Seismic vibrations from wind turbines and their effects on the seismometer array at Eskdalemuir

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Purpose

- CTBT IMS seismometer array station, operating since 1962
- Eskdalemuir Working Group (cross-government/industry) - safeguard
- Can further wind farm development within 50km of the array be accommodated?
- Technical information to aid the Group with policy development

Outputs

- A physical understanding of how wind turbines generate seismic waves (seismic ground vibration “SGV”)
- Develop a model to predict the SGV produced by different wind turbines
- Initial study and further technical reports available from Scottish Government energy consents website

Styles study and 2005 model

- Recommendations agreed by Eskdalemuir Working Group in 2005
- Turbines generate low frequency seismic ground vibrations

- Threshold SGV rms 0.336nm
- Manage using a predictive model (#, MW, distance)
- Consultation zone of 50km radius
- 10km radius exclusion zone
- Predictive model based on,
  - 0.66 mega-watt turbine
  - 40m hub-height
- 2009/2010 threshold reached
- Debates on the planning merits of wind farm applications
- Mega-watt class turbines built in the consultation zone with 80-90m hub-heights
2011 Craig experiment:
Early results: multiple spectral peaks less than 4.5Hz

Threshold 1.5-4.5Hz
Data analysis: the initial study 2012-13

- **Testing of the analysis methodology**, 
  - Power Spectral Density (PSD) of seismic ground displacement 
  - Group PSD by wind speed interval (10 minute average) 
  - Robust statistics (inter-quartile mean) 

- Dun Law data, 5-7 October 2004 
  - 0.5Gb seismic data 
  - Three seismometers detected (2.4km, 1.4km, 5.3km) 

- Craig data, 16 May to 17 July 2011 
  - 32Gb seismic data 
  - Eight seismometers within 1.5km deployed
Craig 2011: AEG Site 5

AEG-Site-5: Bartlett PSD 10 min segment 50% overlap K=20.48s

PSD (mm²/Hz)

Frequency (Hz)

xbig-05-06-4x600sysok.sac
xbig-06-07-4x600sysok.sac
xbig-07-08-4x600sysok.sac
xbig-08-09-4x600sysok.sac
xbig-09-10-4x600sysok.sac
xbig-10-11-4x600sysok.sac
xbig-11-12-4x600sysok.sac
xbig-12-13-4x600sysok.sac
xbig-13-14-4x600sysok.sac
xbig-14-15-4x600sysok.sac
Initial study – Craig 2011 data

- Clear spectral peaks are identified at integer multiples of the blade-passing frequency (around 0.85Hz),
  - Diagnostic of seismic ground vibration (SGV) from operating wind turbines
  - Highest power peak is at a frequency around 1.7Hz (2\textsuperscript{nd} multiple)
  - Power at higher frequencies decreases with increasing multiples
- The frequency and power of each spectral peak increases with increasing wind speed
  - Suggests that the dominant far-field SGV from turbines is generated by the action of the turbine blades passing the tower, and \textbf{not} by excitation of structural resonance modes
  - \textbf{Assumes Nordex N80 turbines (2.5MW, 60m hub height) are typical}
Frequency-distance weighting ("hearing curve" for the array)

\[ \gamma^2(r) = \gamma_0^2 \int_{f_1}^{f_2} F(f) \, T(f, r_{\text{ref}}) \, P(f, r, r_{\text{ref}}) \, df \]

Mean-square SGV (integrated power) at the array,

- Reference single-turbine source-term power spectrum
- Source-term frequency weighting
- Propagation term (frequency-distance weighting)
Source-term power spectrum

- Two sites with the highest signal-to-noise
- Wind speed 11-12m/s
  - Clear SGV peaks
  - Approaching rated-power
- All four 2.5MW turbines are operating
- Direction effect – modelling predicts SGV strongest downwind
- Source of small peak around 2.15Hz – indicated by the blue arrow?
Source-term frequency weighting

- Based on optimal signal detector theory
- Physical properties of signal and noise at the array
- Weak dependence on noise with wind speed
- “Calibrated” to the 1.5-4.5Hz passband used to determine the 0.336nm threshold
Propagation term (frequency-distance weighting)

