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Ground Vibration, Infrasound and Low Frequency Noise Measurements from a Modern Wind Turbine

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Summary
Potential ground vibration and infrasound are concerns often raised at wind farm consent hearings in New Zealand. These concerns are usually addressed using international studies that show the levels from wind turbines to be lower than the thresholds of audibility or perception. This, in turn, raises questions in relation to the age and size of the wind turbines used in those studies and whether they are representative. This paper summarises the results of both ground vibration and infrasound measurements undertaken at Meridian's West Wind wind farm near Wellington in New Zealand. The wind farm comprises 62 Siemens SWT2.3-82VS machines and the measurements were undertaken in 2010.

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1. Introduction

This paper summarises measurements of ground vibration, infrasound and low frequency noise levels monitored at West Wind. The measurements were conducted separately but are being reported here to give a complete set of results. The ground vibration measurements were undertaken using two seismometers, one placed close to an operational turbine the second at more than 2 km from the closest wind turbine. Measurements included a period when the entire wind farm was shut down and again when the closest turbine was shut down in a range of different wind speed conditions. Analysis of the ground vibration data has considered periods when the turbine was running at full rated power (high power output) and again when the turbine was generating in low wind speed conditions (low power output). The results of these two different operational cases have been presented here. The infrasound and low frequency noise measurements were undertaken during a sound power level measurement of a turbine and were undertaken at a distance of about 100 m from the wind turbine. Those measurements included some periods with the turbine shut down to determine the background levels. The turbine was operating at 2300 kW during these tests in a wind speed of 13.7 m/s.

2. The wind farm site

The wind farm is located approximately 8 km west of Wellington. The 62 wind turbines are sited in complex terrain and the site is adjacent to the coast on the western and southern sides. The location of the wind farm in Wellington is shown in Figure 1 and the wind turbine layout is shown in Figure 2. The turbine close to which ground vibration measurements were undertaken is turbine number WWD106 on the eastern side of the wind farm and that is identified in Figure 2. Infrasound and low frequency noise measurements were undertaken on an adjacent turbine, number WWD104 and that location is also shown in Figure 2.

3. Ground vibration measurements

Two seismometers were installed by GNS Science, the organisation which operates the seismic monitoring network in New Zealand. The seismometers were Lennarts LE-3Dlite and sampled at 100 Hz. Data was stored in a Taurus logger. One seismometer was located 92 m from turbine WWD106. The second seismometer was placed in the valley to the east of the wind farm at a location 2.1 km away from the closest wind turbine (WWD101). Both seismometers were tri-axial devices however only the vertical component has been presented here as they showed the highest vibration levels.

Turbine WWD106 was configured to shut down for an hour at midnight during the period of the ground vibration testing. This allowed the difference between the levels with this single turbine on and off to be measured in a range of different wind conditions. Furthermore, during one afternoon of the ground vibration testing (12 December 2010), the entire wind farm was shut down due to work being undertaken on the wind farm sub-station. This shut-

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Figure 1. Location of West Wind wind farm.

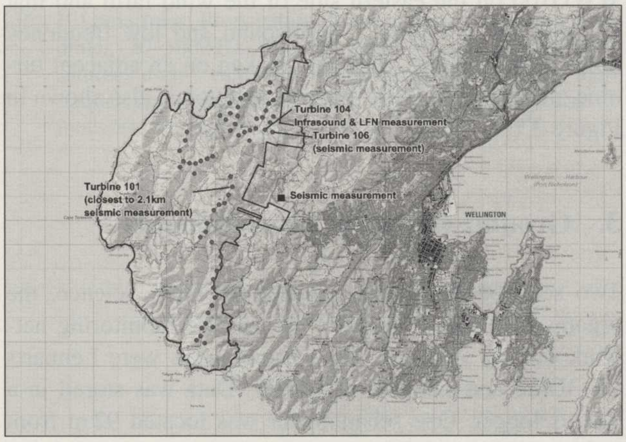

Figure 2. Location of wind turbines and measurements.

down period allowed baseline measurements to be made in the absence of any operational turbines.

