uses survey data to provide insights into the current views of involved English Local Planning Authority (LPA) professionals on how to prevent, control and mitigate industrial wind turbine noise including the phenomenon of excess amplitude modulation (EAM) that gives rise to most complaints. The three questions asked were:*

- *Have you received noise complaints?*
- *Have you received AM complaints? And*
- *If yes, how do you deal with them?*

CONCLUSIONS FROM THE PAPER

3.3.130 [Paraphrased from the INWG author's description] In England, 54 LPAs from 203 responses report having received complaints about noise from industrial wind turbines. Of these 54 LPAs, 17 report having also investigated complaints about EAM. There is a high level of awareness amongst LPAs of EAM, but no consistent approach to complaints. 'Noise only' complaints are generally resolved but most 'AM related' complaints remain unresolved and there is no working solution to the problem. EAM is more common than suggested by government policy. Compliance with ETSU does not correspond with likelihood of AM complaints. EAM nuisance is a 'noise character' not a 'noise level' issue. Guidance is needed on detecting and remedying EAM.

QUALITY, ROBUSTNESS, RELEVANCE

3.3.131 A number of inherent limitations of the study are acknowledged by the author – including that the overall number of noise complaints about WTN or EAM cannot be accurately established. In addition, the survey was introduced via a letter from Christopher Heaton-Harris MP that may have influenced the number and nature of LPA responses: 203 LPAs responded from 265 "*relevant*" LPAs (i.e. deemed likely to have experience of turbines by the authors) within an overall total of 423 LPAs in England. This is an unusually high response rate for a survey of this type. [Responses were based on] only three simple questions. [There are] some inherent limitations to the methodology. The author has relied upon the fuller responses received from a subsample of respondents to produce the discussion.

3.3.132 The statement in 1.1 of the Executive Summary that EAM "*gives rise to most complaints*" is a little misleading because, for example, the total number of complaints cannot be accurately established; the complaints information may be skewed by responses from one or two LPAs; and only 17/54 of those LPAs reporting complaints specifically said they were about AM. However, the author may be drawing on additional information supplied by LPAs to support this statement.

3.3.133 There is no time-frame mentioned in the survey questions, so, the numbers of reported complaints should be regarded as all-time totals and trends over time cannot be reliably ascertained.

3.3.134 There is no attempt to provide context by comparing the reported numbers of complaints about WTN with the total number of consented turbines, nor with the reported numbers of noise complaints about other sources that are received by LPAs,in particular by Environmental Health Practitioners (EHPs).

3.3.135 There is no detailed analysis of why only 4 Noise Abatement Notices were "*considered or served*". A constructive suggestion from one LPA that 'Energy Generation' should become a specific Land Use Category to facilitate a more systematic consideration of wind farms (and solar farms) in the planning system may be worth examining as part of the wider aspects of [the current study on behalf of DECC]. The analysis lacks wider context.

Wind turbine amplitude modulation & planning control study – Work Package 3.2: Excessive amplitude modulation, wind turbine noise, sleep and health (Hanning, 2015) [grey]

SCOPE

3.3.136 Relevant aspect of [the] review: review of effects of EAM on people living close to wind turbines in terms of annoyance, sleep and health effects. In fact [there is] not a lot on AM in the report.

CONCLUSIONS FROM THE PAPER

3.3.137 [As presented]

- Current setback distances for wind turbines recommended by ETSU are not safe for health.
- Reports that wind turbine noise is more annoying than aircraft, road and rail noise, controlling for intensity.
- Disputes that WTN is masked by background noise.
- Suggests that there are effects of low frequency noise on health.
- AM [is deemed] more annoying than unmodulated WTN. [The INWG author] suggests that 2dB AM depth is negligible, 4dB is unreasonable and 6dB is excessive.

QUALITY, ROBUSTNESS, RELEVANCE

3.3.138 A selective review of peer-reviewed literature plus internet-based reports and anecdote. The literature review is not systematic and the interpretation and conclusions are selective. There is little consistent evaluation of the different strengths of the evidence although some studies are pointed out as being uncontrolled. [There is] not a lot on AM in the report.

Wind turbine amplitude modulation & planning control study – Work Package 4: Den Brook (Hulme, 2015) [grey]

SCOPE

3.3.139 To document legal, planning and technical aspects surrounding the Den Brook (North Tawton, West Devon) planning conditions[42]. Den Brook Judicial Review Group (DBJRG) established to ensure acoustic impacts from proposed wind turbines were properly "*conditioned and controlled*" and to represent the interests of local residents. Work package 4 describes the Den Brook timeline where it relates to amplitude modulation.

3.3.140 This paper presents the process of agreeing the conditions for AM in wind farm operations at Den Brook. Inevitably it presents the case from one side.

CONCLUSIONS FROM THE PAPER

3.3.141 [According to the INWG author] The EAM conditions imposed [at Den Brook] seem unclear. Suggestion that conditions might be unenforceable due to false positive background noise. The condition 20 methodology alone cannot reliably distinguish periods of data that do/not contain AM.

QUALITY, ROBUSTNESS, RELEVANCE

3.3.142 The paper outlines the disputes between the developer, the planning authorities and courts and the DBJRG. Technical details on noise are relatively limited. [According to the INWG author] Initial acoustic assessments by the developers were "*found to be flawed*" so the initial planning permission was quashed. The developer then submitted a proposal for substantially weakening the noise conditions; examination on behalf of DBJRG found this to be flawed too. The developer then devised a written scheme. However, precautions taken within this scheme (stage 4c) to filter out "*apparently invalid complaints*" revealed "*substantial discrepancies*" – meaning that EAM noise would be "*significantly and materially understated*". In further meetings it was conceded that EAM is not a rare occurrence. Following this DBJRG plan to carry out 24/7 noise monitoring.

3.3.143 This paper presents the process of agreeing the conditions for AM in wind farm operations at Den Brook. Inevitably it presents the case from one side. The process as reported here is conflictual and does not show parties in a good light. It is also clear that the issues generate high levels of emotion.

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[42] A number of references are made to the "Denbrook" AM condition in various documents. It should be noted there is: a) the AM condition as originally applied at the first Inquiry (referred to as the 'original'); b) the AM condition as amended through the course of various legal challenges; and, c) the AM condition as it currently stands at the time of writing (referred to as the 'final') following a recent amendment by the applicant and subsequent legal challenge.

Wind turbine amplitude modulation & planning control study – Work Package 5: Towards a draft AM condition (Large, Stigwood, & Bingham, 2015) [grey]

SCOPE

3.3.144 [INWG author's description] *Four main methods for assessing or limiting EAM have been critically examined in this work package. These methods are representative of the range of assessment / control methods currently proposed for EAM. Each method was tested with real world data from six different sites ranging from smaller single turbines to large wind farm developments. The methods tested were the RenewableUK template planning condition, a methodology proposed by RES*[43] *for the Den Brook case, the original Den Brook EAM condition and the Japanese DAM*[44] *methodology. In addition BS4142:2014 and BS4142:1997 were tested with data from two of the six sites.*

CONCLUSIONS FROM THE PAPER

3.3.145 [INWG author's description] *This work package shows that existing methods of controlling and assessing AM can be successfully modified and implemented to provide a prescriptive and unified assessment process for EAM. Where wind farm noise level and wind farm noise character require simultaneous assessment the use of BS4142:2014 is recommended. The difficulty of rating EAM for frequency of occurrence and duration in the absence of research looking at long term impact of EAM and subjective response is acknowledged.*

3.3.146 It is concluded that "*assessment of the extent of impact should remain the responsibility of those assessing and enforcing impact*".

3.3.147 [Original INWG author's description] *There are several different methodologies for deriving an AM value but two main differences in how this relates to a control for AM. Firstly the AM value can be used to derive a penalty that ultimately influences the overall noise limit. Thus, AM is controlled by way of lowering the noise level or noise exposure level. Examples include the RenewableUK method. Secondly the AM value is used to judge whether or not AM is acceptable. A higher AM value indicates that AM is not acceptable and that the noise must be mitigated, the lower the value the more likely it will be considered reasonable. Thus the AM value is treated as a trigger point for mitigation measures. Examples include the Den Brook condition. BS4142 provides a hybrid methodology where a penalty is derived to acknowledge intrusive character features and applied to the overall noise level, but importantly this is then compared to the background sound level rather than a threshold noise limit. This latter method has the benefit of adding context to the assessment, both in terms of context of the noise within a specific environment and a human / subjective context.*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.148 First impression is that this is a thorough and balanced review. It contains relevant detail on the derivation of suitable planning conditions and any wider approach to control the impact of AM in the planning system.

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[43] Renewable Energy Systems (developer of the Den Brook Wind Farm)

[44] Refers to the AM depth metric D_{AM}, discussed in section 3.2

3.3.149 The report predates the recommendations of the IOA AMWG[45] for the IOA preferred AM indicator but it uses an approach to compare the available AM indicators that addresses the need for such indicators to go beyond the (acoustic) identification and quantification of AM and to relate to the (human) impact of the noise in a way that will work robustly and fairly in a wider (planning and complaints assessment) context.

3.3.150 The report contains a brief but useful discussion of how the impacts of other sources of noise with character are currently assessed, including judgements of acceptability.

3.3.151 The report contains a useful discussion of the Government's six [tests] for planning conditions with a focus on WTN and a further six objectives that the authors consider desirable.

3.3.152 The need for the chosen AM indicator to relate to the assessment of impact is highlighted and the report provides a logical process diagram to assist with the derivation of a suitable AM planning condition.

3.3.153 The various reviewed AM indicator methodologies are grouped into one of four categories in a useful table that highlights the current differences in approach:

a) Application of a penalty to overall noise limit.

b) Trigger value.

c) Derivation of AM indicator only (no application to impact assessment).

d) Use of context/human judgement.

3.3.154 The report finds that several of the available methodologies work to some extent and could be applied, with some adaptions, to produce a workable method for assessing and controlling EAM.

3.3.155 There is detailed discussion about the strengths and weaknesses of the different methods, including a favourable appraisal of a BS4142:2014 type of approach to the control of wind farm noise with character.

3.3.156 The following quotation is relevant:

> "*There is currently little knowledge or understanding of how features such as frequency and duration, context with background sound environment and time of occurrence specifically impact on the perception of EAM. Based on experience gained from impact of other noise sources it is expected that the more frequent and long lasting the EAM the more intrusive. Evidence suggests that those impacted by noise with character do not habituate to the noise but conversely become sensitised.*"

3.3.157 The discussion concerning the absence of a clear dose-response relationship is particularly pertinent:

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[45] Amplitude modulation working group, formed from membership of the IOA and the Chartered Institute of Environmental Health at the behest of Government to investigate the formulation of a metric for quantification of AM WTN.

"*However, it is common for all noise with character that the more periods of intrusion, the longer the noise occurs, the more noise penetrates dwellings and cannot be escaped, the more noise sensitive periods are effected* [sic] *(i.e. sleep vs. labour or rest and relaxation), then the greater or more extreme the impact will be. It is suggested that in the absence of any clear dose response relationship assessment of these aspects remains addressed through subjective, professional judgement and on the basis that intrusion of more sensitive activities and areas of a dwelling should be prevented.*"

3.3.158 The report recommends that two separate assessment/enforcement methods for EAM should be used. Where the noise from a wind farm is steady, continuous and anonymous ETSU-R-97 could continue to be used for assessment at the planning stage and for compliance testing. Where wind farm noise complaints indicate a variety of impacts including noise level, noise character, and/or tonality then BS4142:2014 can be used as a stand-alone assessment independent of any other assessment. It is suggested that the rating noise level of the wind farm/wind turbine noise should not exceed +10dB above the background sound level. There is no detailed analysis of the implications of this suggestion, in particular whether or not the adoption of such a criterion would have an undue effect on the day to day operation of wind farms.

Wind turbine amplitude modulation & planning control study – Work Package 6.1 (inc. 6.1a Supplementary Paper): Legal issues: the control of excessive amplitude modulation from wind turbines (Cowen, 2015) [grey]

SCOPE

3.3.159 [INWG author's description] *The Objectives of this Work Package are:*

- *Objective 1 – To assess the legality of the Den Brook Condition relating to EAM following the judgement of the Court of Appeal;*
- *Objective 2 – To assess the legal appropriateness of other remedies such as Statutory and Private Nuisance that have been recommended since that judgement or may be available to persons affected by EAM;*
- *Objective 3 – To recommend the most appropriate course of action that will provide legal protection to residents hosting wind farms should EAM occur.*

CONCLUSIONS FROM THE PAPER

3.3.160 [INWG author's description] *Objective 1 has been met by a complete review of the situation regarding a planning condition to control EAM since the judgment of the Court of Appeal in the Den Brook case. The advantage of this procedure is that a suitably worded condition strikes at the heart of this problem. However, it also has to be acknowledged that there are procedures to be followed and these can take time. The question is whether this is the most effective way of addressing the problem.*

3.3.161 [INWG author's description] *Objective 2 has been addressed through discussion of other remedies available under the TCP*[46] *Act if a planning condition is in place, namely the power to serve a stop notice, to serve a breach of condition notice or to seek an injunction. Of these, a Stop Notice runs the risk of substantial compensation being paid and a Breach of Condition notice*

[46] Town and Country Planning

does not have real 'teeth'. However, if an injunction can be obtained, this is likely to be a powerful tool. It may be expensive and perhaps risky to obtain, but if the Court should grant one, it should quickly resolve the problem. It cannot be considered costlier or more protracted that alternative approaches such as SN[47]*.*

3.3.162 [INWG author's description] *In answering Objectives 2 and 3, other potential remedies have been considered. Some of these such as SN have been actively advocated by the Wind Industry and supported by Planning Inspectors. Evidence however suggests that an Abatement Notice is not an effective control to protect nearby residents from EAM. Others such as private nuisance and similar legal actions have been considered but these place too much risk and burden on residents for a problem not of their making with likely long term adverse financial implications. They may however be the only remedies available if a suitably worded condition is not imposed in the Planning Certificate. The inability of the alternative procedures to bring about effective control and exemption from those procedures in some cases may indicate action under the EHRC*[48] *is the only realistic option. This is also a complex, potentially lengthy and dauntingly uncertain process.*

3.3.163 [INWG author's description] *Consideration has also been given to Blight action. This could provide a speedy remedy if there were power to enforce it but, under the current law, this is not an option that is open to residents.*

3.3.164 [INWG author's description*] A final purpose of this paper is to recommend the most effective course of action to protect residents if there is a potential problem caused by EAM from a wind farm or turbine. While no course of action may provide the speedy remedy that is sought, it is firmly recommended that the adoption of a modified Den Brook type condition is appropriate.*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.165 [This is a] carefully written legal review that recommends that control of AM through the planning system is the most appropriate formal/legal course of action, and that the [original] Den Brook condition is the most suitable of the conditions currently available.

3.3.166 This paper assumes that the EAM problem exists, is sufficiently widespread and of such impact (on residential amenity, health and quality of life) that it should be subject to formal control.

3.3.167 The conclusion supports the use of a modified Den Brook condition but it is caveated that a "*suitably worded alternative condition may need to be drafted*" and "*imposed in every planning permission for a wind turbine unless there are clear reasons to show that it is unnecessary*".

3.3.168 The paper describes legal issues surrounding the need for a suitable EAM planning condition, but contains no new proposals.

[47] Statutory Nuisance
[48] European Convention on Human Rights

Wind turbine amplitude modulation & planning control study – Work Package 6.2: Control of AM noise without an AM planning condition using Statutory Nuisance (Gray, 2015) [grey]

SCOPE

3.3.169 To contrast the effectiveness of Statutory Nuisance versus a statutory planning condition for dealing with AM noise from wind turbines.

CONCLUSIONS FROM THE PAPER

3.3.170 [Paraphrased from INWG author's description] Statutory Nuisance is a reactive response to complaints about noise from a householder to the local authority. It does not offer the same protection in law as a clearly defined AM planning condition. Statutory Nuisance should be a fast remedy but it is not. The consequence of using Statutory Nuisance seems to be that the wind farm operator has no legal obligation to control WTN AM. ETSU guidance allows a small amount of AM up to 3dB close to turbines – but apparently this doesn't deal with AM further than 50m from the WT. Despite many complaints about noise reportedly no EHOs have shut down or restricted the activity of wind turbines. Reluctance by local authorities (LAs) to use SN for fear of counter loss of income claims from WT owners. Fines are relatively small for WT owners. DEFRA Guidance for LAs is not practically helpful.

