Wind Turbine Noise - from Source to Receiver
Far-field Noise Issues - AM, Tonality & Impulses

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1. Introduction

2. Measurement & Analysis Techniques
   a) qualitative and quantitative

3. ‘Other’ Amplitude Modulation
   a) what is it & definitions
   b) methods for identification & quantifying
   c) possible theoretical explanations?

4. Other acoustic features
   a) Tones, Impulses, LFN & infrasound

5. Final Thoughts
2 MEASUREMENT TECHNIQUES

• typically far-field noise immission levels, e.g. LA90,10min will be measured according to a compliance programme

• most modern sound level meters capable of making these kind of measurements – same as used for background noise surveys

• fine for verifying compliance with pre-agreed limits

• if far-field acoustic features are present audio recordings should be made

• many modern sound level meters are capable of recording audio

• careful consideration needs to be given to sample & bit rates

• typically use 48 kHz, 16-bits uncompressed WAV files

• generates large of data files!

• change data card frequently!
2 ANALYSIS TECHNIQUES/SOFTWARE

- Tone @ 450 Hz
- Tone @ 370 Hz
- Vertical bands => AM
3a Amplitude Modulation - Where does it come from?
3a ‘Normal’ Amplitude Modulation (‘NAM’ or ‘blade swish’)

What would an observer standing in near-field, downwind of a turbine hear?

Key points:

– occurs at blade passing frequency

– peaks when the blade is moving towards the observer, i.e. 3 am

– conflicts with common perception!

– only apparent close to turbine (ex. crosswind)

– theory suggests maximum predicted level variation ~5 dB (peak-to-trough)

– high frequency noise

[From Oerlemans, 2009]
Key Points:
• ‘Normal’ AM occurs because of the directivity of the dominant boundary layer / trailing edge noise source combined with the rotation of the blades
• it is fundamental to the operation of all turbines
• it is predominantly a ‘near field’ feature
3a ‘Other’ Amplitude Modulation (OAM)

- at some sites, AM is apparent at residential distances (‘far field’)
- observed levels of 5 - 10 dB!
- despite it’s rarity, complaints have sometimes been vociferous and may reflect genuine nuisance
- potentially damaging to reputation of the wind industry, eroding public support and potentially reducing chances of planning success
- ‘other’ amplitude modulation - OAM
Key Points:
• noise shifts to lower frequencies
• the level of AM increases
• it is a ‘far-field’ feature
• unusual and still relatively rare
• often associated with night-time or stable atmospheric conditions
• why is this happening?
Key points of methodology:

- **measure** $L_{\text{Aeq,125 msec}}$
  - a) need rise, and subsequent fall, of $\geq 3$ dB within 2 sec period
  - b) a) must occur $\geq 5$ times in 1 min provided $L_{\text{Aeq,1 min}}$ is $\geq 28$ dB(A)
  - c) b) must occur $\geq 6$ times in 1 hour for AM to regarded as ‘greater than expected’

- **measure at affected residence**:
  - a) $\leq 35$ m from property
  - b) $\geq 3.5$ m any reflective surface
  - c) $\geq 1.2$ m of the ground.
• Analysis performed by Dr Lee Moroney & Dr John Constable of the Renewable Energy Foundation (REF)
• The Den Brook Amplitude Modulation Noise Condition - 1st November 2011
• http://www.ref.org.uk/publications/242-the-den-brook-amplitude-modulation-noise-condition

• Concluded that the methodology worked very well!
But:

- work proceeded with data containing obvious AM
- method clearly *is* good indicator of presence of AM
- implies low rate of ‘false negatives’
- not disputed!

- what of ‘false positives’?
3b - Amplitude Modulation - A Possible Identification Methodology?  

- test methodology with real-world data and assess performance
- background noise is character-free source

1. Turncole, Essex
   – 19 - 27 Aug 2011
   – 185 hours
2. Rotsea, Humberside
   – 20 - 27 Sep 2011
   – 169 hours
Application of AM Test Methodology:
Rotsea Wind Farm: 20 - 27 September 2011:
Total % of 1 hour periods failing test

- Pass: 67%
- Fail: 33%
• not good indicator of presence of AM
• 70 - 80% rate of ‘false positives’
• condition not specific to AM
• cannot be saved by filtering
• not fit for purpose!

• See Acoustics Bulletin article - Nov/Dec 2011 and errata in Jan/Feb 2012 Issue
• implemented the methodology and tested on the Turncole and Rotsea audio data
  – 144 out of 184 hours of data at Turncole breached condition: 78% FPs
  – 107 out of 167 hours of data at Rotsea breached the condition: 65% FPs

• also considered a second interpretation of Condition 20:
  – Rotsea results reduce from 65% to 38% FPs
  – Turncole results reduce from 78% to 49% FPs
  – interpretation likely to have bearing on the rate of false negatives!

