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Monitoring and Mitigation of Low Frequency Noise from Wind Turbines to Protect Comprehensive Test Ban Seismic Monitoring Stations

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Abstract

The first work which described the harmonic tonal nature of vibrations from windfarms was carried out at St Breock's Down, Cornwall, UK and is described in Legerton et al (1996) and more fully in Snow, and Styles (1997). This has since raised concerns about the possible effect of wind farms on sensitive installations. Styles et al (2005) describe an extensive monitoring programme to characterise the low frequency vibration spectra produced by wind turbines of various types, both fixed and variable speed. They demonstrated that small but significant harmonic vibrations controlled by the modal vibrations of the towers and excited by blade passing, tower braking and wind loading while parked, can propagate tens of kilometres and be detected on broadband seismometers. This meant that protective measures had to be implemented to protect the International Monitoring System (IMS) seismic monitoring station located at Eskdalemuir in the Scottish Borders, the UK's contribution to the Comprehensive Test Ban Treaty (CTBT) verification regime which must be observed by international treaty. Over 2 GW of wind turbines were planned for this region and planning restrictions were imposed to control development because of the potential effects on the IMS station. Styles et al (2005) established that vibrations of concern in the 2 to 6 Hz band, while small, were critical for this monitoring. Propagation laws and an aggregate vibration budget were derived and calculated to aid planning and permit appropriate wind farm development. With increasing pressure to reduce carbon emissions through renewable energy contributions in the UK and especially Scotland, the budget has now been reached, with at least 2.5 GW of new wind developments are still in scoping and planning. It is

therefore necessary to find a method to reduce the vibrations from new and existing farms to achieve headroom for new developments.

Reactec Ltd in conjunction, have developed a Seismically Quiet Tower (SQT) system which can be retro-fitted or installed during construction. This can significantly attenuate the vibrations produced and delivered to the ground in the frequency band deleterious to the discrimination capability of the Eskdalemuir station. The SQT can, and is planned to, be fitted to existing close-in wind turbines to reduce their contribution to the vibration budget and potentially release budget for new development elsewhere in the 50 km zone of concern around Eskdalemuir. Keele University have carried out a programme of modelling and seismic monitoring of this system and have confirmed that it does significantly reduce the vibration spectrum in the region of 2 to 6 Hz which has the added benefit of reducing many fatigue loads on the turbine tower itself.

1. Introduction

In order to meet, and in fact exceed, Kyoto targets, the UK government has set the challenge of reducing the UK's carbon dioxide emissions by 60% by 2050. The development of renewable energy, especially wind power, will be an important contributor to the outcome of that policy with a target of 15% of UK energy from renewable sources by 2020. The Scottish Executive has decided that Scotland should aspire to generate 80% of its energy from renewable sources by 2020.

The Southern Uplands of Scotland offer a prime wind resource because of the large region of high topography, appropriate wind conditions, the proximity to the large urban centres of Glasgow and Edinburgh and the main national grid connections between Scotland and England. In excess of 2 GW of onshore wind generation capacity is planned for the Southern Uplands.

However, the United Kingdom seismic monitoring site, which is a component of the International Monitoring System (IMS) for the Comprehensive Nuclear-Test Ban Treaty (CBTB), is situated at Eskdalemuir near Langholm in the Scottish Borders. This is a very low noise vibration site located in the centre of this wind resource region. Concern was expressed by statutory consultees that vibration from wind farm developments might prejudice the detection capability of this facility. The Eskdalemuir Seismic Array is one of 170 IMS seismic stations across the globe used to monitor compliance with the CTBT. The UK is bound by the Treaty not to compromise the detection capabilities of the Eskdalemuir station, and it is the responsibility of the Ministry of Defence (MoD) to safeguard this station.

The MoD therefore initially placed a precautionary blanket objection to any wind farm developments within 80 km of Eskdalemuir in case this compromised UK capability to detect distant nuclear tests and breached the UK’s agreement under the CTBT. This effectively removed at least 40% of the UK renewable on-shore wind resource identified by the then Department of Trade and Industry (DTI).

In 2004, the “Eskdalemuir Working Group” (EWG) was formed and commissioned research carried out by the Applied and Environmental Geophysics Group led by Professor Peter Styles at Keele University to establish the nature of interference from wind turbines on the Eskdalemuir station. This detailed study was funded by MoD, the DTI and the British Wind Energy Association (BWEA, now known as RenewableUK), who mandated research into the levels of vibration and infrasonic noise which might be generated by fixed and variable speed turbine wind farms. A ten station broadband seismic network and a four station infrasound network were established for a six month period at distances out to more than 20 km from a 26 fixed-speed turbine (Vestas V47) wind farm at Dun Law. This wind farm is situated on very similar geology and topography to Eskdalemuir and the planned wind farm developments in the Southern Uplands. The study permitted the identification of the principal propagation mode for ground vibrations from wind turbines and enabled their characterisation.