3.3.171 If "*average dB readings fall within the ETSU LA90 limits, which by design ignore the contribution from the peaks of noise, then the peaks and troughs of AM noise can be at any level of modulation.*"

3.3.172 Example given of Cotton Farm, Cambridgeshire, where continuous noise monitoring demonstrated more EAM than was anticipated.

3.3.173 [INWG author's description] *Statutory nuisance is therefore unlikely to provide a route to resolving an EAM problem. A planning condition is required.*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.174 A reasonable case is made here (particularly because of the permanent nature of the noise source and the possibility of designing in mitigation at the development stage) that a statutory nuisance approach is not the right way to approach this and does weight the outcomes in favour of wind turbine owners.

3.3.175 A planning condition would be better. There is an issue here about if annoyance is largely dependent on sound intensity will a simple reduction in sound intensity reduce the effect on annoyance or distress specifically related to AM?

Wind turbine amplitude modulation & planning control study – Work Package 8: Review of Institute of Acoustics amplitude modulation study and methodology (Cox, 2015) [grey]

SCOPE

3.3.176 [INWG author's description] *To review and summarise the activities of the Institute of Acoustics and its Noise Working Groups with respect to wind turbine noise amplitude modulation.*

CONCLUSIONS FROM THE PAPER

3.3.177 [INWG author's description] *This chronology of the activities by the IOA shows that its NWG and specialist subgroup the AMWG devoted to the study of excess amplitude modulation have consistently operated for the benefit of the onshore wind industry in the UK and to the detriment of local communities hosting wind turbines. This is also arguably against both the IOA code of ethics and that of the Engineering Council. The effect has been to both obfuscate and hide problems related to wind turbine noise assessment from government and from the Planning Inspectorate. Whether or not this behaviour is carried forward into the future remains to be seen (July 2015).*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.178 This paper contains allegations of conflict of interest, and professional malpractice that are outside the scope of this review.

3.3.179 However, paragraph 49 contains a useful critique of the IOA AMWG consultation that is of direct relevance and is therefore reproduced below:

"Comments on, and criticism of, the IoA AMWG consultation document include:

- *The definition of EAM is too narrow as there are also many variable sound characteristics other than simply modulation depth that contribute to what is generally considered as EAM;*
- *Turbine sound emissions also include low frequency sound both audible and non-audible that should not be ignored as it all contributes to the sensation effect;*
- *Consideration of LFN is conspicuously absent from the consultation document. By excluding frequency data below 100Hz, much of the low frequency energy will be eliminated resulting in EAM being under reported;*
- *Turbine sound and EAM should be measured where people will experience it. This should include close to buildings where reflections can affect the noise levels and inside buildings where room resonance effects combined with low background noise can amplify its effects;*
- *Class 1 instrumentation as recommended by the IOA NWG in their Good Practice Guide have been shown to be inadequate in that its 'noise floor' is too high for low background noise environments and is unsuitable for the low frequency measurement capability required for wind turbine sound;*
- *The IOA and wind industry appear obsessed with 'automating' the AM measurement process using software. This will have the effect of removing transparency from the process when what is required is a simple transparent process that a local authority EHO can carry out with or without an acoustics consultant;*
- *The IOA AM study is too narrowly defined and avoids looking at the big picture with regard to AM and how it affects people. This IoA AM study is also widely seen as another wind industry attempt at obfuscation to ensure EAM planning conditions will not unduly constrain wind power development and has nothing to do with protecting those affected by the noise.*"

3.3.180 Observations on these points, based on the subset of literature that has been reviewed as part of [the current study on behalf of DECC], are as follows:

- There is evidence in the reviewed research literature that other WTN and AM characteristics, in addition to modulation depth, are likely to be relevant to adverse effects such as annoyance and sleep disturbance. There is a lack of well-designed long term field based dose-response research in this field.
- There are some attempts in the reviewed research literature to include noise measurements both inside and outside homes, and to relate this to human

response, however a number of difficulties and shortcomings in the assessment of both dose and response have been identified in the reviewed research.

- There are a number of competing demands that are important in the choice of a suitable AM indicator. For the purposes of setting an effective policy control criterion the indicator will need to be more than 'simply' a technically robust metric. In [the opinion of the reviewer], in addition to transparency, repeatability and reproducibility, the indicator will also need to be relevant to perception and to the management of impact (on residential amenity, health and quality of life).
- The [the current study on behalf of DECC] has attempted to systematically identify and review all relevant research literature, particularly on the effects of AM on people. However, there are difficulties in conducting longer term ('big picture') field studies and there are limitations in the amount and quality of the underlying research.

Wind turbine amplitude modulation & planning control study – Work Package 9: The Cotton Farm monitor experience (Gray & Tossell, 2015) [grey]

SCOPE

3.3.181 [INWG author's description] *To document the experience of fighting a wind farm application and the decision to carry out long term noise monitoring by the local community to prove the existence and frequency of noise emanating from a newly built wind farm.*

CONCLUSIONS

3.3.182 [INWG author's description] *Existing wind turbines, as has been proven by the Cotton Farm monitor experience, should be constantly monitored and the data recorded. There has to be a clear understanding of the problems caused by noise and a clear directive for immediate action by the authorities and operators when unacceptable noise conditions do occur. The experience pioneered by the local community around the Cotton Farm wind farm proves this is not only practical but essential for legal and health reasons.*

QUALITY, ROBUSTNESS, RELEVANCE

3.3.183 Continuous unattended noise monitoring (over 2.5 years), met data and resident complaint logs are available. It is not clear if this can be linked with operational data from turbines themselves. There may be an opportunity to undertake dose-response analysis of the data being collected at Cotton Farm but this is not discussed or reported here. It's difficult to assess quality and robustness of measurement of dose and/or response from the information provided. [Response is not scaled on any] standardised rating of annoyance. Residents are able to decide when to complete diaries and how to describe the effects.

3.3.184 Only one measurement position is being used for long term measurements so [the data] may not be representative of levels at all properties.

3.3.185 It is likely only to be those who object to the wind turbines or WTN that are taking part in this project so there is an unavoidable risk of bias.

3.3.186 [There is] no information of direct relevance to [the current study on behalf of DECC] but possible relevance to compliance monitoring [in relation to] planning conditions and to future design of longer term field research studies.

CATEGORY 2 CONCLUSIONS

3.3.187 The category 2 papers reviewed in section 3.3 provide supporting evidence that:

- Perception of amplitude modulation in WTN and other environmental sounds affects subjective annoyance;
- There is an potential association between WTN-related annoyance and increased risks of sleep disturbance and stress;
- There are other non-acoustic factors that play an important role in influencing the subjective annoyance attributed to noise from wind turbines, including sensitivity, attitude, situation, aesthetic perception and economic benefits; and
- Annoyance due to AM WTN seems to be increased during normal resting periods, i.e. late evening / night-time / early morning. This could be due to increased sensitivity, greater AM prevalence or magnitude (e.g. due to diurnal variations in atmospheric conditions) or a combination of these factors.

3.4 LIMITATIONS OF EVIDENCE

3.4.1 The following paragraphs list recommendations for future research based on the identified limitations of the category 1 & 2 papers, and summarises how the conclusions of these papers can be used in their current form.

CATEGORY 1 PAPERS

3.4.2 None of the laboratory studies reviewed address possible differences in sensitivity that might be encountered in different contexts, for example, when trying to get to sleep at night-time. Further work to closely investigate the effects of potential differences in diurnal sensitivities to AM WTN would be informative. Any laboratory results should also be compared or augmented with field study data. This could be especially valuable in view of the results of broader field studies (discussed further in section 3.3), some of which report increased complaints due to WTN in the night-time hours, and generally include much larger samples than the Category 1 studies reviewed.

3.4.3 The limitations of an artificial environment present significant difficulties for achieving wider applicability of the results. One particular difficulty with the laboratory studies that focussed on rating absolute annoyance is the relatively short duration of the stimuli generally used compared with what may be encountered in the field. Consequently, ‘annoyance’ ratings obtained in this way are unlikely to be closely representative of the potentially emotional response that could be experienced by people over varying exposure durations, periods and intermittency, and within other contexts and environments. There was only a single field study (D[49]) identified with potentially useful exposure-response data in this area, which unfortunately had drawbacks of a small sample and high potential for bias. A strong need has been identified for studies focussing on quantifying exposure-response relationships that reflect conditions likely to be experienced by those within the exposed population. The Tokyo study (B) did include large-scale field measurements and social survey data, producing exposure-response relationships for time-averaged levels (L_{Aeq}) (Yano, Kuwano, Kageyama, Sueoka, & Tachibana, 2013). The study also analysed measurement data from 18 wind farm sites, and applied the developed AM metric to produce an estimate of fluctuation sensation at the measurement points. However, the group

[49] (Bockstael, Dekoninck, Can, Oldoni, de Coensel, & Botteldooren, 2012); (Bockstael, Dekoninck, de Coensel, Oldoni, Can, & Botteldooren, 2011)

have not yet published an investigation of direct links between the perceptual results on AM with those obtained from the social survey work. Any such link, if established, could provide potentially valuable information in this area.

3.4.4 None of the category 1 studies reviewed directly investigated the effect of *changes* in an existing noise environment due to (the introduction of) AM WTN, which understandably in a laboratory setting would be very difficult to design representatively. Further work in this area could be valuable, and would ideally be investigated via a longitudinal field study, in which noise measurements and associated social survey data are obtained in an area prior to an impending wind turbine installation that is later developed. Post-installation measurements and survey data, including those from a control group not exposed to WTN could then be compared to establish changes in the environment due to (AM) WTN and any associative changes in perceptual response. Unfortunately it must be acknowledged that this type of study design could be difficult to realise, not least because of the relatively small proportion of the UK population exposed to WTN, and the sensitivities surrounding wind farm proposal sites and public awareness. Further field studies and the implications of the lack of assessment of noise environment changes are discussed in the Category 2 papers section 3.3.

CATEGORY 2 PAPERS

3.4.5 A number of avenues of future investigation are raised:

- Longitudinal field studies incorporating subjective *and* objective measures of response to WTN exposure, with quantification of AM verified with measurement data.
- Studies aimed at identifying the influence of AM WTN exposure on observed responses in realistic situations, specifically addressing:
  - duration;
  - magnitude;
  - frequency of occurrence;
  - both ‘steady state’ and ‘change’ environments; and
  - differences in sensitivity over a range of applicable contexts (e.g. including rest / sleep periods).
- Research to further establish the effectiveness (in terms of subjective perception and response) and availability of mitigation methods for AM in WTN.

SUMMARY

3.4.6 None of the available research reviewed as part of this study has been designed to answer the main aim of the study in its entirety. That research would have ideally included a longitudinal field-based exposure-response study, specifically quantifying both the AM character of WTN, and a scaled response from the sample subjects. The Category 1 study results have questionable applicability to a wider population, due to limited sample representativeness and associated potential for bias (which may be practically unavoidable in laboratory studies), whereas the Category 2 studies generally do not directly address the issue of AM WTN exposure-response (and also carry potential risks for bias). A meta-analysis of the identified studies was not possible due to the incompatibility of the various methodologies employed.

3.4.7 In order to progress this study, it has been necessary to look at all of the available research and make some professional judgements to link the various relevant elements together. This process has been undertaken by the researchers, and reviewed by the independent external reviewers. It should therefore be recognised that the discussions and recommendations made are based on professional judgement and consideration of the best currently available evidence.

3.5 INSTITUTE OF ACOUSTICS METHOD FOR RATING AM

3.5.1 As noted in paragraph 1.1.6, the IOA AMWG have been working on the development of a method for the collection of data for subsequent identification and then rating of amplitude modulation in wind turbine noise. A draft of the Final Report "*A Method Rating Amplitude Modulation in Wind Turbine Noise*" (IOA AMWG, 2016) was made available to our project team in January 2016 for review by the internal research team. The draft Final Report contained the group Terms of Reference in Appendix A and Scope of Work in Appendix B.

SCOPE

3.5.2 [AMWG author's description] *This document has been prepared by the Amplitude Modulation Working Group (AMWG) established by the UK Institute of Acoustics (IOA) to propose a method or methods for measuring and rating amplitude modulation (AM) in wind turbine noise. Amplitude modulation (in this context) is a regular fluctuation in the level of noise, the period of fluctuation being related to the rotational speed of the turbine. This characteristic of the sound might be described by a listener as a regular 'swish', 'whoomph' or 'thump', depending on the cause and the severity of the modulation.*

CONCLUSIONS FROM THE PAPER

3.5.3 [AMWG author's description] *As a result of this analysis, and taking input from the responses to the Discussion Document, the AMWG has now identified a method (the 'Reference Method') for adoption in reliably identifying the presence of amplitude modulated wind turbine noise within a sample of data, and of deriving a metric that, in the AMWG's view, best represents the degree of amplitude modulation present. The method is described in detail in Section 4. It is essentially a development of the 'Hybrid Reconstruction' method (i.e. Method 3) previously described in the Discussion Document* (IOA AMWG, 2015a). *It also draws on elements of the proposed Methods 1 and 2 and incorporates a newly developed 'prominence' criterion which has been found to be very effective at discriminating wind turbine AM from other sources, thereby reducing (but not eliminating) the need for detailed scrutiny of the data.*

3.5.4 [AMWG author's description] *Although* [the Reference Method] *is relatively complex, a degree of complexity is considered inevitable in a method that is sufficiently robust for determining compliance or non-compliance with specific thresholds or limits. A simple preliminary assessment method (the Indicative Method) is also described; this may be useful in some situations where wind turbine AM is subjectively apparent and when noise measurements with minimal contamination by other noise sources are available. However, the Indicative Method must be used with caution and is to be considered as secondary to the Reference Method and in no circumstances as a substitute for it.*

QUALITY, ROBUSTNESS, RELEVANCE

3.5.5 This report contains the details of the work undertaken by the IOA AMWG leading to their recommendation of a 'preferred' metric for AM. A definition for AM is provided, and the limitations of the metric to turbines of typically 500 kW and above are noted due to a focus on turbines with a rotational speed of less than 32rpm.

3.5.6 The report describes the various steps involved with the rating method, illustrating the process in flow charts. The various steps are explained in more detail in the text, with worked examples, and references to the work undertaken or additional research that underpinned the decision making process. The various decisions on analysis techniques are set out and justified. An additional 'prominence test' has been added to the method which further serves to identify clear WTN AM in a range of corrupted signals, addressing a previously identified weakness of other analysis methods.

3.5.7 The report also includes a summary of responses to points raised during the consultation stage in Appendix C, which covers the IOA AMWG's response to many of the points raised in the INWG's WP8 (see 3.3.179).

3.5.8 The methodology proposed by the IOA AMWG has been designed to provide a robust method for providing a precise and reliable determination of the presence of AM within wind turbine noise. As discussed below, the final metric is compatible with several of the Category 1 studies. However, as the AMWG authors note, the method will not necessarily be applicable to turbines of less than 500 kW, or with rotational speeds in excess of 32rpm. Further work would also be needed to develop a method for smaller turbines.

3.5.9 The Institute of Acoustics report is directly relevant to this study as it offers the definitive position of an industry body with a wealth of experience in acoustics and WTN. The IOA AMWG-proposed WTN AM metric is designed to work effectively for field data, addressing the difficulties encountered in analysing real WTN signals for AM content. Their report demonstrates that in overcoming the problems associated with earlier metrics, the proposed metric could provide a robust means for rating AM for assessment in a planning compliance situation. The report also demonstrates that the proposed metric can, over the range of interest, effectively be substituted for the metrics used in the laboratory studies reported by von Hünerbein et al (2013) (2015), and by Yokoyama et al (2013) (2015) with relatively small differences, indicating that values of the IOA AMWG metric can be related directly with the exposure-response research results discussed herein.

4 FACTORS AFFECTING DEVELOPMENT OF A PLANNING CONDITION

4.1 PLANNING POLICY GUIDANCE

4.1.1 Planning Policy for wind turbines in the United Kingdom is devolved to authorities in England, Wales, Scotland and Northern Ireland. Where developments may otherwise be refused, it is normal for planning conditions to be imposed which are designed to mitigate the adverse effects of the scheme. The objectives of planning are best served when the power to attach conditions to a planning permission is exercised in a way that is clearly seen to be fair, reasonable and practicable.