“A method of robustly assessing and proving beyond reasonable doubt whether unacceptable “excess or other AM” is occurring is ultimately desirable; but Condition 20 doesn’t seem to meet this objective.”
“There is a real risk that enforcement of the condition is likely to fail.”
• developed own methodology
  – re-use elements of previous idea
  – use $L_{Aeq,125\text{ msec}}$ data in 1 min blocks
  – frequency based analysis - PSDs
  – looks at modulation at BPF
  – *may give insight into AM waveform?*

• tested on huge array of near- and far-field data to assess levels of AM
  – only 2 % > 3 dB peak to trough
  – average of exceedances is 3.7 dB

• seeking to incorporate in IEC 61400-11 Edition 4?

• shortly to release into public domain
3b - Amplitude Modulation - RES Methodology
in this example, the modulation frequency, $f_c$, is 0.5 Hz

the frequency window over which the 'raw' power spectrum needs to be integrated is 0.9 - 1.1 $f_c$, equal to 0.45 - 0.55 Hz, i.e. 0.1 Hz

as the frequency resolution is (1/64) Hz = 0.015625 Hz, this implies an integration window of 0.1/0.015625 frequency intervals, i.e. 6.4

rounding this up to the next nearest odd integer, gives 7 frequency intervals

the Green line on bottom figure has been generated by integrating the power spectrum using a moving average window of 7 frequency intervals, equivalent to ~ 0.1 Hz

this integrated value is then unit converted, as before, to convert to decibels - giving the Green Line
• in this example, the modulation frequency, $f_c$, is 0.8125 Hz

• the frequency window over which the 'raw' power spectrum needs to be integrated is 0.9 - 1.1 $f_c$, equal to 0.73125 - 0.89375 Hz, i.e. 0.1625 Hz

• as the frequency resolution is (1/64) Hz = 0.015625 Hz, this implies an integration window of 0.1625/0.015625 frequency intervals, i.e. 10.4

• rounding this up to the next nearest odd integer, gives 11 frequency intervals

• the Green line on bottom figure has been generated by integrating the power spectrum using a moving average window of 11 frequency intervals, equivalent to ~ 0.1 Hz

• this integrated value is then unit converted, as before, to convert to decibels - giving the Green Line
At least 4 possible theoretical explanations as to cause of OAM:

1. same explanation as for near-field AM, we just got something wrong!

2. turbulent eddy shedding - vortex streets & trailing edge serrations

3. blade tip stall due to high angles of attack

4. ‘flanging’ - possibly caused by stall-induced blade vibration

5. your idea?

Still don’t have definitive proof of the cause, making mitigation difficult!
3c THEORY 2 - Turbulent Eddy Shedding
• in periods of high wind shear the wind speed increases rapidly with height
• pitch setting appropriate for hub height, but too low for blade tip when at 12 am (TDC)
• stall may occur around the tip of the blade at TDC
• sudden increase in noise (~10 dB) until flow re-attaches
**Key Points:**

- ‘Other’ AM occurs because of blade stall
- main driver is high wind shear
- effect more significant on large machines
- increased low frequency content
- explains high levels of OAM in the far-field
3c  THEORY 3 - Analysis of SCADA Data - A Possible Diagnostic?
3c  THEORY 3 Sidebar - The Effect on Icing
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3c THEORY 3 - Working with Manufacturers To Investigate Mechanism

Acoustic camera measurements

Stall flag development
• if blade stall is the cause, then it’s not just AM which is a problem, but also cyclic blade loads and power performance!

• alternative blade design and geometries?

• alternative pitch control strategies (collective)?

• ‘cyclic’ pitch control, e.g. Mervento, GE (tbc)?

• working closely with a number of manufacturers, e.g. Siemens, Vestas, Repower, GE etc
3c THEORY 4 - Vibration Induced Flanging

- **What is 'flanging'?**

Flanging is an audio effect produced by mixing two identical signals together, with one signal delayed by a small and gradually changing period, usually smaller than 20 milliseconds. This produces a swept comb filter effect: peaks and notches are produced in the resultant frequency spectrum, related to each other in a linear harmonic series.

- Could this result from stall induced vibration?
4 OTHER FAR-FIELD NOISE FEATURES

- Infrasound LFN measurements - use C-weighting?
- Mention Australian measurement systems and results
- Specialist area
- Impulses:
  - Torsional energy/yaw brakes
• the best protection against far field acoustic features is a well written Turbine Supply Agreements (TSAs) with the manufacturer

• contents may differ so that some developers (residents?) have more or less protection than others?

• may explain why the noise problems at some projects sometimes seem to go unresolved?

• should the industry push for a ‘universal’ TSA, or at least a minimal common TSA?

• could this then be shared with local authorities and residents?