Photographs of the two seismometers and their locations are shown in Figures 3 to 6.

4. Ground vibration results

Wind speed and electrical power data for the period 30 November to 20 December 2010, the duration of the ground vibration measurements were plotted. Periods when turbine WWD106 was operational between

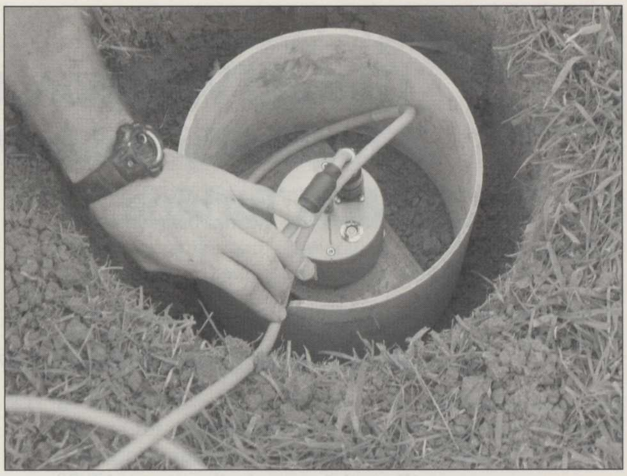

Figure 3. Seismometer 92 m from turbine WWD106.

Figure 4. Turbine WWD106 and seismometer location, 92 m from the turbine.

Figure 5. Seismometer 2.1 km from wind farm.

1500 kW and 2300 kW before and after midnight were identified. The two periods identified as the most suitable for analysis of high power output were the night of the 5–6 December and the night of the 17–18 December. These periods showed relatively consistent and high wind speeds

Figure 6. Seismometer location 2.1 km from wind farm.

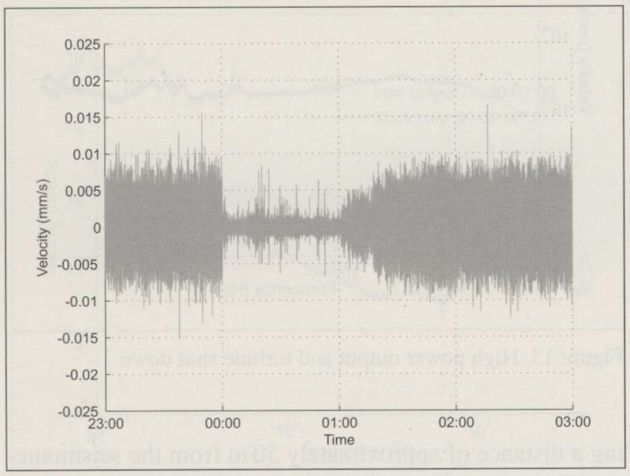

Figure 7. High power output including shutdown.

before, after and during the turbine shut-down. A period of low power output was identified on the night of 14–15 December. During the day of 12 December 2010 the entire wind farm was shut down for a period and this enabled vibration levels to be recorded in the absence of any turbines operating. It was these four discrete events or periods which were analysed further and presented in this paper. The details of the turbine wind speed and electrical power output during each of the four events identified for analysis are listed in Table I.

The time series plots of the ground vibration levels for each of these four events are shown in Figures 7 to 10. Each of those plots shows the ground vibration levels in mm/s, measured close to the turbine over a four hour period. The turbine shut-down (00h00 to 01h00) is clearly seen in the two high wind speed measurements shown in Figures 7 and 8. The low wind speed measurement shown in Figure 9 also includes a turbine shut-down, however, this is not quite as obvious from visual observation.