4.1.2 In England, paragraph 206 of the National Planning Policy Framework states "*Planning conditions should only be imposed where they are:*

1. *necessary;*
2. *relevant to planning and*
3. *to the development to be permitted;*
4. *enforceable;*
5. *precise; and*
6. *reasonable in all other respects."*

4.1.3 The policy requirement above is referred to in the NPPF as the 'six tests'. Similar guidance for the use of planning conditions is used by all Devolved Authorities. The key questions that arise against each test are listed in Table 5 (taken from the Communities website[50]).

Table 5: Validity Tests for Planning Conditions

TEST	KEY QUESTIONS
1. Necessary	• Will it be appropriate to refuse planning permission without the requirements imposed by the condition? → A condition must not be imposed unless there is a definite planning reason for it, i.e. it is needed to make the development acceptable in planning terms. → If a condition is wider in scope than is necessary to achieve the desired objective it will fail the test of necessity.

[50] http://planningguidance.communities.gov.uk/blog/guidance/use-of-planning-conditions/application-of-the-six-tests-in-nppf-policy/

Table 5: Validity Tests for Planning Conditions	
2. Relevant to planning	• Does the condition relate to planning objectives and is it within the scope of the permission to which it is to be attached? → A condition must not be used to control matters that are subject to specific control elsewhere in planning legislation (for example, advertisement control, listed building consents, or tree preservation). → Specific controls outside planning legislation may provide an alternative means of managing certain matters (for example, works on public highways often require highways' consent).
3. Relevant to the development to be permitted	• Does the condition fairly and reasonably relate to the development to be permitted? → It is not sufficient that a condition is related to planning objectives: it must also be justified by the nature or impact of the development permitted. → A condition cannot be imposed in order to remedy a pre-existing problem or issue not created by the proposed development.
4. Enforceable	• Would it be practicably possible to enforce the condition? → Unenforceable conditions include those for which it would, in practice, be impossible to detect a contravention or remedy any breach of the condition, or those concerned with matters over which the applicant has no control.
5. Precise	• Is the condition written in a way that makes it clear to the applicant and others what must be done to comply with it? → Poorly worded conditions are those that do not clearly state what is required and when must not be used.
6. Reasonable in all other respects	• Is the condition reasonable? → Conditions which place unjustifiable and disproportionate burdens on an applicant will fail the test of reasonableness. → Unreasonable conditions cannot be used to make development that is unacceptable in planning terms acceptable.

4.1.4 In considering a planning condition to control AM, it is noted that the project team does not contain legal expertise, but does have a wealth of experience of writing planning conditions. For this reason, an expert legal opinion should be sought to ensure that any AM condition derived from the output of the report stands up to scrutiny, as would happen in most planning situations as a matter of course.

4.1.5 In order to meet the 'six tests', the following aspects are considered by the project team to be important:

- → The presence and level of AM should be robustly identified, ideally objectively;
- → The threshold of unacceptability should be clearly stated (i.e. the point at which the control mechanism begins;
- → The enforcement of the control method should reflect other factors such as the frequency of occurrence, and time of day;
- → The control method should be clear and unambiguous; and

→ The intent of the condition should be to prevent unacceptable impacts, avoid significant impacts, and mitigate to minimise other adverse impacts from AM and WTN. It is likely that for most sites that this condition will be 'mitigating' by bringing about a reduction in the level of AM using engineering methods, such as blade modifications or operational controls. Where the level of AM cannot be reduced, then the control method or 'penalty' should bring about a reduction in the overall time-averaged level of WTN during breach conditions.

4.1.6 Further discussion on these tests is included in Section 4.5.

4.2 FURTHER PLANNING CONDITION CONSIDERATIONS SUGGESTED BY THE INWG

4.2.1 In WP5, the INWG has proposed that there are additional objectives that are desirable for any planning condition to control AM should meet. These are suggested as:

> "*a. The condition must work with real world data. As described above this can vary from single turbines to multiple turbines. It might include cases where a clean AM peak to trough is visible in data and cases where the trace is influenced by multiple peaks and is less clearly defined. It must be able to deal with influences from other noise sources.*
>
> *b. The condition must be comprehensible and practicable to implement. This is both in terms of accessing the location of compliance monitoring but also in the actual assessment of compliance. The condition should be aimed at those most likely to use it, local authority officers, and the tools and skills available to them. It should not require specialist expertise to interpret the data.*
>
> *c. The condition should relate to the impact it is being designed to prevent. Any control should take account of the psychoacoustic response associated with the impact and reported complaints in existing cases.*
>
> *d. The condition should be transparent. The methodology of the condition should be clear and detail any data manipulation or filtering steps. The ability to test data for compliance should be open access including any software required to analyse the data.*
>
> *e. Others have proposed the preference for the condition to be workable with large amounts of data and therefore be largely automated.*
>
> *f. Most importantly it must be shown that the condition is effective, the control(s) must prevent periods of adverse AM.*"

4.2.2 Some of these suggestions are arguably already inherent in the 'six tests'. Any other proposals are not contained in Government planning policy, and therefore fall outside the scope of this study.

4.3 EXISTING PLANNING CONDITIONS

4.3.1 The existence of AM within WTN was acknowledged in ETSU-R-97 (1996), but the types of turbines then in existence were substantially smaller than those found on the larger wind farm sites now. The emergence of AM as being a potential problem grew during the 2000s, and a planning condition to control AM was first discussed and imposed by the Inspector for the Den Brook scheme in 2009. Additional research has since been carried out to further the knowledge of AM, and this has resulted in evolutions of the (original) 'Den Brook condition', and a planning condition proposed by RUK based on their own funded research.

4.3.2 Discussion of these planning conditions and the potential limitations of these conditions are included in the IOA AMWG consultation documents (IOA AMWG, 2015b), and the INWG WP5

(Large, Stigwood, & Bingham, 2015). Whilst there is broad agreement between the various documents on the limitations of the existing conditions, there are differences of opinion on the methods needed to rectify them.

4.4 OTHER POTENTIAL PLANNING CONDITION METHODS

4.4.1 The INWG WP5 review proposes additional methods using the Japanese D_{AM} method, BS4142:1997 (BSI, 1997) and BS4142:2014 (BSI, 2014). They conclude that the D_{AM} method works for sites where levels are not heavily influenced by extraneous noise and that a methodology following the requirements of BS4142:2014 also worked well.

4.4.2 It should be noted that the BS4142:2014 method contains a number of objective and subjective elements, which work well at the planning adjudication stage when the relative merits of each element can be debated and agreed, but introduce additional uncertainty when it comes to enforcement. The 'new' penalty method within BS4142 has not yet been tested in the field, and it is unclear at the present time whether the more subjective tests would work as intended; an element that could be acceptable to one enforcement officer may be unacceptable to another, leaving the operator uncertain as to the level of penalty they will be exposed to. A more objective approach would be more likely to comply with the one of the 'six tests' that advocates precision.

4.5 DISCUSSION

4.5.1 In order to recommend a planning control for AM, the various component parts have been broken down as suggested in paragraph 4.1.5. It should be noted that the information provided upon which to base the writing of a planning condition has been designed only for new planning applications. The applicability for use in Statutory Nuisance investigations on existing wind turbine sites has not been considered as part of this review, since methodologies and acceptability criteria are different to those used for planning enforcement. It is possible that the method may be used as an objective test as part of a nuisance investigation, subject to further testing and evaluation.

IDENTIFICATION AND RATING OF AM

4.5.2 Of the various methods discussed previously, the internal research team considers that the IOA AMWG proposals for the AM metric provide the most robust method available for the identification of AM. The metric is compatible with the available Category 1 papers reviewed, and with the available evidence on exposure-response, subject to the limitations previously noted. The methodology is objective, precise, and has overcome many of the criticisms of previously used metrics for AM in the field. It is acknowledged that the IOA AMWG method does not include some subjective elements which may be relevant to the human perception of AM, (such as impulsivity, distinctiveness, etc.) but the use of these is not clearly supported in the available research, and therefore cannot be recommended at this time.

THRESHOLD OF EXCESSIVE AM

4.5.3 The setting of a threshold for excessive AM is not straightforward. The available research does not identify a clear onset of increased annoyance from AM. The research also does not identify a clear level at which the impact of WTN or AM becomes 'significant', 'excessive' or 'unacceptable'. It *does* suggest an onset of *perception* for AM at about 2 dB (peak-to-trough level difference in the Fast-weighted sound pressure level), and an association of rising annoyance with increasing depth of AM above 2 dB, when relating to L_{Aeq}. Moreover, the research highlights a very strong relationship between annoyance and the overall time-averaged level of noise, with the presence of AM in the noise increasing the annoyance.

4.5.4 As the setting of the threshold of excessive AM is related to current Government policy, it is helpful to review the available policy evidence. ETSU-R-97 is recognised as Government guidance by all of the Devolved Authorities, and notes that the *"modulation of blade noise may result in a variation of the overall A-weighted noise level by as much as 3 dB(A) (peak to trough)… if there are more than two hard, reflective surfaces then the increase in modulation depth may be as much as +/- 6 dB(A) (peak to trough)*". This statement relates to the available turbines at the time, and it is often alleged that it does not necessarily translate to the taller turbines in use now. However, the IOA AMWG report notes that *"On the basis of the comments in ETSU-R-97, the value of 3 dB ('level of AM' or 'modulation depth') is sometimes referred to as the 'expected level' of AM. The Den Brook AM condition*[51] *adopts a 3 dB peak-to-trough value as the threshold above which AM is deemed to be 'greater than expected'"* (IOA AMWG, 2016). The 3 dB value is not supported in any of the available research as being the onset of unacceptable AM, but that does not mean that it is not an appropriate policy stance if there is sufficient policy support towards on-shore wind turbines.

4.5.5 More research is needed to test whether 3 dB peak-to-trough is still 'normal' today (i.e. typical with current turbine models), as, by necessity, the threshold could not penalise the level of AM that was considered to be 'normal' unless this was shown to give rise to complaints; this is not yet proven in the available research. Indeed, commentary from the INWG WP5 concludes that "*If the Den Brook condition (a peak to trough method) were to be treated as a simple metric or trigger value a higher peak to trough value in the region of 6dB would need to be used"* (Large, Stigwood, & Bingham, 2015).

4.5.6 A recently published report[52] on a long term field study of AM from wind farm noise in Massachusetts from both flat and mountainous sites concluded that *"while amplitude modulation is correlated with various meteorological parameters, prediction of the level of amplitude modulation at typical residential distances would not be reliable or practical. At these distance, local and regional background sounds have a significant impact on modulation depth. The analysis shows that larger modulation events (over 4.5 dB) can and do occur at the flat sites, but these events were observed less than 0.13% of the time. They were less common at the mountainous site (0.004%), likely because the multiple turbines at this site turn asynchronously, which tends to blur out modulation events."* This would lend some weight towards confirming that the ETSU-R-97 considerations relating to AM remain valid at least for the 78-80m hub height turbines that were included in the study.

4.5.7 The above statements highlight the variability in AM, and have formed the basis for the subsequent planning conditions drafted to date. ETSU-R-97 states that the absolute noise limits were chosen reflecting the AM character expected, with the addition of a penalty for tonality. It is clear from this statement that the character included the degree of AM experienced from the turbines existing at the time of writing, and therefore it could be considered that, if that AM character has materially changed, then the setting of the absolute limits should be reviewed. ETSU-R-97 also acknowledged that the noise limits were chosen to provide "*a reasonable degree of protection*", or to put it another way, the potential for some loss of local amenity in favour of wider national economic and sustainability benefits of renewable energy. This statement reflects the policy stance adopted by the UK Government at the time ETSU-R-97 was written, and may need to be reviewed against the various planning policies of the respective Governments today. For example, in England the aims of the NPPF are to avoid noise giving rise to significant adverse impacts, mitigate and reduce other adverse impacts, and identify and protect areas of tranquillity. It is unclear if the noise limits in ETSU-R-97 would still accord with these current aims without the policy support for on-shore wind.

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[51] see http://www.masenv.co.uk/Den_Brook_AM_Condition
[52] *Massachusetts study on wind turbine acoustics* (RSG et al., 2016)

4.5.8 It is also recommended that, as the AM control will target an element considered as 'above normal' in the ETSU-R-97 guidance, the control should be over and above the existing provisions for adverse sound characteristics, i.e. the control for AM should be considered in addition to the existing provision for tonality. This recommendation is not unprecedented: tonality and other adverse acoustic characteristics (impulsivity, intermittency etc.) are also considered separately within BS 4142:2014 (BSI, 2014), which is supported by the research cited in the standard. It follows that the two decibel WTN character penalties (tonality and modulation) should be additive in this case.

4.5.9 Successive UK Governments to date have stated their support for onshore wind, and confirmed the reliance on the ETSU-R-97 guidance, although the UK Government has set out proposals to end financial subsidies for new onshore wind projects across Great Britain and has introduced additional planning considerations for projects in England through a Parliamentary statement[53] . It could be argued that there is policy support for the choice of a 'normal AM' unacceptability limit (or a higher cut-in for the 'penalty'), whatever normal may be considered to be. This is based on the current policy statements, and may be subject to a wider review by the relevant Government Departments in the future.

4.5.10 To summarise the potential range of excessive AM thresholds, and initially generalising for the sake of simplicity, i.e. not taking into account whether the threshold relates to a single instantaneous event or the average of a series of events:

- the onset of perception for AM is around 2 dB 'peak-to-trough value';
- 'Normal AM' is considered to be in the range 2 to 6 dB 'peak-to-trough value'; and
- 'Excessive AM' may be above 6 dB 'peak-to-trough value'

4.5.11 In the Phase 1 report, it was suggested that it may be possible to define the AM penalty range in terms of the effect levels defined in the Noise Policy Statement for England (DEFRA, 2010) for the:

- No Observed Effect Level (NOEL);
- Lowest Observed Adverse Effect Level (LOAEL); and
- Significant Observed Adverse Effect level (SOAEL).

4.5.12 Planning Practice Guidance issued in 2014[54] added a further effect level for impacts increased beyond the SOAEL range:

- Unacceptable Adverse Effect level (UAEL).

4.5.13 Based on the research, the NOEL would likely be set at 2 dB, since up to 2 dB there is no apparent perception for most people. It would not be possible to set a LOAEL, SOAEL or UAEL without taking other factors into account such as the absolute noise level, which is outwith the scope of this report, and contextual factors considered below.

4.5.14 As noted, the choice of a threshold level only addresses a component of the expected response or effect, with how often and when the threshold is breached being important as well. Wind turbine operations can vary considerably over the course of even a 10 minute period, where wind

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[53] http://www.parliament.uk/documents/commons-vote-office/June%202015/18%20June/1-DCLG-Planning.pdf
[54] http://planningguidance.communities.gov.uk/blog/guidance/noise/noise-guidance/

speed and directions can change. Similarly, noticeable AM can occur as infrequent short bursts, or continuously in long periods of several hours. Whilst the number of incidences of 'unacceptable AM' are disputed, there now seems to be a broad consensus emerging in the most recent research (e.g. INWG WP5) that a single 10 second breach occurring over a period of two weeks would not be sufficient cause for planning enforcement, whereas a two hour continuous period occurring for several nights in a row clearly would. This suggests that an AM 'accumulative dose' might be the way forward, similar to the daily dose used for vibration in British Standard BS 6472:2008 (BSI, 2008), in which exposure levels and durations aggregate into a single number for easy analysis. There is currently no research to support the development of a suitable AM accumulative dose parameter, although one may be desirable if, through experience or further research, a suitable parameter and dose can be defined.

4.5.15 Analysis of the RUK conditions reveals that (presumably in order to account for frequency of occurrence), the amount of AM is rated for a 10 minute period (consistent with the ETSU-R-97 time periods for noise level), and a best fit line is drawn for each of the 10 minute periods at each integer wind speed. The penalty is then derived from the best fit curve. No separate account is made for time of day. This method is consistent with that used for the derivation of noise limits within ETSU-R-97 (albeit without the separation of day and night periods), and makes some attempt to account for duration of exposure. However, by averaging what is already an average number of AM peaks, there is the potential to under-rate the level and duration of AM. This in turn could potentially lead to a lower level of protection in some situations. Whilst this could be overcome with setting a lower threshold of unacceptability, this may not be reasonable given that the solution may also affect non-AM periods and / or may not be supported by the available research.

4.5.16 As previously noted, analyses of the evidence indicates that:

- The 'penalty' scheme should be linked to the absolute level of the noise; and
- It may be appropriate to set a sliding scale of 'penalty' since overall average levels are controlled at present using the L_{A90}.