In 2005 the study concluded that micro-seismic noise is propagated through the ground from wind turbine structures, as the rotation of the blades excite modes of vibration of the tower, which in turn resonate at the detection frequencies of the seismic array especially in the 4 to 5 Hz band generated by the strongly excited second bending modes of the tower and are strongly coupled into the ground.

The principal conclusions were as follows:

- Wind turbines generate low frequency vibrations which are multiples of blade passing frequencies and can be detected on seismometers buried in the ground many kilometres away from wind farms, even in the presence of significant levels of background seismic noise.
- Energy from wind turbines travels to the seismometers as seismic surface waves with cylindrical spreading. Co-located, coincident seismic and infrasound records show that infrasound energy propagation is optimal in quiet wind conditions and decreases as the wind speed (and turbulence) increase while, conversely, the observed seismic amplitude increases with wind speed. Clearly, there cannot be a causal relationship between the seismic amplitude and the infrasound if they have different behaviours with wind speed.
- At that time (2005) there were no current, routinely implemented vibration mitigation technological solutions which could reduce the vibration from wind turbines. Technologies which were helpful in the reduction of vibration from mechanical systems did exist and in the long-term and at some additional cost it should be possible for manufacturers to modify/augment these for application to wind turbines to reduce the levels of vibration transmitted into the ground. However, the recommendations were based on current turbine designs as built at that time.

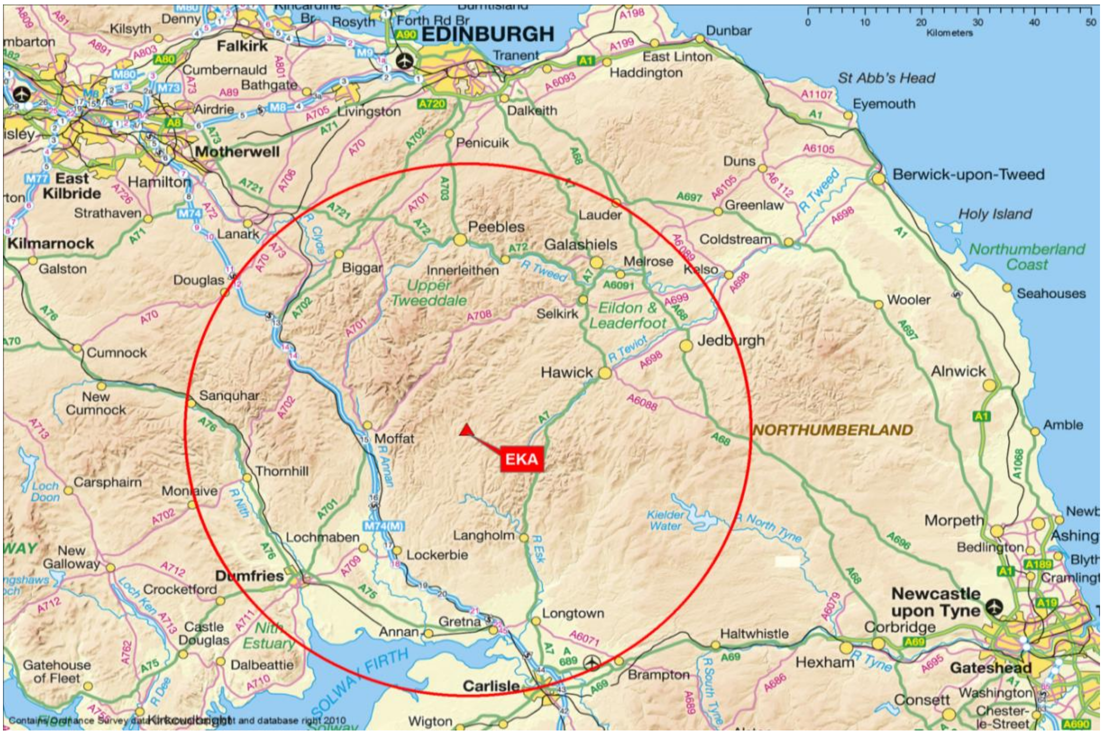
The results of the research allowed the development of a predictive model for the aggregate vibration contribution from any planned distribution of wind turbines for comparison with ambient vibration levels as presently experienced at Eskdalemuir. Under contract with MoD, the Atomic Weapons Establishment (AWE) is responsible for operating and maintaining the Eskdalemuir station. AWE recommended to the EWG a maximum permissible background noise increase at Eskdalemuir due to wind turbines (a noise budget) of 0.336nm at Eskdalemuir, this was agreed by the group, and was presented to Working Group B of the CTBT Organisation in Vienna during the second half of 2005. By carefully considering the present ambient background noise experienced at the monitoring site it was possible to set a noise budget permissible at Eskdalemuir without compromising its detection capabilities, and we have demonstrated that at least 1.6 GW of planned capacity can be installed and have developed software tools which allow the MoD and planners to assess what further capacity can be developed against criteria established by this study.