In order to obtain some everyday comparative ground vibration levels a few on-site tests were undertaken in close proximity to the ground vibration sensor close to turbine WWD106. Turbine WWD106 was shut-down during

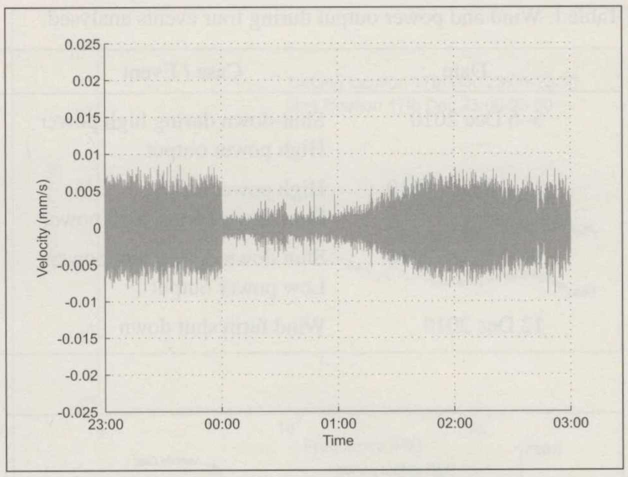

Figure 8. High power output including shutdown.

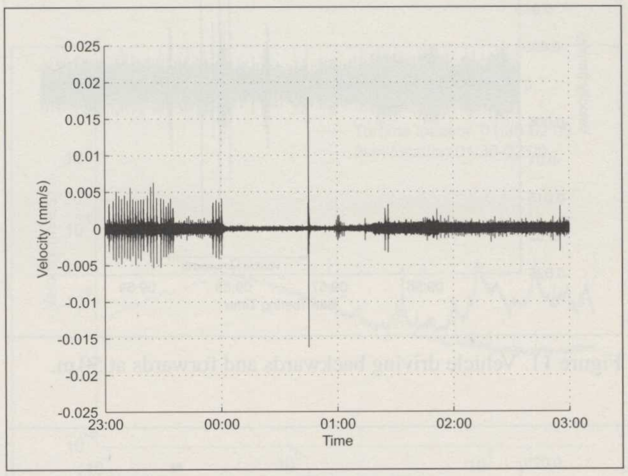

Figure 9. Low power output including shut down.

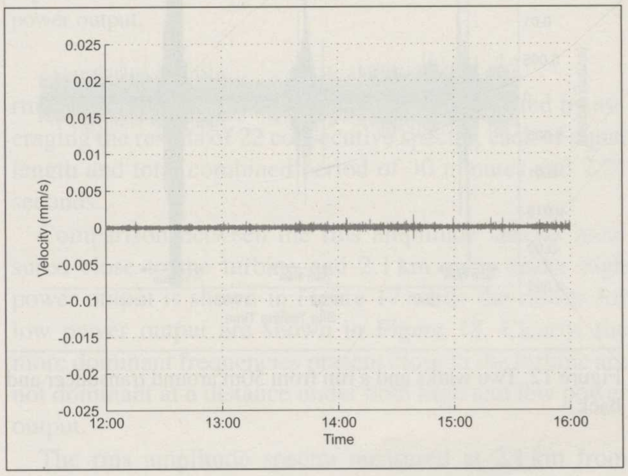

Figure 10. Entire wind farm shut down.

these tests. The on-site tests included a vehicle been driven at 50 m away from the transducer and people walking and running from 50 m, around the seismometer and returning to the 50 m starting point.

The results of these on-site tests have been overlaid with representative measurement data with the turbine operat-

Table I. Wind and power output during four events analysed.