4.5.17 In view of the limited specific, robust research into the effect of duration and frequency of occurrence of AM exposure on the response, gauging acceptability at the current state of knowledge is largely reduced to professional judgement; these judgements can be made at the enforcement stage.

4.5.18 Acousticians and planning decision makers are used to making occurrence frequency and duration judgements for noise sources as a matter of routine, the general rule being that the more often it occurs, and the more sensitive the time period, the more likely it is to need controlling. It is widely reported that complaints related to AM occur in the early to late evening, night, and early morning periods of the day (these are the periods of highest wind shear, and the periods when properties are most likely to be occupied), which covers a wider period than just the night time – a factor that needs to be recognised when setting the penalty level as different noise limits can apply during these times. That is not to say that AM does not need to be controlled at other times if it does occur.

4.5.19 To summarise the difficulty in identifying how often the AM threshold needs to be breached to trigger a penalty, it is concluded that there is currently no identified targeted research on which to base this decision. It is therefore recommended that the judgements on when enforcement action[55] is taken will be reliant on professional judgement based on elements such as the time of day, the number and frequency of occurrence of the 10 minute breaches. Clearly, the expectation would be that the more breaches that occur over a given time period, the more adverse the response effect, and the more unacceptable the potential impact. However, in line with other policy guidance, such as the NPPF in England, the context of potential environmental effects also needs to be considered when defining the parameters of a condition; sensitivities of receptors vary, as do the environments in which they are located. It could be that the respective Government Departments consider it necessary to be prescriptive over the interpretation of compliance, but as stated before, a 'one size fits all' solution may not work as intended.

4.5.20 The prevalence of unacceptable AM has not been evaluated as part of this study, and current state of the art is that the likely occurrence cannot be predicted at the planning stage. That does not preclude future research to determine the likelihood of AM occurring coming forward, and the development of a risk based evaluation, or similar. Due to the lack of ability to predict AM occurring on a site, and the reported difficulties in applying Statutory Nuisance provisions to control AM on existing sites, it is likely that the default position for a decision maker would be to apply the condition on all sites unless evidence is presented to the contrary.

CONTROL SCHEME FOR AM

4.5.21 As noted in paragraph 4.1.5, the main purpose of the control or 'penalty' is to bring about a reduction in the impact as a result of the period of unacceptable AM, and as currently proposed this consists of a two-tiered approach. The first tier would be seeking a reduction in the depth and/or occurrence of AM of ≥3 dB depth (rated using the IOA metric) by way of engineering methods, i.e. reduce the AM to an acceptable degree of impact. Where the degree of AM cannot be reduced, then, in order to prevent, avoid or mitigate the impact, the penalty should bring about a reduction in the overall average level of WTN during periods of complaint / breach conditions[56]. Therefore a decibel penalty added to the overall average noise level during periods of unacceptable AM should lead to a breach of the planning condition for the overall average level of wind turbine noise, and subsequent action to reduce the noise level to bring the site back into compliance.

4.5.22 Therefore in its simplest form, the condition would be worded to the effect that, where an AM exceedance in level and duration occurs, steps must be taken to reduce the AM, or to reduce the overall noise level. The work by Cand et al. (2015b) shows two potential methods for reducing AM, one involving a modification to the turbine blades, and one through reprogramming of the turbine to reduce periods of blade stall. Although these methods are relatively new, both were demonstrably successful at reducing AM, but it is not necessarily expected that either of these methods will be available to every model of turbine. In this situation, the Category 1 papers by von Hünerbein et al. (2015) and Lee et al. (2011) clearly show that to reduce annoyance at the same level of AM, a suitable reduction in absolute noise level would be effective.

4.5.23 Planning conditions based on the RUK proposal suggest a penalty starting at 3 dB of AM (albeit rated using a slightly different parameter to the IOA metric now proposed) and a sliding penalty scale from 3 to 5 dB, which is similar to the tonal penalty in ETSU-R-97 as shown in Figure 11.

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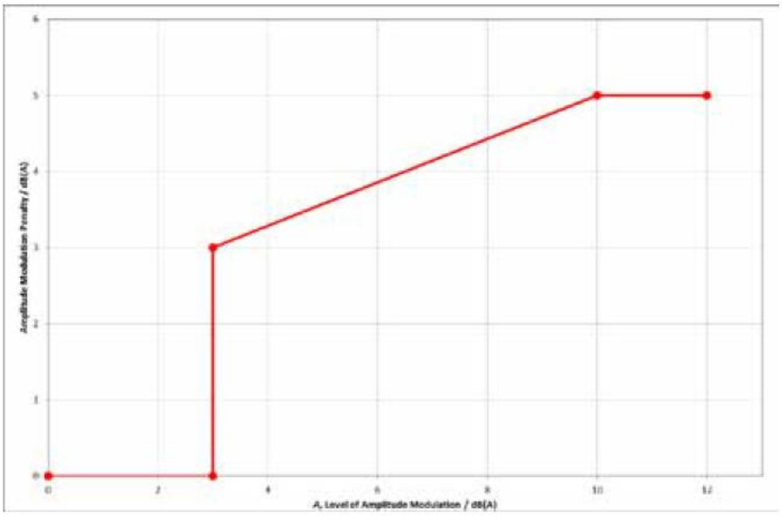
[55] It is noted that the NPPF (for England) states that enforcement action is discretionary, and local planning authorities should act proportionately in responding to suspected breaches of planning control. It therefore follows that not every breach of the AM condition would lead to enforcement and / or require the operator to take action. This may not be the case in other areas.

[56] Whilst the inherent problem of a 'reactive' approach to control AM is acknowledged, it would be unreasonable to penalise operators when periods of AM are not cause for complaint, thus the condition is targeted only to periods that give rise to valid / justified complaints. It is possible that high levels of AM may occur at other times of the day which, for a number of reasons, do not lead to complaints.



The interpretation of this penalty scheme is as follows:

- *for AM with a peak to trough level of < 3 dB there is no AM penalty*
- *for AM with a peak to trough level of 3 – 10 dB there is a sliding scale of penalties ranging from 3 – 5 dB*
- *for AM with a peak to trough level of ≥ 10 dB there is 5 dB penalty.*

Figure 11: RenewableUK Proposed Penalty Scheme[57]

4.5.24 The internal research team have compared the RUK penalty scheme to the outcomes of the research review, and concluded the following:

- The onset for the penalty at 3 dB of AM (derived from the IOA metric) appears to be consistent with starting the penalty scheme above the level of AM currently considered to be ‘normal’, and representative of the approximate onset of fluctuation perception for the majority of people;
- The magnitude of the decibel penalty starting at 3 dB is considered appropriate, for two main reasons:
  i. A 3 dB difference represents a reduction that would be expected to be clearly noticeable by people in the real situations that the penalty is intended to address;
  ii. Although the laboratory studies examining the equivalence of an AM signal with a steady-amplitude noise suggest a smaller ‘lower bound’ penalty of around 1.5-1.7 dB, the evidence is based on tests conducted using a modulation frequency of less than 1 Hz; to support the use of the penalty up to the slightly higher rotational speeds considered (equivalent to a blade-pass frequency of around 1.6 Hz), a 3 dB penalty would be more appropriate[60].
- The research evidence behind a sliding penalty above the 3 dB onset (e.g., in contrast with a stepped increase) is not definitive, but the general principle that increasing depths of AM should be avoided is considered reasonable[58]; and

[57] *The Development of a Penalty Scheme for Amplitude Modulated Wind Farm Noise Description and Justification*, (RenewableUK, 2013).

- The upper penalty magnitude of 5 dB initially appears to be higher than the evidence suggests would represent perceptual equivalence with a steady noise; typically, the laboratory adjustments to make a modulating noise subjectively equivalent with a steady noise are no more than around 3.5 dB[59]. However, these results are typically based on a modulation frequency of slightly below 1 Hz. In view of the intention to control AM impacts in the range up to (approximately) 1.6 Hz, an upper penalty limit of 5 dB is considered appropriate[60].

4.5.25 The above considerations are based on the available evidence, and the limitations identified.

4.5.26 ETSU-R-97 accommodates different noise lower bound limits for day and night time[61], the latter being less stringent. Application of the above penalty method without further consideration of this difference could in some cases result in a situation in which an AM-penalised WTN level does not breach the associated limit (implying no requirement for enforcement action), despite on-site evidence to the contrary. The conclusions drawn from the category 2 studies indicate that the greatest period of residential AM sensitivity is typically sunset to sunrise, with more focus around the onset of sleeping hours. Therefore it is recommended that to account for the higher ETSU-R-97 lower bound limits at night, an additional allowance be added to the penalty at night equivalent to the difference between the night and day limits for each integer wind speed bin. NB. This addition would not apply to situations in which specific planning conditions dictate the limits to be set as lower for night-time than for daytime.

4.5.27 Therefore the resulting action imposed on the operator during periods of AM complaint would be to either:

a) reduce the degree of AM to below the 3 dB rating threshold during the complaint periods identified; or

b) reduce the penalised overall time-average level below the limit. The sliding scale decibel AM penalty would be added to the overall noise level (day or night), plus the addition of X dB at night (where X is the difference between the night and day limits for each integer wind speed bin, applicable if, and only if, the numerical limit for night-time is set higher than that for daytime), again during the periods in which AM impacts had been identified.

4.5.28 It is acknowledged that enforcement of the planning condition relating to the overall time-average level of noise requires consideration of the background noise level, and methods are currently in place to account for background based either on averaging in situations where the turbine noise level is close to or below the prevailing background noise level, or by periodic shut-down of the turbines. This ‘averaging’ may not be a suitable approach for the determination of a specific 10 minute period of an AM breach, and an alternative method may be required to be devised or agreed as part of the enforcement process, along with the less desirable option (for operators) of a periodic shut-down.

4.5.29 With current technologies, mitigation in most cases will likely be achieved through pitch control of the turbine blades, or in the worst case the switching off of one or more turbines during periods of

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58 This is also supported by the subsequent research summarised in Annex 1.
59 This is also supported by the subsequent research summarised in Annex 2.
60 Human sensitivity to modulation in a noise signal has been shown [e.g. by Fastl & Zwicker (2007)] to rise with increasing modulation frequency to a peak within the range of around 2-6 Hz (4 Hz is the peak value most often-quoted).
61 Daytime is defined in ETSU-R-97 as 07.00 to 23.00, and has lower bound limits of 35-40 dB L_{A90}. Night time is defined as 23.00 to 07.00 and has a lower bound limit of 43 dB L_{A90}

unacceptable AM. Note that a more proactive mitigation solution is desirable as opposed to a reactive one, but it may not be possible to separate out periods of AM leading to complaint from the available meteorological data, resulting in mitigation being applied at times not leading to AM complaints. Further research by turbine manufacturers and wind farm operators may assist with making more effective proactive solutions in the future, which could help to reduce curtailments to energy yield, as well as minimising the noise impacts.

4.5.30 This method is by necessity an interim recommendation based on the available evidence to date, and supplemented with professional experience. It is suggested that any planning condition derived from this report would be subject to a period of testing and review. The period should cover a number of sites where the condition has been implemented, and would be typically in the order of 2-5 years from planning approval being granted. The review would involve the analysis of any new AM research at the time, and case studies from sites where a condition has been implemented.

SUMMARY OF PLANNING CONDITION CONSIDERATIONS

4.5.31 To summarise, the planning condition to control AM should apply during periods of complaints, and first seek to reduce the AM in the WTN, since this is a trigger for increasing annoyance. Where this is not possible, it is recommended that the 'penalty' should bring about a reduction in the overall noise level during complaint / breach periods, since this also controls the annoyance response. An outline suggestion for a possible condition is as follows (noting that the example given is intended for information only; the setting of specific planning conditions is a matter for Local Planning Authorities (LPAs) to determine, and producing a recommendation for a specific condition wording to be applied by LPAs is not within the scope of this research report. Legal advice would need to be sought to ensure any proposed condition meets the NPPF 'six tests' requirements):

> During periods of complaint, the IOA metric should be applied to the data collected[62] to derive the reconstructed AM values for consecutive 10-minute periods. For each period with an AM value of equal to or greater than 3 dB, a penalty should be assigned in accordance with Figure 11, and added to the absolute level of noise. Each summed value of Overall average level (corrected for background where necessary) + AM penalty + Tonal Penalty (if applicable) should be binned into wind speeds of 1 m/s intervals over the range of the data for when the turbine is operating and complaints occurring. Where the number of 10-minute breaches at any given wind speed during the period of complaint is considered to be unacceptable, the operator should be required to submit details of a scheme describing proposals for suitable mitigation of the unacceptable AM periods to reduce the number of breaches during the operational conditions giving rise to the complaint, to that considered acceptable by the relevant authority.

4.6 OPERATIONAL IMPACTS AND MITIGATION

4.6.1 It is to be expected that any reduction in operational capacity of a wind turbine will have an impact on the power generation of the development, and consequent reduction in the operating revenue. It is not known at this stage whether an AM control can be brought in by Government as a

[62] Data should be collected in accordance with the IOA Supplementary Guidance Note 5 at http://www.ioa.org.uk/sites/default/files/IOA%20GPG%20SGN%20No%205%20Final%20July%202014.pdf (Checked 29.03.16)

practical enhancement to the existing planning guidance, or whether it would be necessary to consider it as a formal change of policy.

4.6.2 In either event, it is helpful to ascertain the likely burden to industry of the proposed changes through consideration of the engineering/cost trade-offs of possible mitigation measures. The last work package in the RUK study is an investigation on the likely cause of AM, and the suggested methods of mitigation. These include pitch control on the blades, reprogramming the power curve of the turbine to avoid stall conditions, and, ultimately, curtailment of the turbine completely in the wind conditions where it occurs. The results will vary from one site to the next due to different turbine models, and different wind regimes.

4.6.3 A potential cause of unacceptable AM is the occurrence of blades stalling only during part of the rotation. This mechanism is described in (Cand & Bullmore, Understanding amplitude modulation of noise from wind turbines: causes and mitigation, 2015a) along with results of mitigation measures involving both modifications of the blades and the operational characteristics of wind turbines.

4.6.4 Although the modification of blades is mentioned as a potential mitigation measure, costs and details related to these modifications are not currently available. Therefore only the curtailment strategies involving changes to the operational characteristics of wind turbines can be estimated. Also it should be borne in mind that turbines cannot be programmed (at the current state of the art) to respond to individual 10-minute breaches, and therefore a proactive mitigation strategy may currently also have to target non breach periods without complaints in order to address the meteorological periods during which complaints occur.

4.6.5 Wind speed will impact on the yield and therefore the cost of any curtailment strategy. More accurate estimates could be made where the site in question is known. The impact of the curtailment strategy itself is also very site-specific. It is therefore concluded that insufficient data exists on which to accurately predict the likely impact of restrictions imposed on a wind turbine as a result of having to comply with an AM penalty. The expectation is that this could range between 0 and 5% in terms of yield reduction, but at sites more prone to AM the value could be greater.

5 CONCLUSIONS

5.1 AM

5.1.1 WSP | Parsons Brinckerhoff has undertaken a review of research into the effects of and response to the acoustic character of wind turbine noise (WTN) known as Amplitude Modulation (AM). The objective was to review the current evidence on the human response to AM, evaluate the factors that contribute to human response, and to recommend how excessive AM might be controlled through the use of a planning condition.

5.1.2 The work has involved the collation and critical review of relevant papers, existing planning conditions, and existing planning policies where they relate to AM from wind turbines. The review established a clear need for AM control, a clear link between overall turbine noise level and annoyance, and a correlation between the degree of AM and an equivalent level without AM. It also established that the sensitive period for wind farm neighbours to AM coincides with operational conditions (between sunset and sunrise) where the prevalence of AM occurs. These findings raise the question about whether the noise limits in ETSU-R-97, which are generally higher at night, accord with current Government policies to avoid, significant adverse noise impacts, and mitigate or minimise adverse impacts.

5.1.3 Based on the evidence found, a recommendation has been made on the elements required to construct a planning condition to control AM. It is noted that the AM control has only been designed for use with new planning applications, and applicability for use in Statutory Nuisance investigations on existing wind turbine sites, where the regime is different and outside the project scope, has not been considered as part of this review.

5.1.4 Any condition developed using the elements proposed in this study should be subject to a period of testing and review. The period should cover a number of sites where the condition has been implemented, and would be typically in the order of 2-5 years from planning approval being granted.