On the basis of the results of the commissioned research and the calculated noise budget, the EWG recommended that MoD should introduce a statutory consultation zone of 50km around Eskdalemuir, but made no recommendation on implementation, which is a policy matter for the UK Government. The MoD permitted development on a first come first served basis as projects entered the planning system, until this noise budget was reached. As a result of this study, planning guidance was given to the Scottish Executive, the MoD and local planning officers to protect the functionality of this important facility whilst optimising wind energy resource exploitation in the Southern Uplands of Scotland. It seems that wind farm developments, either permitted or currently being considered in the planning system have now consumed much, if not all, of the calculated noise budget.

At the time of the EWG commissioned study into the effects of wind turbines on Eskdalemuir, no technical solution was available to address the noise generation of wind turbines. It was postulated that it could be possible to reduce turbine ground vibration by mechanical damping. Additionally the study concentrated on the fixed-speed machines which were predominant at that time, while larger turbines with variable speed are now becoming more and more prominent.

With increased pressure to deploy sources of renewable energy generation, especially wind farms and as the noise budget limit is rapidly approaching, it is important to refine the analysis in order to explore whether changes in turbine design and new developments in damping technologies have significance for planning and permission of future wind farm applications.

Little additional work has been done internationally since that published by the Keele Group in Ledgerton et al (1996), Styles et al. (2005), and Schofield (2000), but Fiori et al (2009) report work which they carried out in 2005 in connection with the gravitational wave detector GEO-600 in Hannover FRG and independently confirm many of the conclusions of the report of Styles et al. (2005). Their site was much noisier than Eskdalemuir as can be seen from figure 3 as compared to the extremely low level ambient noise in the Eskdalemuir region of the Scottish Southern Uplands which approaches the Peterson Low Noise Model (Peterson 1993). Fiori et al. (2009) also assume that most of the propagation takes place in highly attenuating soil layers, which is unlikely to be the case for surface waves (of both Rayleigh and Love modes) propagating in the Southern Uplands (Macbeth & Burton 1987). At frequencies of 1-10 Hz surface waves travel at around 2000ms^{-1} with corresponding wavelengths of 200m to 2km and sample the earth to comparable or greater depths.



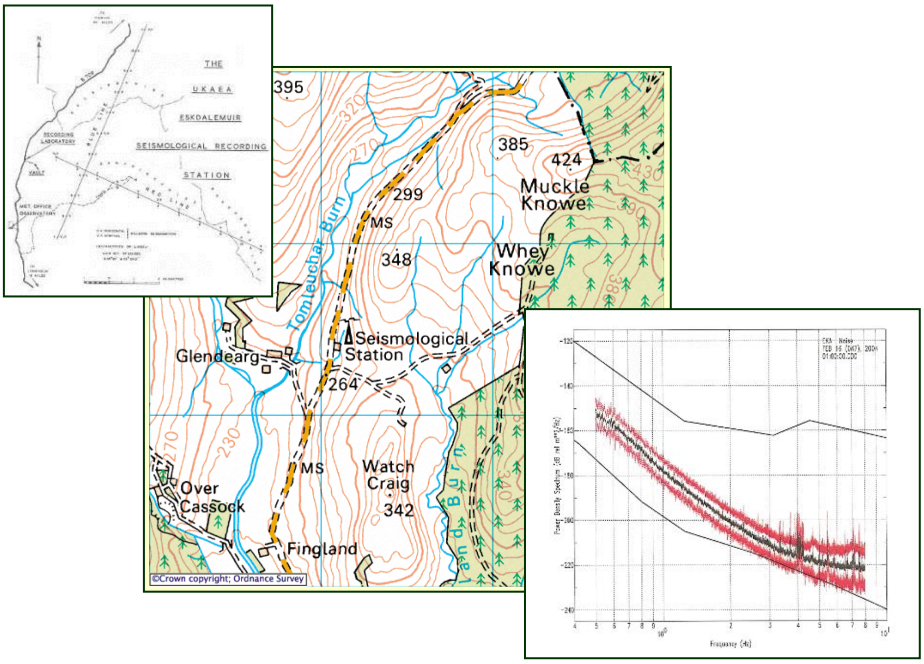


Figure 2. The Eskdalemuir Site and its noise spectrum which closely approaches the Low Noise Model of Peterson (1993).