Date	Case / Event	Time	Wind Speed (m/s)	Power (kW)
5–6 Dec 2010	Shut-down during high power	00h20 to 00h50	12.4 m/s	Shut down
	High power output	01h30 to 02h00	12.6 m/s	2119 kW
17–18 Dec 2010	High power output	23h00 to 23h30	10.5 m/s	1663 kW
	Shut down during high power	00h20 to 00h50	12.5 m/s	Shut down
14–15 Dec 2010	Shut down during low power	00h00 to 00h30	4.2 m/s	Shut down
	Low power output	01h30 to 02h00	5.1 m/s	91 kW
12 Dec 2010	Wind farm shut down	14h00 to 14h30	6.0 m/s	Shut down

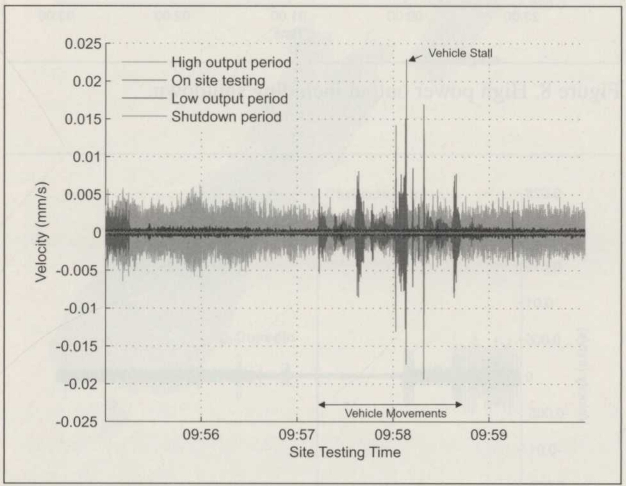

Figure 11. Vehicle driving backwards and forwards at 50 m.

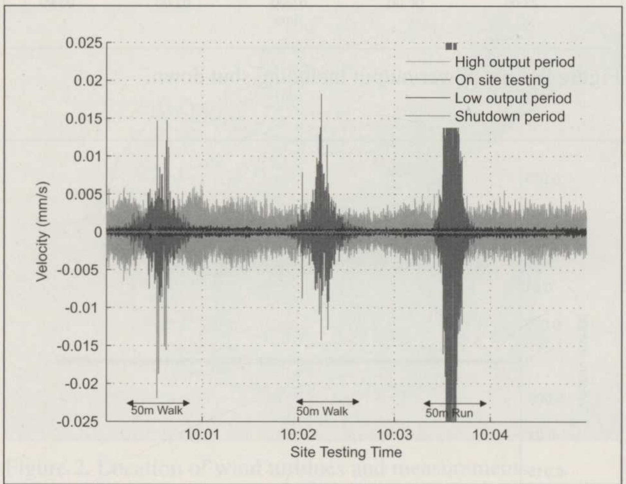

Figure 12. Two walks and a run from 50m around transducer and back.

ing at high and low power output and with the wind farm turned off. These results are compared in Figures 11 and 12 and the colour shades used in the figures are those used in the previous four plots, each representing a different operational case. The site test results are shown in dark grey and the times shown in the two figures are those during the on-site testing undertaken on 14 December 2010.

During the time 9h57:13 to 9h58:51, a vehicle was driven forward and backwards four times while maintaining a distance of approximately 50 m from the seismometer. These results are shown in Figure 11. The larger measurements close to the middle of the testing was when the vehicle stalled and was restarted before moving backwards again. The overlay of these measurements show that the ground vibration levels 50 m from a moving vehicle are of approximately similar magnitude to those measured about 90 m from the wind turbine operational at high power. Both of these levels are generally in the order of about 0.005 mm/s, however there is variation in the levels, especially for the moving vehicle.