5.2 PROPOSAL FOR PENALTY SCHEME

5.2.1 The review found that the penalty scheme should include the following elements:

- ✓ The AM condition should cover periods of complaints (due to unacceptable AM);
- ✓ The IOA metric should be used to quantify AM;
- ✓ Analysis should be made using individual 10 minute periods, applying the appropriate decibel ‘penalty’ to each period (according to the regime illustrated in Figure 12), with subsequent wind speed analysis;
- ✓ The AM decibel penalty should be additional to any decibel penalty for tonality;
- ✓ An additional decibel penalty is proposed during the night time period to account for the current difference between the night and day limits on many sites to ensure the control method works during the most sensitive period of the day;
- ✓ Professional judgement should be used for planning enforcement of the AM condition in terms of frequency and duration of breaches identified; and

✓ The scheme is designed for upwind, 3-bladed turbines with rotational speeds up to 32 RPM[63]. Further research would be needed to address turbines with blade-pass frequencies higher than 1.6 Hz.

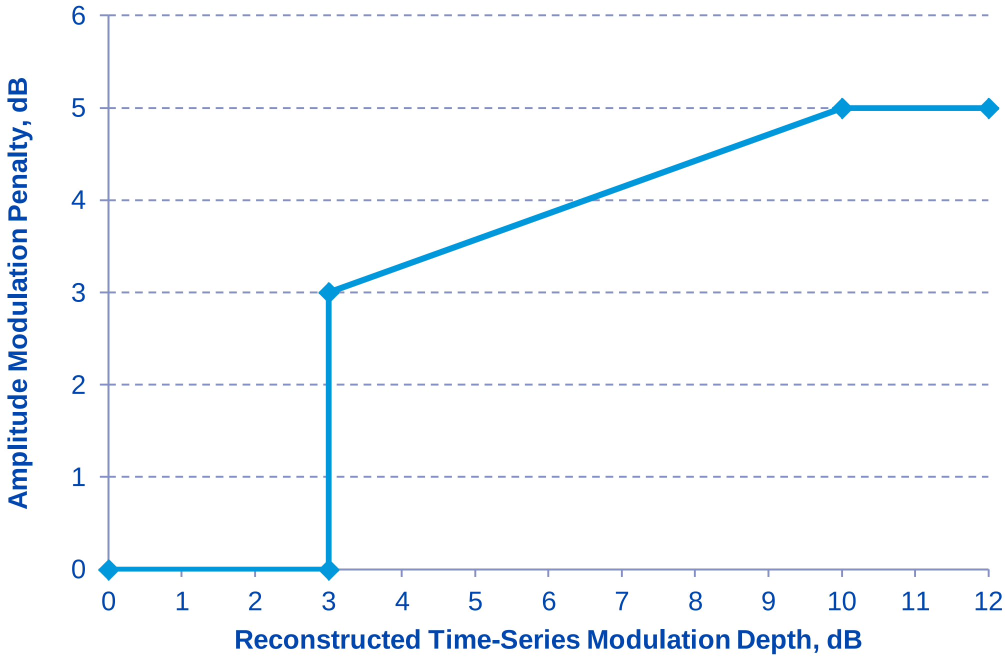


Figure 12: Proposed Level Penalty Regime

5.2.2 Further research has been recommended to supplement the limitations of the available research which underpins the above recommendation, although if the proposed penalty system, when implemented in a suitable planning condition, achieves the aim of reducing the impact from AM, then this research may not be required.

[63] Specifically, the IOA metric is limited to a working upper modulation frequency of around 1.6 Hz, and the exposure-response research underpinning the proposed penalty system addresses modulation frequencies up to approximately 1.5 Hz. This does not preclude faster rotating turbines with lower numbers of blades, provided the blade-pass frequency is no higher than 1.6 Hz.

6 REFERENCES

AECOM. (2015). Survey of Noise Attitudes (SoNA) 2013. Prepared for: DEFRA. Report Ref: 47067932.NN1501.R1/02. DEFRA.

Bengtsson, J., Persson Waye, K., & Kjellberg, A. (2004). Sound characteristics in low frequency noise and their relevance for the perception of pleasantness. Acta Acustica united with Acustica, 171-180.

Bockstael, A., Dekoninck, L., Can, A., Oldoni, D., de Coensel, B., & Botteldooren, D. (2012). Reduction of wind turbine noise annoyance: an operational approach. Acta Acustica united with Acustica, 392-401.

Bockstael, A., Dekoninck, L., de Coensel, B., Oldoni, D., Can, A., & Botteldooren, D. (2011). Wind turbine noise: annoyance and alternative exposure indicators. Forum Acusticum (pp. 345-350). Aalborg, Denmark: EAA.

Bradley, J. S. (1994). Annoyance caused by constant-amplitude and amplitude-modulated sounds containing rumble. Noise Control Engineering Journal, 203-208.

BSI. (1997). BS 4142:1997 Method for rating industrial noise affecting mixed residential and industrial areas. London: British Standards Institution.

BSI. (2008). BS 6472-1:2008 Guide to evaluation of human exposure to vibration in buildings. Part 1. Vibration sources other than blasting. London: British Standards Institution.

BSI. (2014). BS 4142:2014 Methods for rating and assessing industrial and commercial sound. London: British Standards Institution.

Bullmore, A., & Cand, M. (2013). Wind turbine amplitude modulation: research to improve understanding as to its cause & effect. Work package C: Collation and analysis of existing acoustic recordings. RenewableUK.

Bullmore, A., Jiggins, M., Cand, M., Smith, M., von Hünerbein, S., & Davis, R. (2011). Wind turbine amplitude modulation: research to improve understanding as to its cause & effect. 4th International Meeting on Wind Turbine Noise. Rome, Italy: INCE Europe.

Cand, M., & Bullmore, A. (2015a). Understanding amplitude modulation of noise from wind turbines: causes and mitigation. Acoustics in Practice, 45-52.

Cand, M., & Bullmore, A. (2015b). Measurements demonstrating mitigation of far-field AM from wind turbines. 6th International Meeting on Wind Turbine Noise. Glasgow, UK: INCE Europe.

Council of Canadian Academies. (2015). Understanding the evidence: wind turbine noise. Ottawa: The Expert Panel on Wind Turbine Noise and Human Health, Council of Canadian Academies.

Cowen, R. (2015). Wind turbine amplitude modulation & planning control study – Work Package 6.1: Legal issues: the control of excessive amplitude modulation from wind turbines . Retrieved 2015, from www.heatonharris.com.

Cox, R. (2015). Wind turbine amplitude modulation & planning control study - Work Package 2.1: Review of reference literature. Retrieved 2015, from www.heatonharris.com.

Cox, R. (2015). Wind turbine amplitude modulation & planning control study – Work Package 8: Review of Institute of Acoustics amplitude modulation study and methodology. Retrieved 2015, from www.heatonharris.com.

DCLG. (2012). National planning policy framework. London: Department for Communities and Local Government.

DEFRA. (2010). Noise policy statement for England. London: Department for Environment, Food and Rural Affairs.

Di Napoli, C. (2009). Case study: wind turbine noise in a small and quiet community in Finland. 3rd International Meeting on Wind Turbine Noise. Aalborg, Denmark: INCE Europe.

Di Napoli, C. (2011). Wind turbine noise assessment in a small and quiet community in Finland. Noise Control Engineering Journal, 30-37.

Dittrich, K., & Oberfeld, D. (2009). A comparison of the temporal weighting of annoyance and loudness. Journal of the Acoustical Society of America, 3168-3178.

Energy Technology Support Unit Working Group on Noise from Wind Turbines. (1996). ETSU-R-97 The assessment and rating of noise from wind farms. DTI.

Fastl, H., & Menzel, D. (2013). Psychoacoustic aspects of noise from wind turbines . Inter-noise. Innsbruck, Austria: I-INCE.

Fastl, H., & Zwicker, E. (2007). Psychoacoustics: facts and models. Berlin: Springer-Verlag.

Gabriel, J., Vogl, S., Neumann, T., Hübner, G., & Pohl, J. (2013). Amplitude modulation and complaints about wind turbine noise. 5th International Conference on Wind Turbine Noise. Denver, USA: I-INCE.

Gray, B. (2015). Wind turbine amplitude modulation & planning control study – Work Package 6.2: Control of AM noise without an AM planning condition using statutory nuisance. Retrieved 2015, from www.heatonharris.com.

Gray, B., & Tossell, J. (2015). Wind turbine amplitude modulation & planning control study – Work Package 9: The Cotton Farm monitor experience. Retrieved 2015, from www.heatonharris.com.

Hanning, C. D. (2015). Wind turbine amplitude modulation & planning control study – Work Package 3.2: Excessive amplitude modulation, wind turbine noise, sleep and health. Retrieved 2015, from www.heatonharris.com.

Hansen, K. L., Zajamšek, B., & Hansen, C. H. (2015). Quantifying the character of wind farm noise. 22nd International Congress on Sound and Vibration. Florence, Italy: IIAV.

Health Canada. (2014a). Environmental and workplace health. Wind turbine noise and health study: summary of results. Retrieved 2015, from www.hc-sc.gc.ca: http://www.hc-sc.gc.ca/ewh-semt/noise-bruit/turbine-eoliennes/summary-resume-eng.php

Health Canada. (2014b). Environmental and workplace health. Health impacts and exposure to sound from wind turbines: updated research design and sound exposure assessment. Retrieved 2015, from www.hc-sc.gc.ca: http://www.hc-sc.gc.ca/ewh-semt/consult/_2013/wind_turbine-eoliennes/research_recherche-eng.php

Hulme, M. W. (2015). Wind turbine amplitude modulation & planning control study – Work Package 4: Den Brook. Retrieved 2015, from www.heatonharris.com.

Independent Noise Working Group. (2015). Wind turbine amplitude modulation & planning control study - Terms of reference. Retrieved 2015, from www.heatonharris.com.

IOA. (2013). A good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise. St Albans: Institute of Acoustics.

IOA AMWG. (2015a). IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group Discussion Document: Methods for rating amplitude modulation in wind turbine noise. St Albans: Institute of Acoustics.

IOA AMWG. (2015b). IOA Consultation Questionnaire for "Methods for rating amplitude modulation in wind turbine noise". St Albans: Institute of Acoustics.

IOA AMWG. (2016). IOA Noise Working Group (Wind Turbine Noise) Amplitude Modulation Working Group Final Report: A method for rating amplitude modulation in wind turbine noise. St Albans: Institute of Acoustics.

ISO. (2003). ISO/TS 15666:2003 Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys. Geneva: International Standards Organization.

Kaczmarek, T., & Preis, A. (2010). Annoyance of time-varying road traffic noise. Archives of Acoustics, 383-393.

Kageyama, T., Yano, T., Kuwano, S., Sueoka, S., & Tachibana, H. (2014). ◊ Exposure-response relationship of wind turbine noise with subjective symptoms on sleep and health: a nationwide socio-acoustic survey in Japan. 11th International Congress on Noise as a Public Health Problem. Nara, Japan: ICBEN.

Kantarelis, C., & Walker, J. G. (1988). The identification and subjective effect of amplitude modulation in diesel engine exhaust noise. Journal of Sound and Vibration, 297-302.

Kelley, N. D., McKenna, H. E., Hemphill, H. E., Etter, C. L., Garrelts, R. L., & Linn, N. C. (1985). Acoustic noise associated with the MOD-1 wind turbine: its source, impact and control. Colorado, USA: Solar Energy Research Institute.

Klein, A., Marquis-Favre, C., & Weber, R. T. (2015). Spectral and modulation indices for annoyance-relevant features of urban road single-vehicle pass-by noises. Journal of the Acoustical Society of America, 1238-1250.

Knopper, L. D., Ollson, C. A., McCallum, L. C., Whitfield Aslund, M. L., Berger, R. G., Souweine, K., et al. (2014). Wind turbines and human health. Frontiers in Public Health, 2(63).

Krogh, C. M., Gillis, L., Kouwen, N., & Aramini, J. (2011). WindVOiCe, a self-reporting survey: adverse health effects, industrial wind turbines, and the need for vigiliance monitoring. Bulletin of Science, Technology and Society, 334-345.

Kurpas, D., Mroczek, B., Karakiewicz, B., Kassolik, K., & Andrzejewski, W. (2013). Health impact of wind farms. Annals of Agricultural and Environmental Medicine, 595-605.

Kuwano, S., Yano, T., Kageyama, T., Sueoka, S., & Tachibana, H. (2014). Social survey on wind turbine noise in Japan. Noise Control Engineering, 503-520.

Large, S. (2015). Wind turbine amplitude modulation & planning control study - Work Package 2.2: AM evidence review. Retrieved 2015, from www.heatonharris.com.

Large, S., & Stigwood, M. (2014). Noise characteristics of ‘compliant’ wind farms that adversely affect its neighbours. Inter-noise. Melbourne, Australia: I-INCE.

Large, S., Stigwood, D., & Bingham, D. (2015). Wind turbine amplitude modulation & planning control study - Work Package 5: Towards a draft AM condition. Retrieved 2015, from www.heatonharris.com.

Lee, S., Kim, K., Choi, W., & Lee, S. (2011). Annoyance caused by amplitude modulation of wind turbine noise. Noise Control Engineering Journal, 38-46.

Lee, S., Kim, K., Lee, S., Kim, H., & Lee, S. (2009). An estimation method of the amplitude modulation in wind turbine noise for community response assessment. Third International Meeting on Wind Turbine Noise. Aalborg, Denmark: INCE Europe.

Lee, S., Lee, S., & Lee, S. (2013). Numerical modeling of wind turbine aerodynamic noise in the time domain. Journal of the Acoustical Society of America, JASA Express Letters.

Legarth, D. V. (2007). Auralization and assessments of annoyance from wind turbines. Second International Meeting on Wind Turbine Noise. Lyon, France: INCE Europe.

Makarewicz, R., & Gołębiewski, R. (2015). Influence of blade pitch on amplitude modulation of wind turbine noise. Noise Control Engineering Journal, 195-201.

McCunney, R. J., Mundt, K. A., Colby, W. D., Dobie, R., Kaliski, K., & Blais, M. (2014). Wind turbines and health: a critical review of the scientific literature. Journal of Occupational and Environmental Medicine, 108-130.

Merlin, T., Newton, S., Ellery, B., Milverton, J., & Farah, C. (2013). Systematic review of the human health effects of wind farms. Canberra, Australia: National Health and Medical Research Council.

Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., et al. (2016). Effects of wind turbine noise on self-reported and objective measures of sleep. Sleep, 97-107.

Michaud, D. S., Keith, S. E., Feder, K., Soukhovtsev, V., Marro, L., Denning, A., et al. (2013). Self-reported and objectively measured health indicators among a sample of Canadians living within the vicinity of industrial wind turbines: social survey and sound level modelling methodology. Noise/News International, 14-23.

Moorhouse, A. T., Waddington, D. C., & Adams, M. (2013). Erratum: a procedure for the assessment of low frequency noise complaints [J. Acoust. Soc. Am. 126, 1131-1141 (2009]. Jorunal of the Acoustical Society of America, 2336.

Moorhouse, A. T., Waddington, D. C., & Adams, M. D. (2007). The effect of fluctuations on the perception of low frequency sound. Journal of Low Frequency Noise, Vibration and Active Control, 81-89.

Moorhouse, A. T., Waddington, D. C., & Adams, M. D. (2009). A procedure for the assessment of low frequency noise complaints. Journal of the Acoustical Society of America, 1131-1141.

Nissenbaum, M. A., Aramini, J. J., & Hanning, C. D. (2012). Effects of industrial wind turbine noise on sleep and health. Noise and Health, 237-243.

Nobbs, B., Doolan, C. J., & and Moreau, D. J. (2012). Characterisation of noise in homes affected by wind turbine noise. Proceedings of Acoustics 2012. Freemantle, Australia: Australian Acoustics Society.

Oerlemans, S. (2015). Effect of wind shear in amplitude modulation of wind turbine noise. International Journal of Aeroacoustics, 715-728.

Ollson, C. A., Knopper, L. D., McCallum, L. C., & L, W.-A. M. (2013). Letter to Editor: Are the findings of "Effects of industrial wind turbine noise on sleep and health" supported? Noise and Health, 148-150.

Onakpoya, I. J., O'Sullivan, J., Thompson, M. J., & Heneghan, C. J. (2015). The effect of wind turbine noise on sleep and quality of life: a systematic review and meta-analysis of observational studies. Environmental International, 1-9.