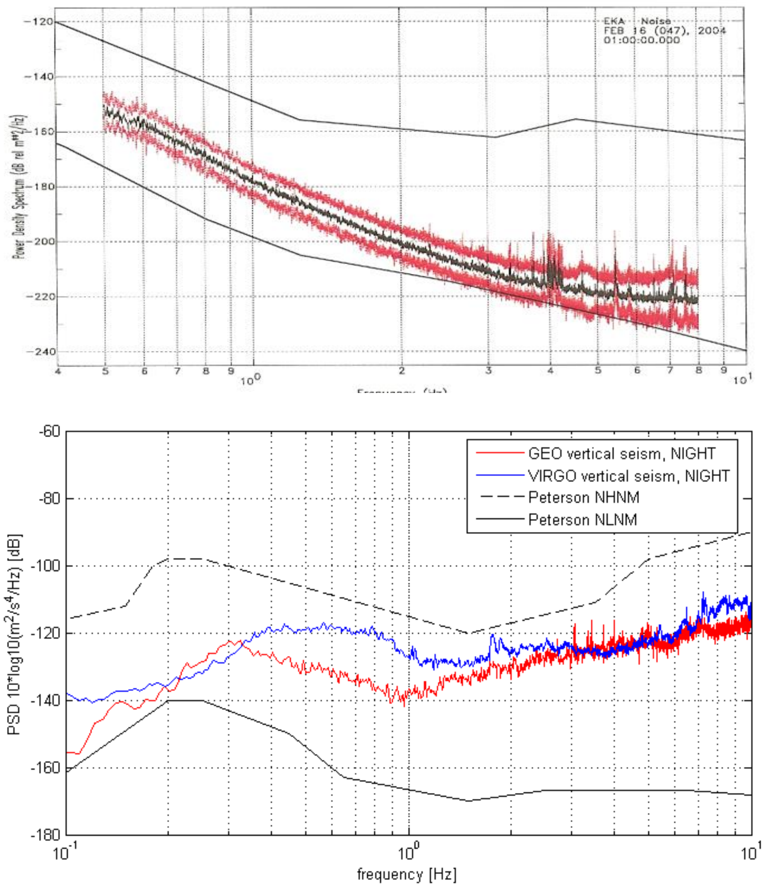
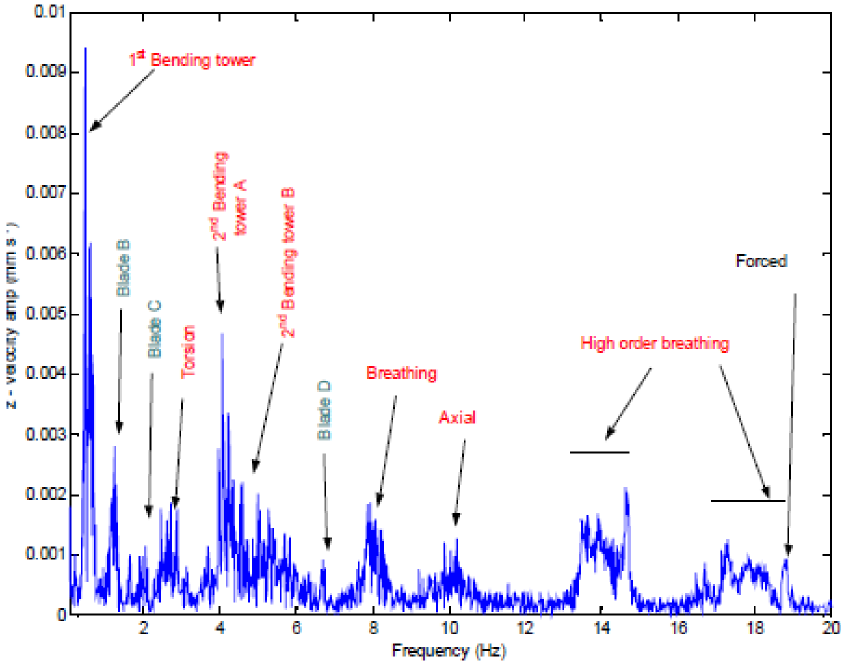


Figure 3. Vibrational noise spectra observed by Fiori et al at the GEO600 site near Hannover (lower) and at the VIRGO site in Italy as compared to the spectra observed at Eskdalemuir (upper).

2. Vibration Mitigation Measures

As a possible solution to the issues which were raised in our final report (Styles et al., 2005) about the limitations of current turbine design, Reactec, a company that specialise in the reduction of vibration in commercial applications, developed a solution that will reduce ground vibration produced by wind turbines and can be either retrofitted or installed at the time of construction. The Reactec solution is intended to initially increase the remaining available budget by significantly reducing the ground vibration produced by the Craig Wind farm, which is the site closest to the Eskdalemuir array.

Craig Wind Farm, near Carlesgill farm, is about 20 km from the Eskdalemuir array and consists of four 2.5 MW Nordex N80 wind turbines with an additional turbine consented at the site. A further three wind farms planned between 20 and 24 km from the Eskdalemuir array, are being considered. The Reactec solution focuses on reducing the ground waves in the 4-5 Hz band, shown to be strong from analysis of data from a N80 turbine at Crystal Rig.This would allow the important wind energy potential of the area to be exploited without adversely affecting the detection capability of the Eskdalemuir Seismic array. Figure 4 show the results of monitoring a turbine tower at Crystal Rig, near Longformacus in Southern Scotland. The monitoring was used to determine the fundamental modes of vibration of a NORDEX N80 machine, along with a structural interpretation based on subsequent modelling results. A Tuned Mass Damper (TMD) system was designed to reduce the power in the two second bending moments. It is effective at damping both the 4.1 Hz mode related to the 2nd bending mode A and the 4.6 Hz mode related to the 2nd bending mode B both of which are particularly problematic for nuclear test monitoring at Eskdalemuir.