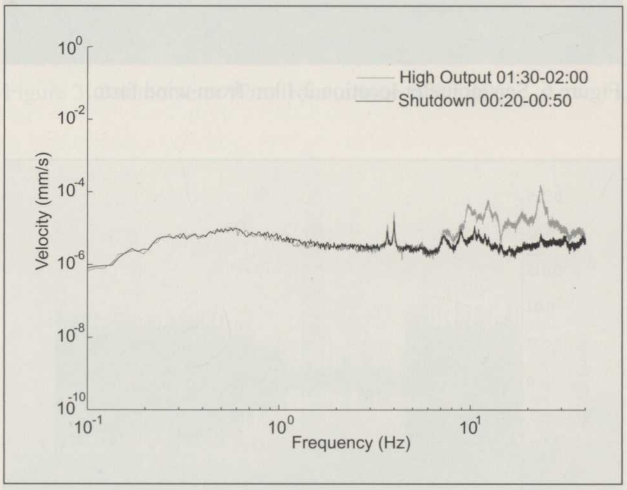

Figure 13. High power output and turbine shut down.

A second test undertaken on site was having someone walk from 50 m towards and around the seismometer and then back to the 50 m starting position. These results are shown in Figure 12. The first two events in Figure 12 show a person walking from 50 m, the third event is someone running from 50 m. The results show that the ground vibration levels in close proximity to someone walking reach 0.01 to 0.015 mm/s and are greater than the levels at 90 m from the wind turbine running at high power output. The level of ground vibration from someone running, even at 50 m away, are significantly greater than the ground vibrations at 90 m from the turbine running at high power output.

The ground vibration velocity time series presented above have been further analysed into their frequency components using FFT analysis. Various comparisons

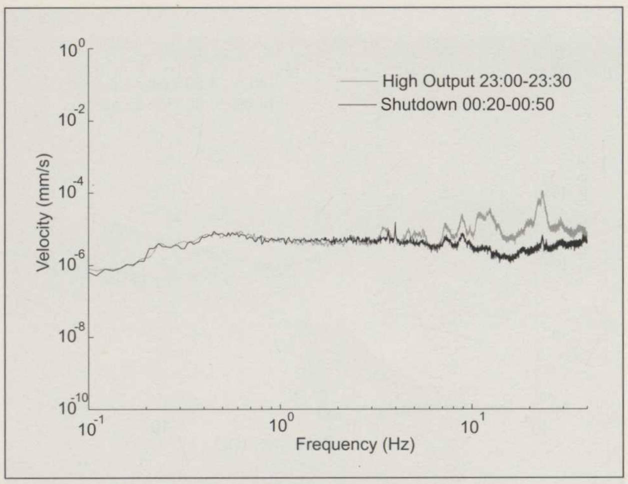

Figure 14. High power output and turbine shut down.

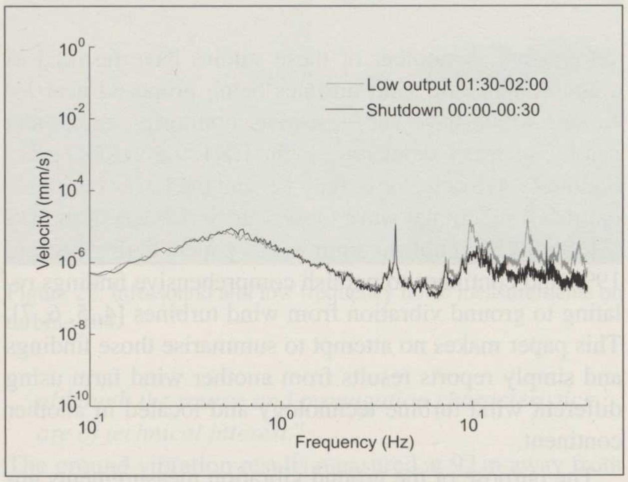

Figure 15. Low power output and turbine shut down.