Pedersen, E., & Persson Waye, K. (2004). Perception and annoyance due to wind turbine noise – a dose-response relationship. Journal of the Acoustical Society of America, 3460-3470.

Pedersen, E., van den Berg, F., Bakker, R., & Bouma, J. (2009). Response to noise from modern wind farms in The Netherlands. Journal of the Acoustical Society of America, 634-643.

Persson Waye, K., & Öhrström, E. (2002). Psycho-acoustic characters of relevance for annoyance of wind turbine noise. Journal of Sound and Vibration, 65-73.

RenewableUK. (2013). The development of a penalty scheme for amplitude modulated wind farm noise. London: RenewableUK.

RSG et al. (2016). Massachusetts study on wind turbine acoustics. Massachusetts: Massachusetts Clean Energy Centre and Massachusetts Department of Environmental Protection.

Schmidt, J. H., & Klokker, M. (2014). Health effects related to wind turbine noise exposure: a systematic review. PLoS ONE, 9(12).

Seong, Y., Lee, S., Gwak, D., Cho, Y., Hong, J., & Lee, S. (2013a). An experimental study on annoyance scale for assessment of wind turbine noise. Journal of Renewable and Sustainable Energy.

Seong, Y., Lee, S., Gwak, D., Cho, Y., Hong, J., & Lee, S. (2013b). An experimental study on rating scale for annoyance due to wind turbine noise. Inter-noise. Innsbruck, Austria: I-INCE.

Sherman, T. (2015). Wind turbine amplitude modulation & planning control study – Work Package 3.1: Study of noise and amplitude modulation complaints received by local planning authorities in England. Retrieved 2015, from www.heatonharris.com.

SLR & Hoare Lea. (2015). Wind farm impacts study - Final report. Edinburgh: ClimateXChange.

Smith, M. G. (2013). Wind turbine amplitude modulation: research to improve understanding as to its cause & effect. Work package A(2): Fundamental research into possible causes of amplitude modulation. RenewableUK.

South Australia Environmental Protection Agency. (2015). Waterloo Wind Farm Environmental Noise Study. Retrieved 2015, from www.epa.sa.gov.au: http://www.epa.sa.gov.au/environmental_info/noise/types_of_noise/wind_farms/waterloo_wind_farm_environmental_noise_study

Stigwood, M., Large, S., & Stigwood, D. (2013). Audible amplitude modulation - results of field measurements and investigations compared to psychoacoustical assessment and theoretical research. 5th International Conference on Wind Turbine Noise. Denver: USA.

Stigwood, M., Stigwood, D., & Large, S. (2014). Initial findings of the UK Cotton Farm Wind Farm long term long term community noise monitoring project. Inter-noise. Melbourne, Australia: I-INCE.

Tachibana, H. (2014). Outcome of systematic research on wind turbine noise in Japan. Inter-noise. Melbourne, Australia: I-INCE.

Tachibana, H., Yano, H., Fukushima, A., & Sueoka, S. (2014). Nationwide field measurements of wind turbine noise in Japan. Noise Control Engineering Journal, 90-101.

The Senate Community Affairs Reference Committee. (2011). The social and economic impact of rural wind farms. Commonwealth of Australia.

Thorne, R. (2014). Perception and effect of wind farm noise at two Victorian wind farms. Brisbane, Australia: Noise Measurement Services.

van den Berg, F. (2009). Why is wind turbine noise noisier than other noise? Euronoise. Edinburgh, Scotland: INCE Europe.

van den Berg, F. (2011). Effects of sound on people. In G. Leventhall, & D. Bowdler, Wind turbine noise. Brentwood: Multi-Science Publishing.

van den Berg, F. (2013). Wind turbine noise: an overview of acoustical performance and effects on residents. Proceedings of Acoustics. Victor Harbour, Australia: Australian Acoustical Society.

van den Berg, F., & Bowdler, D. (2011). Amplitude modulation. In G. Leventhall, & D. Bowdler (Eds.), Wind turbine noise. Multi-Science Publishing.

van den Berg, G. P. (2004). Effects of the wind profile at night on wind turbine sound. Journal of Sound and Vibration, 955-970.

van den Berg, G. P. (2005). The beat is getting stronger: the effect of atmospheric stability on low frequency modulated sound of wind turbines. Journal of Low Frequency Noise, Vibration and Active Control, 1-24.

von Hünerbein, S., & Piper, B. (2015). Affective response to amplitude modulated wind turbine noise. 6th International Meeting on Wind Turbine Noise. Glasgow, UK: INCE Europe.

von Hünerbein, S., King, A., Piper, B., & Cand, M. (2013). Wind turbine amplitude modulation: research to improve understanding as to its cause & effect. Work package B(2): development of an AM dose-response relationship. RenewableUK.

Vos, J., & Houben, M. M. (2010a). Analysis of wind turbine sound recordings. TNO.

Vos, J., Houben, M. M., van der Ploeg, F., & Buikema, E. (2010b). Annoyance caused by low frequency sounds: spectral and temporal effects. Inter-noise. Lisbon: I-INCE.

Wells, G. A., Shea, B., O'Connell, D., Peterson, J., Welch, V., Losos, M., et al. (n.d.). The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. Retrieved 2015, from www.ohri.ca/.

WHO. (2009). Night noise guidelines for Europe. Geneva: World Health Organization.

WHO. (2011). Burden of disease from environmental noise: quantification of healthy life years lost in Europe. Geneva: World Health Organization.

Yano, T., Kuwano, S., Kageyama, T., Sueoka, S., & Tachibana, H. (2013). Dose-response relationships for wind turbine noise in Japan. Inter-noise. Innsbruck, Austria: I-INCE.

Yelland, J. V. (2015). Wind turbine amplitude modulation & planning control study - Work Package 1: The fundamentals of amplitude modulation of wind turbine noise. Retrieved 2015, from www.heatonharris.com.

Yokoyama, S., Koboyashi, T., Sakamoto, S., & Tachibana, H. (2015). Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise. 6th International Meeting on Wind Turbine Noise. Glasgow: INCE Europe.

Yokoyama, S., Sakamoto, S., & Tachibana, H. (2013). Study on the amplitude modulation of wind turbine noise: part 2 – auditory experiments. Inter-noise. Innsbruck, Austria: I-INCE.

Yokoyama, S., Sakamoto, S., & Tachibana, H. (2014a). Audibility of low frequency components in wind turbine noise. Forum Acusticum. Kraków, Poland: EAA.

Yokoyama, S., Sakamoto, S., & Tachibana, H. (2014b). Perception of low frequency components in wind turbine noise. Noise Control Engineering Journal, 295-305.

Zeng, X., Zhang, Y., Kwong, J. S., Zhang, C., Li, S., Sun, F., et al. (2014). The methodological quality assessment tools for preclinical and clinical studies, systematic review and meta-analysis, and clinical practice guideline: a systematic review. Journal of Evidence-based Medicine, 2-10.

Appendix A

GLOSSARY & CONCEPTS

GLOSSARY

Term	**Description**
Amplitude Modulation	The variation of amplitude with time. In the context of rotating machines, e.g. wind turbines, the modulation of the amplitude typically has a periodic character.
Amplitude Modulation Factor	The degree of variation in a modulated sound pressure relative to its mean value. Modulation factor is defined as $(A_{max} – A_{min}) / (A_{max} + A_{min})$, where A is the signal amplitude.
AM Depth / Modulation Depth	The depth of amplitude modulation in a signal with varying level is a measure of the difference between the highest (peak) and lowest (trough) levels. In real signals the peak and trough levels vary and there is no agreed definition in this context. Typically for WTN, the modulation depth is taken as the peak-to-trough level difference ΔL (dB) between the L_{pAF} level envelope, or the 'short term' L_{Aeq} integrated over contiguous 100-125ms periods. As the peak/trough levels will typically vary, the overall 'modulation depth' within an interval is sometimes established via a statistical method, e.g. arithmetic averaging. As a simple level difference parameter, modulation depth is often applied to filtered sound pressure levels (e.g. A-weighted, or individual third-octave bands). Therefore comparisons of 'modulation depths' must be made with caution; the sound level parameter must be identical for comparability. See the Concept Diagrams for an illustration.
A-Weighting	The human ear can detect a wide range of frequencies, from 20Hz to 20kHz, but it is more sensitive to some frequencies than others. Generally, the ear is most sensitive to frequencies in the range 1 to 4 kHz. The A-weighting is a filter that can be applied to measured results at varying frequencies, to mimic the frequency response of the human ear, and therefore better represent the likely perceived loudness of the sound. SPL readings with the A-weighting applied are sometimes denoted as 'dB(A)', or with the weighting subscripted in the level descriptor, e.g. 'L_{pA}'.
Background Sound or Background Noise	A component of the ambient sound environment, comprising the steady sounds underlying those sources that fluctuate in level within a period of consideration. This can be evaluated using the L_{90} metric. In UK wind turbine noise assessments, background sound levels are typically established from statistical analysis of relatively long periods of measurements. When sound is considered 'unwanted' it is usually termed 'noise'.
Band-Pass Filter	A band-pass filter allows defined sound frequencies with a certain range (or band) to pass with little or no impediment, while removing or impeding any other frequencies in the signal.
Blade Passing Frequency (BPF)	The frequency with which a blade passes any particular point in a rotation cycle per second. Applicable to any rotating mechanism with blades (fans, turbines etc.). BPF is related to revolutions-per-minute (RPM) as BPF = Number of blades × RPM/60.
C-Weighting	As for A-weighting, but only follows the frequency sensitivity of the human ear at very high noise levels. The C-weighting scale is quite flat, and therefore includes much more of the low-frequency range of sounds than the A scales.

GLOSSARY

Term	Description
Decibel (dB)	The logarithmic decibel scale is used in relation to sound. The decibel scale compares the level of a sound relative to another. The human ear can detect a wide range of sound pressures, typically between 2×10^{-5} and 200 Pa, so the logarithmic scale is used to quantify these levels using a more manageable range of values.
Equivalent Continuous Level ($L_{eq,T}$)	The Equivalent Continuous Level represents a theoretical continuous sound, over a stated time period, T, which contains the same amount of energy as a number of sound events occurring within that time, or a source that fluctuates in level. For example, a noise source with an SPL of 80 dB(A) operating for two hours during an eight-hour working day, has an equivalent A-weighted continuous level over eight hours of 74 dB, or $L_{Aeq,8hrs}$ = 74 dB. The time period over which the L_{eq} is calculated should always be stated.
Fast/Slow Time Weighting	The sound pressure level is calculated from the root-mean-square (RMS) value of the instantaneous acoustic pressure. Calculation of the RMS value requires a finite time interval over which to calculate the mean. Sound level meters use a time-weighted average, which multiplies the squared pressure sample by an exponential function of the constant time interval over which the average is calculated. Standard time constants in current use include 'Fast' and 'Slow', which have values of 0.125s and 1s respectively, and are represented by designated subscripts attached to a level descriptor, e.g. $L_{p,F}$; L_{Smax} etc.
Fluctuation Sensation	The auditory perception of a sound which exhibits temporal variation.
Fluctuation Strength	A psychoacoustic metric for perception of sounds that fluctuate in amplitude, based on the model devised by Zwicker and Fastl. Parameters included in the model are modulation frequency, modulation factor and overall sound level. Measured in units of *vacil*, where 1 vacil is the fluctuation strength of a 60dB 1kHz sinusoid 100% modulated (i.e. modulation factor = 1; see footnote[64]) at a modulation frequency of 4Hz.
G-Weighting	As for A-weighting, but G-weighting is designed to reflect human response to infrasound. The curve is defined to have a gain of zero dB at 10Hz. Between 1Hz & 20Hz the slope is approximately 12dB per octave. The cut-off below 1Hz has a slope of 24dB per octave, and above 20Hz the slope is -24 dB per octave.

[64] In general the modulation factor and modulation percentage do not take the same value, but in the special case of an AM sinusoid, they are equal.

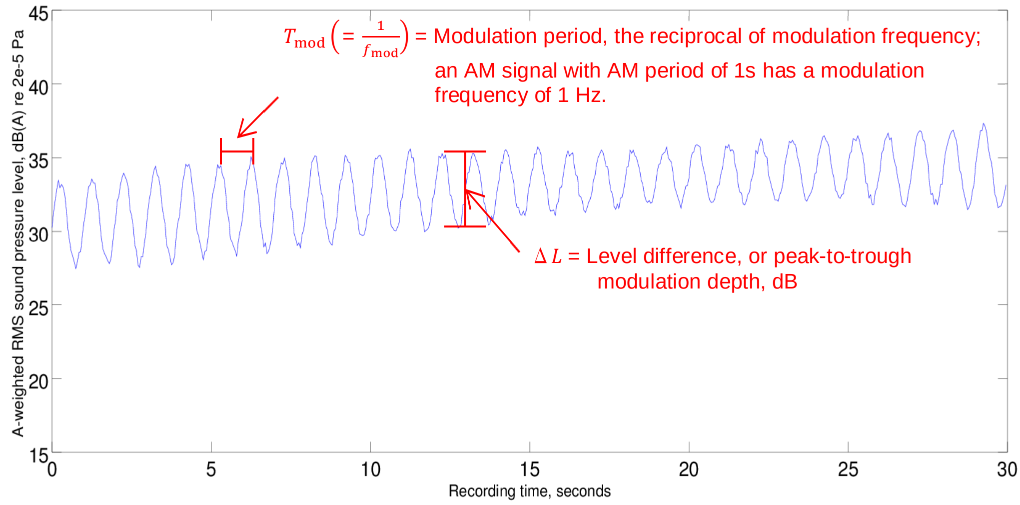
GLOSSARY

Term	Description
L_{90} or L_{A90} (and/or other 'percentile' measures)	Represents the SPL which is exceeded for 90% of the measurement time, expressed in dB or dB(A). L_{A90} is typically used to quantify background sound levels and, in the UK, wind turbine noise levels. In UK WTN assessment, the L_{A90} is used as a proxy level for the L_{Aeq}. This is because the L_{Aeq} is more susceptible to influence by non-WTN sounds in the environment, and WTN is generally relatively steady in level, compared with many other environmental noise sources. Other percentile levels such as L_{01}, L_{10}, L_{50}, L_{99} etc. can be used in various types of noise assessment. As an RMS SPL-based statistical level, the percentile measures should normally also have the time weighting included in the descriptor, as well as the time period of the measurement, e.g. $L_{AF90,10min}$.
Level Difference ΔL	In the context of amplitude modulation, the level difference expresses the difference in level between the highest and lowest amplitudes in the signal, and is also called the peak-to-trough level, or '*modulation depth*'. The level difference is related to the modulation factor *m* (see '*amplitude modulation factor*') by the expression $\Delta L = 20\log_{10}[(1 + m)/(1 - m)]$. A difference in sound levels is expressed in terms of dB. See the Concept Diagrams for an illustration.
Level Envelope	The envelope of a signal describes its variation in amplitude over time, and 'encloses' the signal levels.
Longitudinal and Cross-Sectional Studies	A longitudinal study is conducted by making observations from the same sample at more than one point in time. A cross-sectional study examines results observed from a sample at a single point in time (or cross-section).
Masking Noise	The human perception of a sound is affected by the presence of other audible sounds. Noise can provide masking for sounds that would otherwise be more clearly perceived. A masked sound may appear less distinct or may even not be detectable at all by a listener when a masking noise is present. In some situations, such as wind farms with residential neighbours, some masking noise (such as wind blowing through local vegetation) may be desirable.
Modulation Frequency / Period	The frequency of modulation is the number of times within a second that the amplitude fluctuates over the observed cycle, i.e. from maximum to minimum and back to maximum. The period of modulation is the reciprocal of frequency, i.e. the length of time between two amplitude peaks in a modulation cycle. See the Concepts Diagrams for an illustration.
Octave Band or Third Octave Band	A sound consisting of more than one frequency can be described using a frequency spectrum, which shows the relative magnitude of the energy in the different frequencies within it. The possible range of frequencies is continuous, but can be split up into discrete bands, often an octave or third-octave in width. Each band is referred to by its centre frequency, e.g. (for octave bands) 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz etc. Separation of the spectrum in this way is typically implemented via band-pass filters.
Periodicity	A sound wave with a repeating form can be described as periodic. The level of a sound with periodic amplitude displays a regular fluctuation, although the peaks and troughs in the level may still vary.