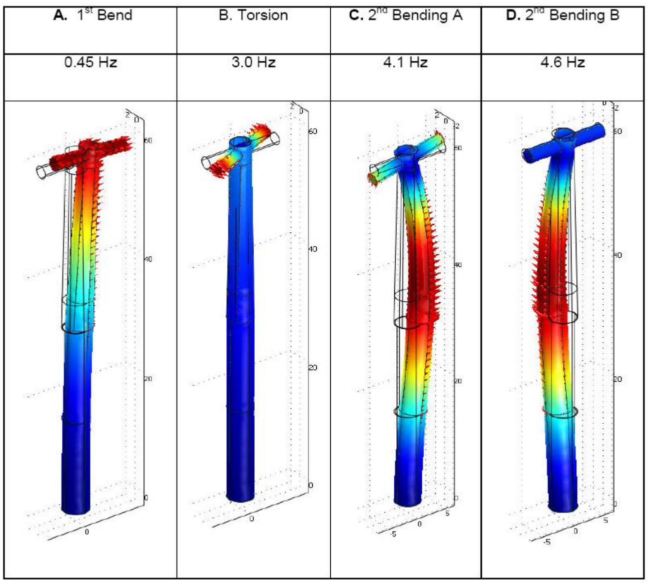


Figure 4. Frequency response based on FFT and eigenfrequency analysis of vibrations measured at the base of Tower 5 at Crystal Rig on a Nordex N80 wind turbine.

3. Validation of the Damping system at Craig Wind Farm

Instrumentation was deployed at Craig in November 2007 to monitor the effectiveness of the damping system. A Güralp CMG 6-TD seismometer was installed in the ground at a distance of 1.1 km from the turbine in the manner described fully in Styles et al. (2005).The CMG-6TD is a lightweight three-component seismometer. It contains an on board digitiser and has low power consumption, enabling it to be powered off a single 12v car battery for a month. It is ideally suited to medium-noise sites. A set of six Güralp accelerometers were installed in Turbine 1.. The uniaxial accelerometers are Güralp CMG-5U devices and can be situated either horizontally or vertically, recording in a single direction only. These do not contain onboard digitisers but are connected to a separate seismic data acquisition system, the Güralp CMG-DM24S12AMS. This 'black box' allows up to twelve uniaxial accelerometers and six 5TDs to be connected simultaneously.

Data were obtained for two days to establish the spectra and vibration levels especially in the 4 to 5 Hz band for the turbines before any damping mechanism was installed. Figure 6 shows the spectrogram for an hour of data for an undamped turbine, while Figure 7 shows the power spectra for North and Vertical components again for an undamped turbine. The power in the 4 to 5 Hz band is clearly strongest exceeding the power in the lower frequencies. As wind speed and conditions obviously vary continuously it is necessary to normalise the spectra associated with the second bending mode(s), which lie at c 4-5 Hz. For a preliminary assessment this has been done by using the peak acceleration power of the first low-frequency peak, corresponding to the first bending mode of the tower, which lies at c 0.45 Hz (Figures 3 and 4). This is shown in Figure 8 – note that the ratio varies, but the mean is around unity

Figure 5. Installation of Güralp CMG-5U uniaxial accelerometers in Turbine 1.

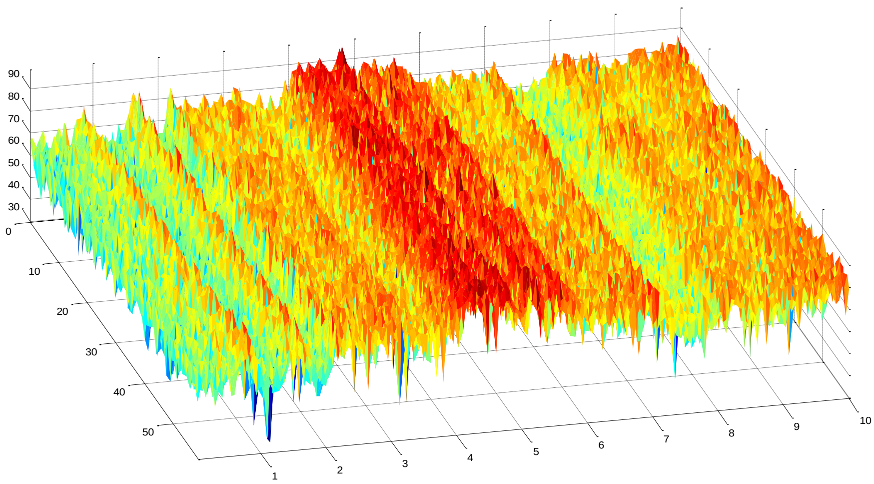


Figure 6. Spectrogram (Upper Waterfall Plot) from Turbine 1 with accelerometers installed on the base and inside the turbine structure, on the 7th November 2007 between 2300 hours and midnight on the North-South accelerometer (Ch1), showing the main spectral bands between 4 to 6 Hz for an undamped turbine.