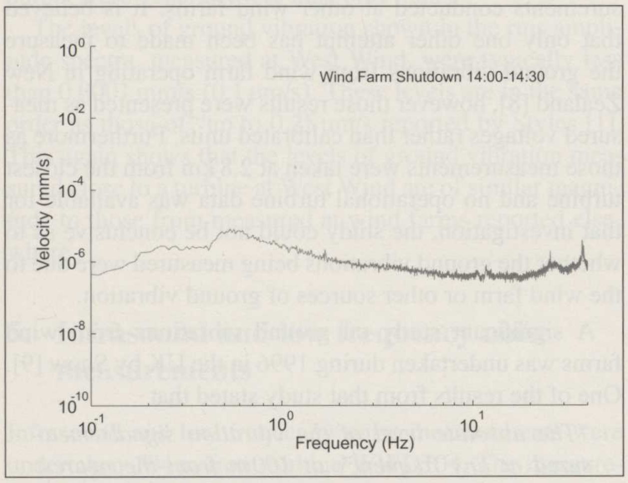

Figure 16. Entire wind farm shut down.

have been made between the rms amplitude spectra measured during turbine operation and during shut-down in Figures 13 to 15. The rms amplitude spectra during the wind farm shut-down, calculated from measurements close to turbine WWD106 is shown in Figure 16. All the

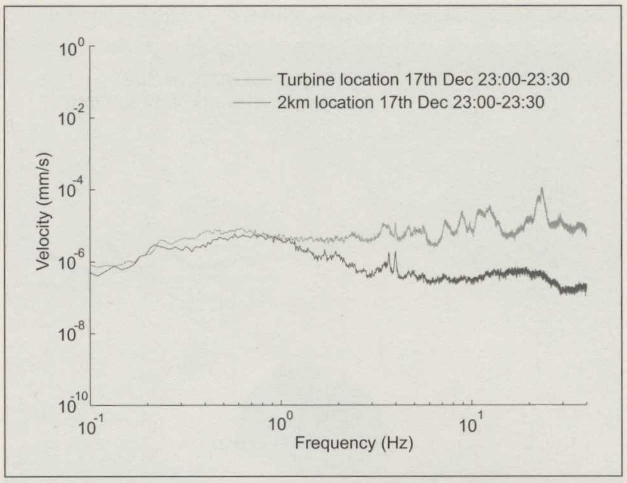

Figure 17. Comparison between turbine and 2 km location–high power output.

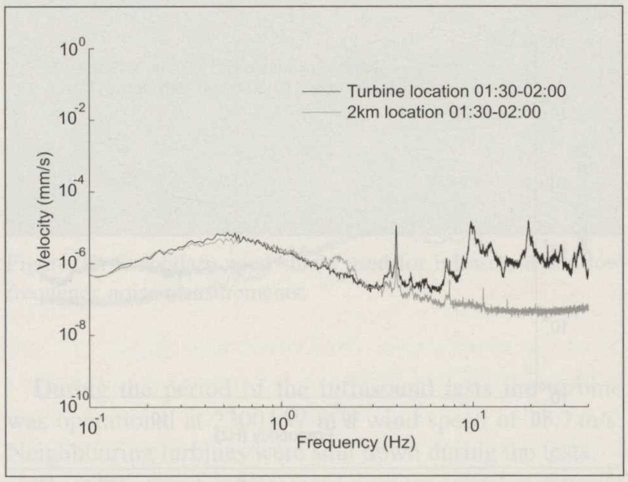

Figure 18. Comparison between turbine and 2km location - low power output.

rms amplitude spectra shown have been calculated by averaging the results of 22 consecutive spectra, each of equal length and total combined period of 30 minutes and 2.24 seconds.

Comparison between the rms amplitude spectra measured close to the turbine and 2.1 km away under high power output is shown in Figure 17 while the results for low power output are shown in Figure 18. Clearly, the more dominant frequencies present close to the turbine are not dominant at a distance under both high and low power output.