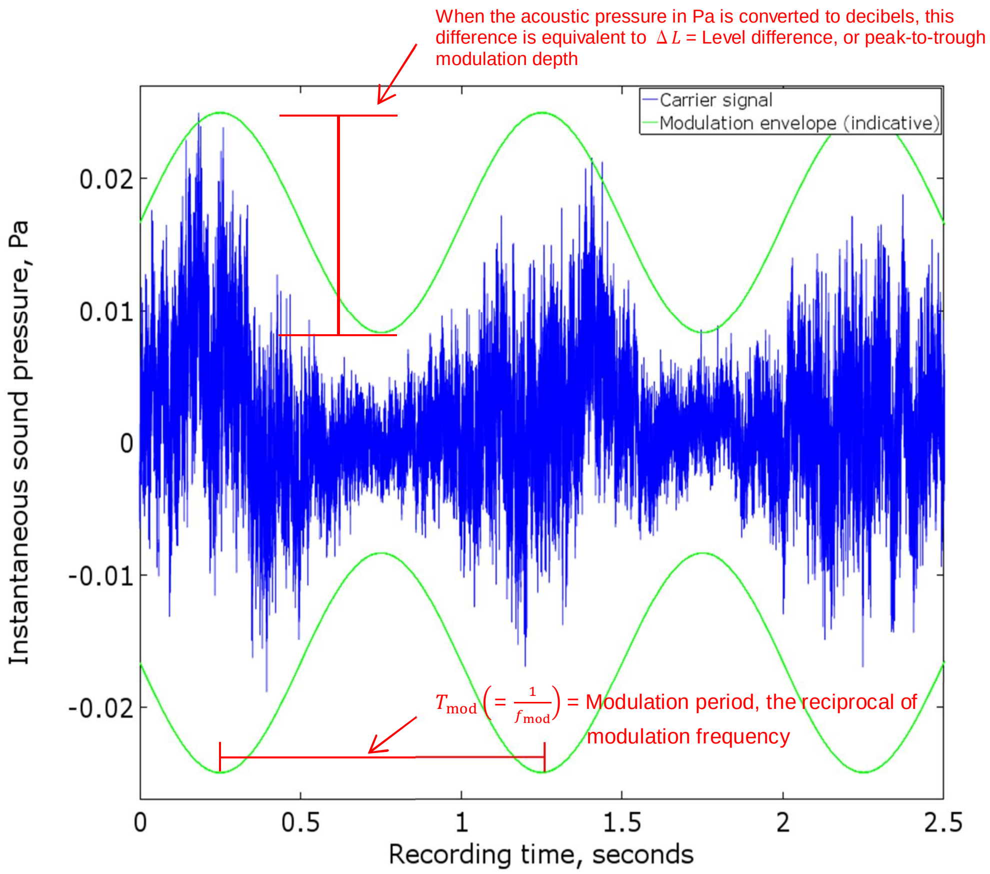
GLOSSARY

Term	Description
Pink Noise	Noise in theoretical acoustic terms is sound energy with random variation. 'White' noise has equal sound energy at every frequency; 'pink' noise has a sound energy that is inversely proportional to frequency, which results in a more low frequency sound compared with white noise.
RMS/root-mean-square sound (acoustic) pressure	Acoustic pressure waves comprise perturbations of air pressure, and the instantaneous pressure values at any given point in space therefore take positive and negative values around the mean, which is the steady local atmospheric pressure. In order to represent a meaningful amplitude, it is necessary to square the values (to make all values positive), calculate the mean (over some time interval), and take the square root of the result. The acoustic energy (or power, for finite signals) can be described by the mean-square of the pressure amplitude. The square root reduces the mean-square value to linear (amplitude), rather than squared, units.
Sound Pressure Level (SPL)	The Sound Pressure Level has units of decibels, and compares the level of a sound to the smallest sound pressure generally perceptible by the human ear, or the reference pressure. It is defined as follows: SPL (dB) = $10 \text{ Log}_{10}(P/P_{ref})^2$ Where P = root-mean-square (see '*RMS*') sound pressure (in Pa) P_{ref} = Reference pressure $2\text{x}10^{-5}$ Pa An SPL of 0 dB suggests the sound pressure is equal to the reference pressure. This is the approximate threshold of normal hearing. An SPL of 140 dB represents the approximate threshold of pain. SPL is also often denoted as 'L_p'.
Spectral content	Sounds are typically made up of acoustic energy present in many frequencies of the audible spectrum. The frequency spectrum describes this signal 'content'.

CONCEPT DIAGRAMS



The RMS sound pressure level shown in the above diagram is evaluated over a (short) averaging time and therefore represents the 'level envelope' of the signal rather than instantaneous sound pressure values. The envelope concept is also illustrated below, related to instantaneous acoustic pressure.



The diagram above shows a pink noise carrier signal modulated in level by a sine wave.
NB: Concept plots show simulated signals and do not display real wind turbine noise data.

Appendix B

FULL LIST OF PUBLICATIONS

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Abbasi, M, et al.	2015	Impact of Wind Turbine sound on general health, sleep disturbance + annoyance of Workers - a pilot Study in ManjilWind Farm, Iran	Journal of Environmental Health, Science and Engineering	[black]	2d
Abbasi, M, et al.	2015	Effect of Wind Turbine Noise on Workers' Sleep Disorder: A Case Study of ManjilWind Farm in Northern Iran	Fluctuation and Noise Letters	[black]	2d
Aslund,MLW et al	2013	Projected contributions of future wind farm development to community noise + annoyance levels in Ontario, Canada	Energy Policy	[black]	2e
Bakker,RH et al	2012	Impact of wind turbine sound on annoyance, self-reported sleep disturbance + psychological stress	Science of the Total Environment	[black]	2d
Bauer,M et al	2015	Investigation of perception at infrasound frequencies by functional magnetic resonance imaging fMRI and magnetoencephalography (MEG)	International Congress on Sound and Vibration	[grey]	2e
Bengtsson,J et al	2004	Sound characteristics in low frequency noise + their relevance for the perception of pleasantness	Acta Acustica united with Acustica	[black]	2c
Berger,RG et al	2015	Health-based audible noise guidelines account for infrasound + low-frequency noise produced by wind turbines	Frontiers in Public Health	[black]	2d
Bockstael,A et al	2012	Reduction of wind turbine noise annoyance- an operational approach	Acta Acustica united with Acustica	[black]	1
Bockstael,A et al	2011	Wind turbine noise - annoyance + alternative exposure indicators	Forum Acusticum	[grey]	1
Bolin,K	2007	Investigating the audibility of wind turbines in the presence of vegetation noise	International Meeting on Wind Turbine Noise	[grey]	2e
Bradley,JS	1994	Annoyance caused by constant-amplitude and amplitude-modulated sounds containing rumble	Noise Control Engineering Journal	[black]	2c
Brink,M et al	2010	Field study of the exposure-annoyance relationship of military shooting noise	Journal of the Acoustical Society of America	[black]	2c

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Bullmore, A et al	2011	Wind turbine amplitude Modulation- Research to Improve Understanding as to its Cause & Effect	International Meeting on Wind Turbine Noise	[grey]	2a
Bunk,O	2009	Investigation of day-/nighttime differences in sound emissions of high wind energy systems	Euronoise	[grey]	2e
Cand,M et al	2015	Practical Investigations of AM Mitigation	Acoustics 2015	[grey]	2b
Cand,M et al	2015	Measurements demonstrating mitigation of far-field AM from wind turbines	International Meeting on Wind Turbine Noise	[grey]	2b
Cand,M et al	2015	Understanding amplitude modulation of noise from wind turbines- causes and mitigation	Acoustics in Practice	[grey]	2b
Cassidy,M et al	2015	Addressing the Issue of Amplitude Modulation- A Developer's Perspective	International Meeting on Wind Turbine Noise	[grey]	2f
Council of Canadian Academies	2015	Understanding the evidence - wind turbine noise	Independent report	[black]	2d
Cowen,R	2015	INWG Work package 6.1A- Legal issues - the control of excessive amplitude modulation from wind turbines	Independent report	[grey]	2f
Cowen,R	2015	INWG Work Package 6.1A – Legal Issues: the Control of Excessive Amplitude Modulation from Wind Turbines Supplementary Paper	Independent report	[grey]	2f
Cox,R	2015	INWG Work Package 8 - Review of Institute of Acoustics Amplitude Modulation Study and Methodology	Independent report	[grey]	2f
Cox,R et al,	2015	INWG Work Package 2.1 - Review of reference literature	Independent report	[grey]	2e
Crichton, F et al	2015	Health complaints + wind turbines-the efficacy of explaining the nocebo response to reduce symptom reporting	Environmental Research	[black]	2d

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Crichton,F et al	2015	Framing sound- using expectations to reduce environmental noise annoyance	Environmental Research	[black]	2e
Cummings, J	2013	The Variability Factor in Wind Turbine Noise	International Conference on Wind Turbine Noise	[grey]	2f
Davis,J et al	2007	Noise Pollution From Wind Turbines - Living with amplitude with modulation, lower frequency emissions and sleep deprivation	International Meeting on Wind Turbine Noise	[grey]	2e
DEFRA	2008	Research into improvement of management of helicopter noise - nanr235-project-report	Independent report	[grey]	2e
Di Napoli,C	2009	Case study- wind turbine noise in a small+ quiet community in Finland	International Meeting on Wind Turbine Noise	[grey]	2b
Di Napoli,C	2011	Wind turbine noise assessment in a small and quiet community in Finland	Noise Control Engineering Journal	[black]	2b
Di Napoli,C et al	2015	Current challenges of assessing excess amplitude modulation character in wind turbine noise during EIA/planning phase	International Meeting on Wind Turbine Noise	[grey]	2f
Dittrich,K et al	2009	Comparison of the temporal weighting of annoyance + loudness	Journal of the Acoustical Society of America	[black]	2c
Falourd,X et al	2015	Low Frequency Amplitude Modulation related to Doppler frequency shift: an experimental study of a 101m diameter wind turbine in a swiss valley.	International Meeting on Wind Turbine Noise	[grey]	2e
Fastl,H et al	2013	Psychoacoustic aspects of noise from wind turbines	Inter-noise	[grey]	2a
Feder,K et al	2014	An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines.	Environmental Research	[black]	2d
Fredianelli,F et al	2014	Looking for a wind turbine noise legislation paying attention to annoyance: which metric?	International Congress on Noise as a Public Health Problem	[grey]	2f
Gabriel,J et al	2013	Amplitude Modulation and Complaints about Wind Turbine Noise	International Conference on Wind Turbine Noise	[grey]	2b

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Gray,B	2015	INWG Work package 6.2- Control of AM noise without an AM planning condition using Statutory Nuisance	Independent report	[grey]	2f
Gray,B	2015	INWG Work Package 9 – The Cotton Farm Monitor Experience	Independent report	[grey]	2e
Hanning,C et al	2011	Selection of outcome measures in assessing sleep disturbance from wind turbine noise	International Meeting on Wind Turbine Noise	[grey]	2d
Hanning,CD	2015	INWG Work package 3.2- Excess amplitude modulation, wind turbine noise, sleep and health	Independent report	[grey]	2d
Hansen, KL et al	2015	Quantifying the character of wind farm noise	International Congress on Sound and Vibration	[grey]	2b
Health Canada	2014	Wind Turbine Noise and Health Study- Summary of results [online]	Independent report	[grey]	2d
Health Canada	2014	Health impacts and exposure to sound from wind turbines - Updated research design + sound exposure assessment [online]	Independent report	[grey]	2d
Hulme,M	2015	INWG Work Package 4 - Den Brook	Independent report	[grey]	2e
Inagaki,T et al	2015	Analysis of aerodynamic sound noise generated by a large-scaled wind turbine and its physiological evaluation	International Journal of Environmental Science and Technology	[black]	2a
Jabben,J et al	2012	Options for assessment and regulation of low-frequency noise	International Meeting on Low Frequency Noise and Vibration	[grey]	2e
Janssen,SA et al	2011	A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources	Journal of the Acoustical Society of America	[black]	2d

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Janssen,SA et al	2009	Exposure-response relationships for annoyance by wind turbine noise: a comparison with other stationary sources	Euronoise	[grey]	2d
Jeffery,RD et al	2014	Industrial wind turbines and adverse health effects.	Canadian Journal of Rural Medicine	[black]	2d
Kaczmarek,T et al	2010	Annoyance of time-varying road-traffic noise	Archives of Acoustics	[black]	2c
Kageyama,T et al	2014	Exposure-response relationship of wind turbine noise with subjective symptoms on sleep and health: a nationwide socio-acoustic survey in Japan	International Congress on Noise as a Public Health Problem	[grey]	2d
Kantarelis,C et al	1988	Identification+subjective effect of AM in diesel engine exhaust noise	Journal of Sound and Vibration	[black]	2c
Kelley,ND et al	1985	Acoustic noise associated with the MOD-1 wind turbine- its source, impact and control	Independent report	[grey]	2a
Klein, A et al	2015	Spectral + modulation indices for annoyance-relevant features of urban road single-vehicle pass-by noises	Journal of the Acoustical Society of America	[black]	2c
Knopper, LD et al	2011	Health effects and wind turbines- a review of the literature	Environmental Health	[black]	2d
Knopper, LD et al	2014	Wind turbines and human health	Frontiers in Public Health	[black]	2d
Kugler,K et al	2014	Low-frequency sound affects active micromechanics in the human inner ear	Royal Society Open Science	[black]	2e
Kurpas,D et al	2013	Health impact of wind farms	Annals of Agricultural and Environmental Medicine	[black]	2d
Kuwano, S et al	2014	Social survey on wind turbine noise in Japan	Noise Control Engineering Journal	[black]	2d

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Kuwano, S et al	1999	Loudness, annoyance + unpleasantness of amplitude modulated sounds	Inter-noise	[grey]	2c
Large, S et al	2015	INWG WP5- Towards AM planning condition	INWG	[grey]	2f
Large, S et al	2014	Noise characteristics of 'compliant' wind farms that adversely affect its neighbours	Inter-noise	[grey]	2b
Large,S	2015	INWG Work Package 2.2 - AM Evidence Review	Independent report	[grey]	2e
Laszlo, HE et al	2012	Annoyance and other reaction measures to changes in noise exposure: a review	Science of the Total Environment	[black]	2e
Lee,S et al	2011	Annoyance caused by amplitude modulation of wind turbine noise	Noise Control Engineering Journal	[black]	1
Lee,S et al	2009	An estimation method of the amplitude modulation in wind turbine noise for community response assessment	International Meeting on Wind Turbine Noise	[black]	1
Legarth,SV	2007	Auralization + assessments of annoyance from wind turbines	International Meeting on Wind Turbine Noise	[grey]	2a
Lenchine,VV	2009	Amplitude modulation in wind turbine noise	Acoustics 2009	[grey]	2a
Lichtenhan,J et al	2013	Amplitude modulation of audible sounds by non-audible sounds - understanding the effects of wind turbine noise	International Congress on Acoustics	[grey]	2a
Magari,SR et al	2014	Evaluation of community response to wind turbine-related noise in Western New York State	Noise and Health	[black]	2d
Marshall Day Acoustics	2013	Examination of the significance of noise in relation to onshore wind farms	Independent report	[grey]	2e
Matsuda,H et al	2012	Measurement of Psychological Response and Evaluation of Task Performance on Low-frequency Sound	International Meeting on Low Frequency Noise and Vibration	[grey]	2c
McCunney,RJ et al	2014	Wind Turbines and Health A Critical Review of the Scientific Literature	Journal of Occupational and Environmental Medicine	[black]	2d

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Merlin,T et al	2013	Systematic review of the human health effects of wind farms	Independent report	[black]	2d
Michaud,DS et al	2015	Effects of Wind Turbine Noise on Self-Reported and Objective Measures of Sleep	Sleep	[black]	2d
Michaud,DS et al	2013	Self-reported and Objectively Measured Health Indicators Among a Sample of Canadians Living Within the Vicinity of Industrial Wind Turbines: Social Survey and Sound Level Modelling Methodology	Noise News International	[grey]	2d
Moorhouse, AT et al	2009	A procedure for the assessment of low-frequency noise complaints	Journal of the Acoustical Society of America	[black]	2c
Moorhouse, AT et al	2007	The effect of fluctuations on the perception of low frequency sound	Journal of Low Frequency Noise, Vibration and Active Control	[black]	2c
Nissenbaum, M et al	2011	Adverse health effects of industrial wind turbines: a preliminary report	International Congress on Noise as a Public Health Problem	[grey]	2d
Nissenbaum, MA et al	2012	Effects of industrial wind turbine noise on sleep and health	Noise and Health	[black]	2d
Nobbs,B et al	2012	Characterisation of noise in homes affected by wind turbine noise	Acoustics 2012	[black]	1
Onakpoya,IJ et al	2015	The effect of wind turbine noise on sleep and quality of life: A systematic review and meta-analysis of observational studies	Environment International	[black]	2d
Pawlaczyk-Luszczynsk,M et al	2014	Evaluation of annoyance from the wind turbine noise: A pilot study	International Journal of Occupational Medicine and Environmental Health	[black]	2d
Pawlaczyk-Luszczynsk,M et al	2013	Assessment of annoyance due to wind turbine noise	Meetings on Acoustics	[grey]	2d