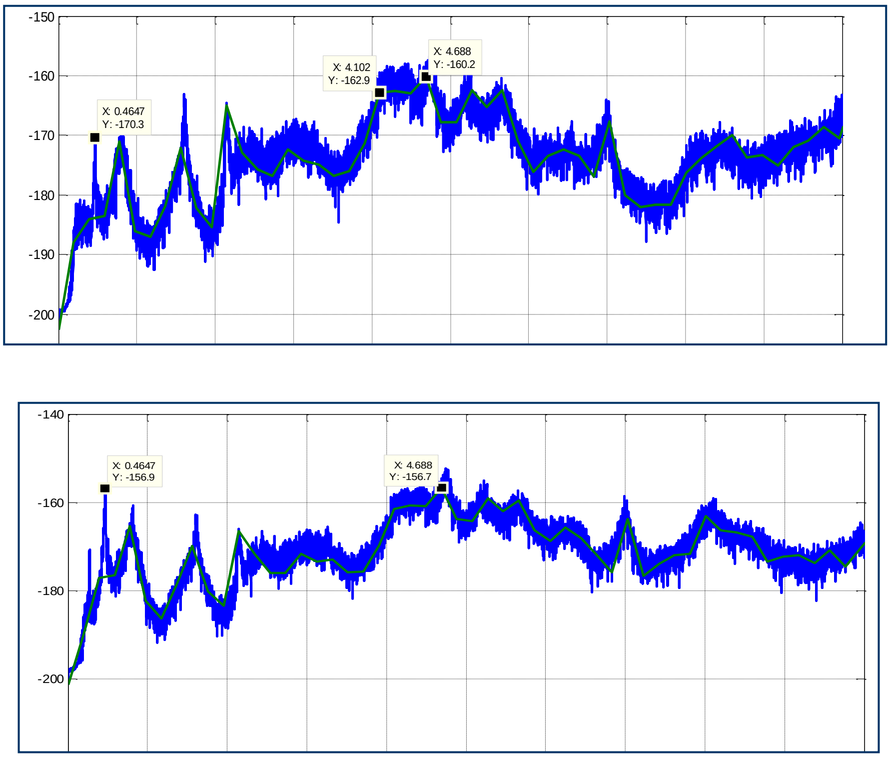
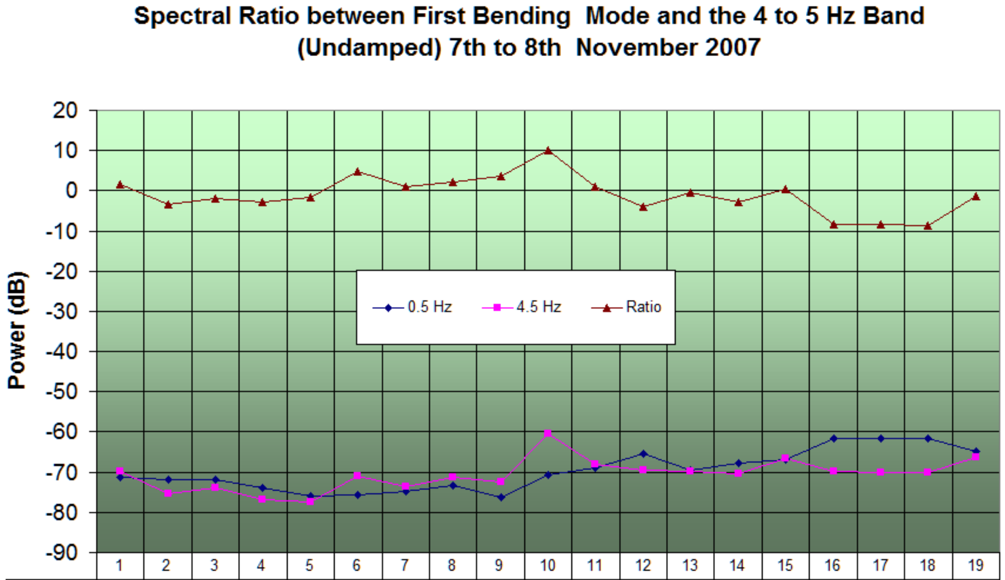