The rms amplitude spectra measured at 2.1 km from the wind farm during high power output and low power output are compared against the levels during the entire wind farm shut-down in Figures 19 and 20 respectively. As noted previously the measurements made during the entire wind farm shut-down are during low wind speed conditions. The results in Figure 19 show the wind farm vibration levels to be just greater than "normal" background levels at a distance of 2.1 km using sensitive monitoring equipment. The difference in levels apparent in Fig-

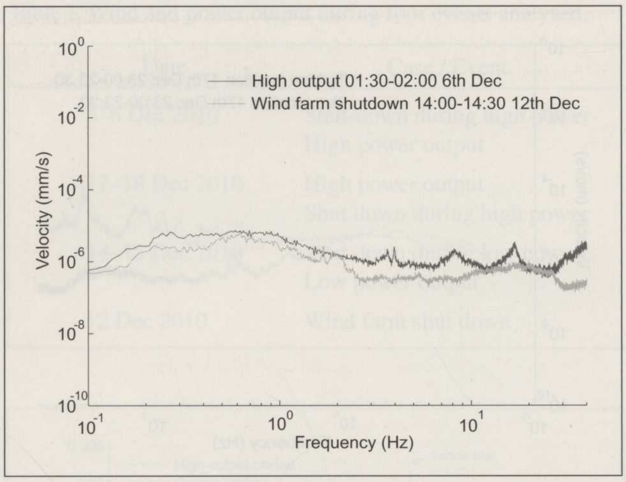

Figure 19. 2 km location: High power output, versus wind farm shut down.

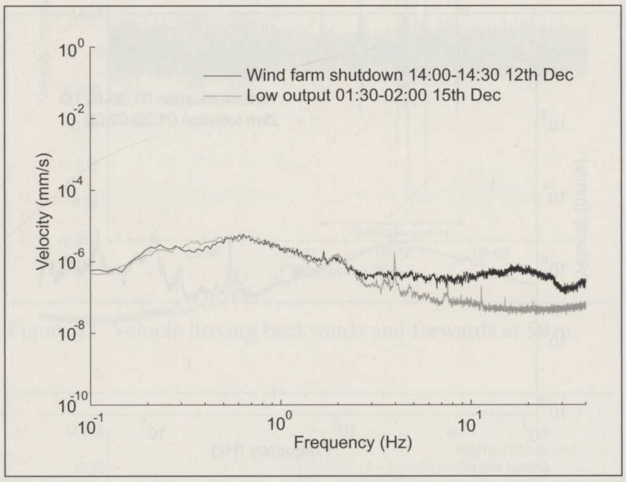

Figure 20. 2 km location: Low power output, versus wind farm shut down.

ure 20 show the ground vibration levels during the entire wind farm shut-down to be slightly greater than under low power output. This difference is therefore due the other sources of ground vibration in the environment.

Finally Figure 21 shows the rms amplitude spectra measured close to the turbine and at 2.1 km during the wind farm shut-down. These levels are very similar.

The turbines at West Wind are variable speed turbines and have blade passing frequency of 0.30 to 0.86 Hz. From the results shown in Figures 13 to 20 it is evident that in the case of the measurements undertaken at West Wind, the blade passing frequency is not evident in any of the rms amplitude spectra.

4.1. Ground vibration results. Comparison with other studies

Numerous studies have published results on different aspects of ground vibrations from wind turbines. These cover both the measurement of ground vibrations from operating wind farms and wind turbines and the modelling of ground vibration levels from proposed wind farm de-

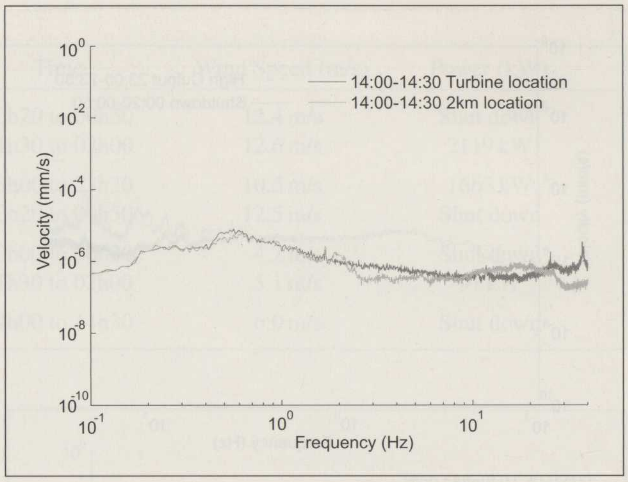

Figure 21. Comparison between turbine and 2km location–wind farm shut down.