- Same parameters as in the 2005 model
- Reference distance 1km shown
- \[\text{dB} = 10 \log_{10}(\text{SGV power})\]
Effective SGV power spectrum at the array

- Curves shown are frequency-distance weighted power spectra for AEG-5 when all four turbines are operating.
- Area under each curve is the integrated power (Gamma-square).
- Square-root of Gamma-square is the rms SGV for all four 2.5MW turbines operating.
Initial study: results

- All four 2.5MW turbines at Craig operating
- Initial results indicate apparent “headroom”, but this is distance dependent and assumes a Nordex N80 turbine (at Craig) is representative of turbines in the consultation zone
- Initial study calculations have been verified by a consultant contracted by the Eskdalemuir Working Group (Xi Engineering)
- Further substantial work,
  - Consider direction and/or site effects (e.g., seismometer on a steep slope)
  - Turbine blade size may be important (slower rotation rates?)
- Substantive research to quantify any “headroom”
Substantive research (Xi Engineering, 2014)

- In-depth analysis of,
  - 2004 Dun Law (0.66MW, hub height 40m, rotor diameter 47m)
  - 2011 Craig (2.5MW, hub height 60m, rotor diameter 80m)
  - 2013 Clyde (2.3MW, hub height 78.3m, rotor diameter 93m)

- Far-field and turbine base (foundation) data
- Turbine rotation (rpm) data
- Wind direction effect
- Scaling assuming conservation of energy
- “Worst-Case Turbine” model
Craig AEG-5: predicted blade-pass multiples from rpm data (Xi 2014)
Craig: turbine base PSD differs from far-field PSD (Xi 2014)
Xi (2014)

- Clyde wind farm
- 152 turbines
- 2.3MW Siemens
- Hub height 78.3m
- Rotor diameter 93m
- 14 June to 10 July 2013
- Clyde rpm data
- Turbine base PSD differs from far-field PSD
- 2.8Hz peak does not match blade-pass multiple
Comparison of cross-wind and in-line (Xi 2014)
Comparison of N80 and S2.3MW PSDs (corrected to single turbine at 1km)

[Graph showing comparison of N80 and S2.3MW PSDs for a single turbine at 1km in 12m/s wind]
Scaling using conservation of energy hypothesis

- If the proportion of the available kinetic energy that partitions into seismic energy is independent of the wind speed and swept area then,

\[ \int_{t} u(t)^2 \, dt \propto v_w(t)^3 A_w. \]

- Following Parseval’s theorem,

\[ S_w(f) = S_{WCT}(f) \left( \frac{v_w}{v_{ref}} \right)^3 \frac{A_w}{A_{ref}}. \]

- The wind speed at different hub heights (wind shear) is,

\[ v_w = v_{ref} \frac{\log(z_w/z_0)}{\log(z_{ref}/z_0)}, \quad \text{if } z > z_0, \]
Testing the energy scaling hypothesis (Xi 2014)
“Worst-Case Turbine” model spectrum

- Three parts,
  - Broadband (from Craig shutdown experiments)
  - Blade-pass multiples (median blade tip speed 77.5 m/s)
  - Structural resonance

- Scaled by,
  - Swept area
  - Hub height wind speed relative to a reference of 12 m/s at a height of 80 m
Revised safeguarding model

- Physics based prediction of seismic ground vibration from a wind turbine depends on,
  - Distance from the cross-over point of the Eskdalemuir array
  - Hub height of the turbine
  - Rotor diameter of the turbine

- All parameters are required as part of existing wind farm planning consultation requirements of the UK safeguarding authority

- Exclusion zone extended to 15km to guard against sterilisation of headroom by a few close-in wind farms

- Worse Case Turbine model valid for upwind three-bladed turbines, adopt a precautionary approach,
  - In practice minimum hub height of 40m assumed
  - Applied to downwind turbines (including two-blade systems)

- Endorsed by the Eskdalemuir Working Group on 28 April 2014

- Further wind farm development permitted in the consultation zone until 90% of threshold reached, then undertake a future review of the arrangements
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