Figure 7. Power Spectrum for Turbine 1 on the 7 November 2007 2300 Ch1 (N component Upper and Vertical Component Lower)) showing power in various peaks for an undamped turbine.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
0.5 Hz	-71.15	-71.79	-71.86	-73.87	-75.92	-75.8	-74.74	-73.26	-76.17	-70.56	-69.08	-65.5	-69.52	-67.66	-66.92	-61.58	-61.5	-61.52	-64.91
4.5 Hz	-69.67	-75.28	-73.82	-76.73	-77.53	-71.08	-73.73	-71.23	-72.44	-60.45	-68.1	-69.57	-69.93	-70.41	-66.66	-69.87	-70	-70.07	-66.3
Ratio	1.48	-3.49	-1.96	-2.86	-1.61	4.72	1.01	2.03	3.73	10.11	0.98	-4.07	-0.41	-2.75	0.26	-8.29	-8.5	-8.55	-1.39

Figure 8. Spectral Ratio between the First and Second Bending Modes for Ch1, the North-South component

4. Monitoring of tower vibrations after installation of the TMD system

The Tuned Mass Damping System designed by REACTEC was installed in Turbine 1 and the data acquisition and interpretation repeated for the damped tower in June 2008. The reduction in the power in the 4 to 5 Hz band is clear in the spectrum and spectrogram in Figure 9 where the power in the 4 to 5 Hz band is now clearly equal or less than the fundamental mode at c 0.5 Hz.

An assessment of the damping factor was made using the peak of the acceleration power spectra corresponding to the first and second bending moments. This assumes that the addition of the TMD does not affect the response of the first bending mode which seems reasonable (at least to first order), based on results of comparing velocity spectra from the base of a damped turbine at Craig (Turbine 1) and from the base of a nearby undamped turbine (Turbine 3).

The damping appears to be most effective when the noise is highest which is almost certainly when the wind is strongest. The Tuned Mass Damping System has produced a 7 to 8 dB damping (and higher for certain conditions) compared to measurements recorded before damping.

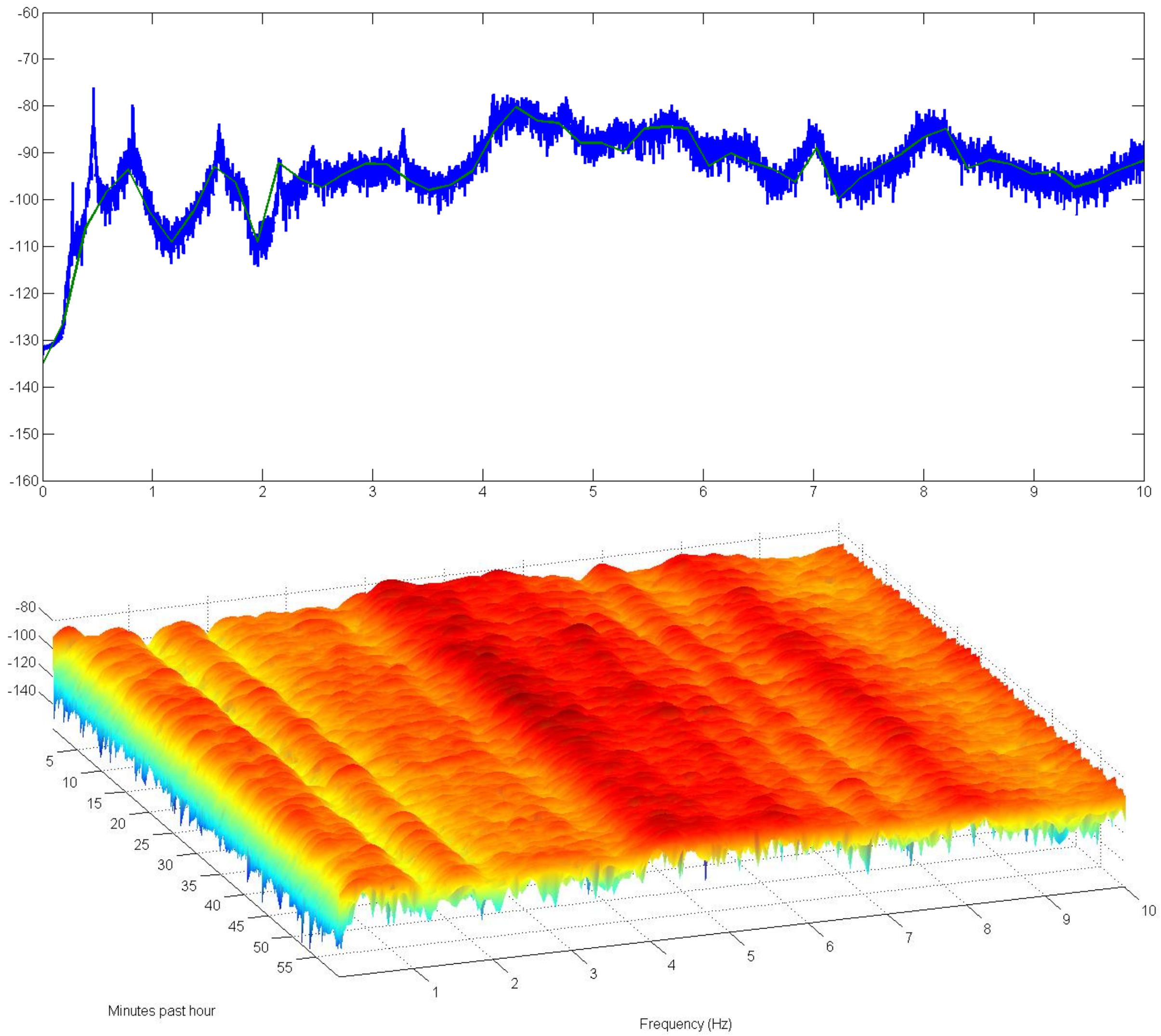
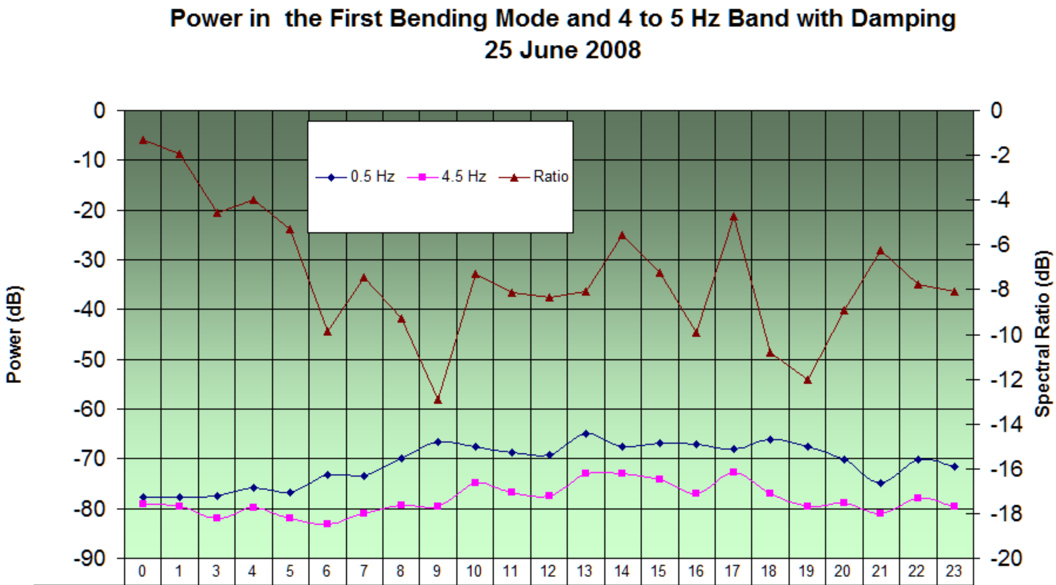