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Pedersen, E	2011	Health aspects associated with wind turbine noise: results from three field studies	Noise Control Engineering Journal	[black]	2d
Pedersen,CS et al	2012	Low-frequency noise from large wind turbines-additional data+assessment of Danish regulations	International Meeting on Low Frequency Noise and Vibration	[grey]	2f
Pedersen,E et al	2004	Perception + annoyance due to wind turbine noise- a dose-response relationship	Journal of the Acoustical Society of America	[black]	2d
Pedersen,E et al	2010	Can road traffic mask sound from wind turbines - response to wind turbine sound at different levels of road traffic sound	Energy Policy	[black]	2d
Pedersen,E et al	2009	Response to noise from modern wind farms in the Netherlands	Journal of the Acoustical Society of America	[black]	2d
Pedersen,E et al	2009	Wind turbine sound – how often is it heard by residents living nearby?	Euronoise	[grey]	2e
Pedersen,E et al	2007	Wind turbine noise, annoyance and self-reported health and well-being in different living environments.	Occupational and Environmental Medicine	[black]	2d
Pedersen,E et al	2005	Human response to wind turbine noise – annoyance and moderating factors	International Meeting on Wind Turbine Noise	[grey]	2d
Persson Waye, K	2004	Effects of low-frequency noise on sleep	Noise and Health	[black]	2f
Persson Waye, K et al	2002	Psycho-acoustic characters of relevance for annoyance of wind turbine noise	Journal of Sound and Vibration	[black]	2a
Persson Waye, K et al	2001	The prevalence of annoyance + effects after long-term exposure to low-frequency noise	Journal of Sound and Vibration	[black]	2e
Renewable UK	2013	Template planning condition on amplitude modulation	Independent report	[grey]	2f
Renewable UK	2013	Development of a penalty scheme for amplitude modulated wind farm noise	Independent report	[grey]	1

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Rennies,J et al	2015	Spectro-temporal characteristics affecting the loudness of technical sounds-data + model predictions	Acta Acustica united with Acustica	[black]	2c
Roberts, M et al	2009	Evaluation of the scientific literature on the health effects associated with wind turbines and low frequency sound	Independent report	[grey]	2d
RSG et al	2016	Massachusetts study on wind turbine acoustics	Independent report	[grey]	2a
Salt, AN et al	2010	Responses of the ear to low frequency sounds, infrasound + wind turbines	Hearing Research	[black]	2e
Schmidt, JH et al	2014	Health Effects Related to Wind Turbine Noise Exposure: A Systematic Review	PLOS One	[black]	2d
Seong,Y et al	2013	An experimental study on rating scale for annoyance due to wind turbine noise	Inter-noise	[grey]	1
Seong,Y et al	2013	An experimental study on annoyance scale for assessment of wind turbine noise	Journal of Renewable and Sustainable Energy	[black]	1
Shepherd, D et al	2011	Evaluating the impact of wind turbine noise on health-related quality of life.	Noise and Health	[black]	2d
Sherman,T	2015	INWG Work Package 3.1 - Study of Noise and Amplitude Modulation Complaints Received by Local Planning Authorities in England	Independent report	[grey]	2e
SRL & Hoare Lea	2015	Wind farm impacts study	Independent report	[grey]	2a
Stelling,K	2015	Infrasound-low frequency noise and wind turbines	Independent report	[grey]	2e
Stigwood,M et al	2013	Audible amplitude modulation - results of field measurements and investigations compared to psychoacoustical assessment and theoretical research	International Conference on Wind Turbine Noise	[grey]	2e

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Stigwood,M et al	2014	Initial findings of the UK Cotton Farm Wind Farm long term community noise monitoring project	Inter-noise	[grey]	2b
Tachibana,H et al	2014	Outcome of systematic research on wind turbine noise in Japan	Inter-noise	[grey]	2a
Tachibana,H et al	2014	Nationwide field measurements of wind turbine noise in Japan	Noise Control Engineering Journal	[black]	1
Takahashi,Y	2013	Present situation + research task on the assessment of psychological effects caused by low-frequency noise	Japanese Journal of Hygiene	[black]	2e
Thorne,R	2014	The perception and effect of wind farm noise at two Victorian wind farms	Independent report	[grey]	2d
Thorne,R	2007	Assessing intrusive noise and low amplitude sound	Independent report	[black]	2e
van den Berg,F	2011	Wind Turbine Noise Chapter 6 - Effects of sound on People	Wind Farm Noise Book	[grey]	2a
van den Berg,F	2013	Wind turbine noise- an overview of acoustical performance + effects on residents	Acoustics 2013	[grey]	2a
van den Berg,F	2009	Why is wind turbine noise noisier than other noise?	Euronoise	[grey]	2a
van den Berg,GP	2004	Do wind turbines produce significant low frequency sound levels	International Meeting on Low Frequency Noise and Vibration	[grey]	2e
van den Berg,GP	2004	The beat is getting stronger - the effect of atmospheric stability on low frequency modulated sound of wind turbines	Noise Notes	[grey]	2a

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
van den Berg,GP	2005	The beat is getting stronger - the effect of atmospheric stability on low frequency modulated sound of wind turbines	Journal of Low Frequency Noise, Vibration and Active Control	[grey]	2a
van Renterghem,T et al	2013	Annoyance, detection and recognition of wind turbine noise	Science of the Total Environment	[black]	2d
von Hünerbein et al	2015	Affective Response to Amplitude Modulated Wind Turbine Noise	International Meeting on Wind Turbine Noise	[grey]	1
von Hünerbein et al	2013	Wind Turbine Amplitude Modulation- Research to Improve Understanding as to its Cause & Effect. Work Package B(2)- Development of an AM Dose-Response Relationship	Independent report	[grey]	1
Vos,J et al	2010	Analysis of wind turbine sound recordings	Independent report	[grey]	2a
Vos,J et al	2010	Annoyance caused by low frequency sounds- spectral + temporal effects	Inter-noise	[grey]	2c
Yano et al	2013	Dose-response relationships for wind turbine noise in Japan	Inter-noise	[grey]	2d
Yano, T et al	1990	Assessing intrusive noise and low amplitude sound	Environment International	[black]	2c
Yelland,J	2015	INWG Work Package 1 – The Fundamentals of Amplitude Modulation of Wind Turbine Noise	Independent report	[grey]	2e
Yokoyama et al	2015	Subjective experiments on the auditory impression of the amplitude modulation sound contained in wind turbine noise	International Meeting on Wind Turbine Noise	[grey]	1
Yokoyama et al	2014	Perception of low frequency components in wind turbine noise	Noise Control Engineering Journal	[black]	1
Yokoyama et al	2014	Audibility of low frequency components in wind turbine noise	Forum Acusticum	[grey]	1

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS	CATEGORY
Yokoyama et al	2013	Study on the amplitude modulation of wind turbine noise part 2- auditory experiments	Inter-noise	[grey]	1

Appendix C

REVIEW RESPONSE CATEGORIES

REVIEW RESPONSE CATEGORIES

Noise source	[Describe the noise stimuli and applicability/similarity to WTN AM]
Exposure-response	[If applicable, describe the exposure-response approach and scale used, e.g. reported complaints/annoyance, 11-point annoyance scale, etc.]
Main scope of work	[Outline the scope]
Conclusions of paper	[Summarise the relevant conclusions]
Quality, robustness and relevance of work, risk of bias	[Overall comments]
Independently peer-reviewed	[Yes or no, plus details if important]
Funding source	[Public/private/mixed/unstated]
Lab or field study	
Lab exposure method	[e.g. loudspeakers or headphones]
Sample size and response rate	
Exposure	[Measured/calculated/estimated]
Response	[e.g. specify type and scale used]
Robustness	Exposure [Comments] Response [Comments]
Reviewer weighting 0-9	[Attach a subjective importance weighting to the paper/study based on the previous box, referring back to the study aims. Conflicts will be resolved by discussion]
Newcastle-Ottawa Scale overall rating	[if relevant, score according to the NOS manual and checklist, max overall score 9]
GSR checked?	[confirm Y if relevant and checked; otherwise INDEPENDENT REPORT]

Newcastle-Ottawa Score Table

Selection	[max 4 stars]
Comparability	[max 2 stars]
Outcome	[max 3 stars]

ANNEX 1

CATEGORY 1 STUDY F

Title: Effect of modulation depth, frequency, and intermittence on wind turbine noise annoyance

Authors: Ioannidou, C., Santurette, S, & Jeong, C-H.

Institution: Technical University of Denmark

Publication: Journal of the Acoustical Society of America 139(3) pp1241-1251

Publication date: 23rd March 2016

Details

This laboratory study comprised three listening test-based experiments with 10, 14 and 13 participants respectively (aged 23-28 years).

The subjects were presented with a range of WTN recordings, synthesised stimuli and combinations via headphones, in the subjective context of garden relaxation. They were asked to rate annoyance felt after presentation of 30-second samples on an 11-point scale.

The experiments were designed to investigate the effect on annoyance of i) modulation depth; ii) modulation frequency; iii) temporal variation in AM depth.

Results

The results of experiment one showed a significant association between increasing mean modulation depth[65] and rated annoyance.

The results of experiment two indicated a trend but statistically insignificant relationship between modulation frequencies over the range 0.5 to 2 Hz and rated annoyance.

The results of experiment three suggested that the 'baseline' modulation depth outside intermittent periods of increased depth may dictate the rated annoyance, i.e. shorter periods of increased AM do not necessarily lead to increased annoyance.

Implications

The results of experiment one suggest a slightly stronger influence of modulation depth on annoyance than is clear from the Category 1 studies examined in the main report. This lends additional support to the proposed use of a sliding scale for rating AM, rather than a stepped scale approach.

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[65] Modulation depth in this study was defined as the mean depth over the frequency range of the 'modulation depth spectrum', established using the same Fourier process established by the Seoul University study group discussed under 'Study A' in the main report. These modulation depths cannot therefore be compared directly with AM depths defined in a different way – see Appendix A .

The results of experiment two indicate that, over the turbine rotation speed range addressed in the main report, i.e. up to 32 RPM, there is no strong need to directly consider modulation frequency as a modifying factor in determining a rating for AM (assuming a 3-bladed turbine), given that some uncertainty 'headroom' within the penalty magnitude has been included for this purpose. The results do appear to exhibit the expected relationship for modulated noise, i.e. that perceptual sensitivity increases steadily from 0 Hz, and on this rationale the trend could probably be extrapolated up to around 4 Hz, which would be the expected peak sensitivity (further increases in modulation frequency would then be expected to show decline in sensitivity). In the absence of further research aimed at establishing equivalent perceptual responses corresponding to higher modulation frequencies, the condition as proposed should be limited to the advised upper frequency limit, i.e. approximately 1.6 Hz.

The results of experiment three suggest that short periods of higher AM are probably not as annoying as a sustained period of reduced AM depth.

Limitations

The main limitations of the study are the small sample size and limited age group, the artificiality of the exposure (laboratory, headphones) and the short exposure periods.

The results address laboratory ratings of absolute annoyance; these should not be interpreted as directly indicative of responses in real field situations.

Conclusion

The outputs of this study appear to support the planning control approach proposed in the main report.

ANNEX 2

CATEGORY 1 STUDY G

Title: Short-term annoyance reactions to stationary and time-varying wind turbine and road traffic noise: a laboratory study

Authors: Schäffer, B., Schlittmeier, S.J., Pieren, R., Heutschi, K., Brink, M., Graf, R. & Hellbrück, J.

Institution: Empa / Catholic University of Eichstätt-Ingolstadt / Federal Office for the Environment (CH)

Publication: Journal of the Acoustical Society of America 139(5) pp2949-2963

Publication date: May 2016

Details

This laboratory study included a sample of 60 participants aged 18-60 years (median: 35 yrs).

The study objective was to compare rated annoyance responses to WTN and road traffic noise (RTN) stimuli, presented in controlled listening tests.

The subjects were presented with synthesised WTN stimuli and edited recordings of RTN via loudspeakers. They were asked to rate their annoyance to the 25s samples on an 11-point scale.

The AM component in the WTN stimuli set was introduced in two ways: periodic fluctuations, and random. The periodic AM had a 3 dB standard deviation in the level fluctuation, and a modulation frequency of 0.75 Hz. The random AM had the same standard deviation in the level fluctuation, and a varying modulation frequency of 0.3-1.1 Hz. The maximum WTN modulation depths shown in the $L_{pA,F}$ signals appeared to be in the range 7-10 dB.

Results

The results indicated that:

- For similar time-average levels, subjects typically rated WTN more annoying than RTN (replicating results known from field studies); and were slightly quicker to assign a rating to WTN than to RTN;
- The ratings indicated a difference (in the time-averaged level) of around 4-5 dB for equivalent annoyance between WTN and RTN;
- Periodicity in the AM of the WTN did not appear to have more of an influence on the ratings of annoyance than random AM;
- A linear mixed effects model was developed from the data, indicating the relationship between the annoyance ratings and the time-averaged level for each sample type. This suggested that the AM WTN samples could elicit the same annoyance rating at around 1-2 dB lower L_{Aeq} than a WTN sample with no AM.
- A logistic regression model was also developed from the data, to enable a relationship between the ‘Probability of High Annoyance’ (pHA) and the time-averaged level to be estimated for each sample type. This model suggested that the maximum difference in the time-averaged level for

equivalent pHA between the WTN samples without AM, and those with AM (whether periodic or random, as the models were very similar), was around 2.5 dB.

Implications

The authors conclude that the results suggest the increased annoyance associated with WTN (compared with RTN) is not caused by the periodicity in the fluctuations, as might be thought, but instead appears more likely to be due to its modulation frequency, which is closer to that of expected human peak sensitivity (~4Hz).

The results suggest that the equivalence in annoyance due to the AM component in WTN may be smaller than the proposed penalty rating system, in the order of around 1-3 dB, rather than the 3-5 dB proposed. However, the modulation frequency range employed (up to around 1 Hz), does not cover the full range of potential modulation the control is designed to address, and equivalent annoyance at higher modulation frequencies (up to 1.6 Hz) would be expected to be higher than the study results suggest.

Limitations

The sample size for this laboratory study (60) was unusually large compared with the other lab studies examined. There was also a range of age groups represented and an almost even gender split. The authors acknowledge however that the sample represents a limited geographic region and are mainly drawn from research institutions, and no residents affected by wind farm noise were recruited.

The authors also enter into a detailed discussion of the differences between the type of 'annoyance' being rated in the laboratory and the annoyance experience by people in field situations, pointing out that these differences limit the comparability of the results. They conclude that the study addresses only 'short-term annoyance' and applicability to long-term exposure would need to be validated (e.g. by further field investigations).

Conclusion

The outputs of this study appear to support the planning control approach proposed in the main report.

ANNEX 3

HEALTH CANADA COMMUNITY NOISE AND HEALTH STUDY LITERATURE

AUTHOR	YEAR	TITLE	PUBLICATION	STATUS
Feder, K et al.	2015	An assessment of quality of life using the WHOQOL-BREF among participants living in the vicinity of wind turbines	Environmental Research	[black]
Michaud, D et al.	2016	Effects of wind turbine noise on self-reported and objective measures of sleep	Sleep	[black]
Michaud, D et al.	2016	Exposure to wind turbine noise: perceptual responses and reported health effects	Journal of the Acoustical Society of America	[black]
Michaud, D et al.	2016	Self-reported and measured stress related responses associated with exposure to wind turbine noise	Journal of the Acoustical Society of America	[black]
Michaud, D et al.	2016	Personal and situational variables associated with wind turbine noise annoyance	Journal of the Acoustical Society of America	[black]
Voicescu, S.A. et al	2016	Estimating annoyance to calculated wind turbine shadow flicker is improved when variables associated with wind turbine noise exposure are considered	Journal of the Acoustical Society of America	[black]