Figure 9. Spectrum and spectrogram for 2300 on 25 June 2008 for Channel 3 (E-W)



	0	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0.5 Hz	-78	-78	-77	-76	-77	-73	-74	-70	-67	-68	-69	-69	-65	-67	-67	-67	-68	-66	-68	-70	-75	-70	-72
4.5 Hz	-79	-80	-82	-80	-82	-83	-81	-79	-80	-75	-77	-78	-73	-73	-74	-77	-73	-77	-80	-79	-81	-78	-80
Ratio	-1.3	-1.9	-4.6	-4	-5.3	-9.9	-7.5	-9.3	-13	-7.3	-8.2	-8.3	-8.1	-5.6	-7.3	-9.9	-4.7	-11	-12	-8.9	-6.3	-7.8	-8.1

Figure 10. The damping ratio between the First Bending and Second Bending Models on the 25th June 2008 after the final installation of the TMD system

5. Conclusions

Microseismic and vibration monitoring of Craig Windfarm in the Southern Uplands of Scotland (Turbine 1) has been carried out over three periods from November 2007 until July 2008. It appears from these measurements that the TMD has reduced the power in the band between 4 to 6 Hz which is of critical concern to the ability of the Eskdalemuir array to detect Clandestine (or Overt!) nuclear explosions. The monitoring data demonstrate that the TMD installation has clearly attenuated the power in the 4 to 5 Hz Band (Second Bending Modes) normalised by the fundamental mode (First Bending Mode) (0.46 Hz) over a long period of monitoring by 7 to 8 dB (relative to data collected in November 2007 when no damping was present).

This has several implications; the reduction in vibration at these critical normal modes is clearly advantageous in reducing wear and tear on the tower and reducing maintenance costs.

More importantly, for this situation, a reduction in power in these bands means that it should be possible to install a greater generating capacity of wind power in this protected area without compromising the detection capabilities of the Eskdalemuir International Monitoring System station of the Comprehensive Test Ban Treaty.

This technology also has the potential for application wherever there are potential problems of wind farm turbines generating frequencies and/or amplitudes which might be problematic for critical installations such as Laser Interferometric

Gravitational Observatory (LIGO), the Large Hadron Collider (LHC) at CERN and the Battelle Gravitational Observatory in the US.

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