velopments. A number of these studies have resulted as a consequence of wind turbines being proposed near locations which have very sensitive monitoring equipment nearby, such as Eskdalemuir in the UK1, the VIRGO gravitational wave detector in Italy [2] and the Laser Interferometric Gravitational wave Observatory (LIGO) in the US [3]. Styles has published numerous papers dating back to 1996 and continues to publish comprehensive findings relating to ground vibration from wind turbines [4, 5, 6, 7]. This paper makes no attempt to summarise those findings and simply reports results from another wind farm using different wind turbine technology and located in another continent.

The purpose of the ground vibration measurements undertaken at West Wind was to measure the levels to allow comparisons to be made with ground vibration measurements conducted at other wind farms. It is believed that only one other attempt has been made to measure the ground vibrations from wind farm operating in New Zealand [8], however those results were presented as measured voltages rather than calibrated units. Furthermore as those measurements were taken at 2.8 km from the closest turbine and no operational turbine data was available for that investigation, the study could not be conclusive as to whether the ground vibrations being measured were due to the wind farm or other sources of ground vibration.

A significant study on ground vibrations from wind farms was undertaken during 1996 in the UK by Snow [9]. One of the results from that study stated that

"The absolute level of the vibration signals measured at any frequency at 100 m from the nearest wind turbine generally do not exceed 1.5×104 nm/s ($2 \cdot 10^{-2}$ mm/s). These levels are sufficiently low to meet the off-site criteria recommended for human exposure in critical working areas such as precision laboratories or the (higher) recommended limits for day or night time exposure in residential premises which are given by British Standards (BS) (4). They therefore do not demonstrate any cause for concern,

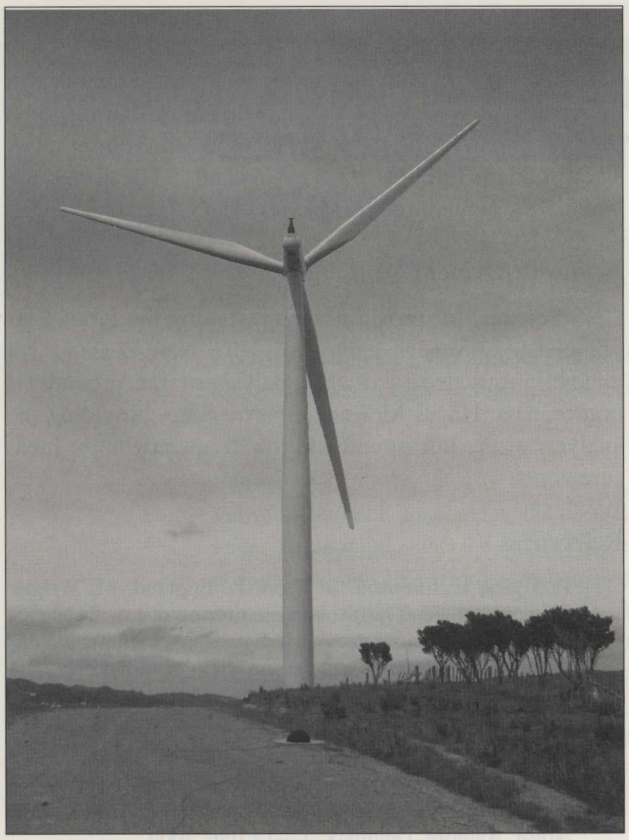

Figure 22. Infrasound and low frequency noise measurements on turbine 104.

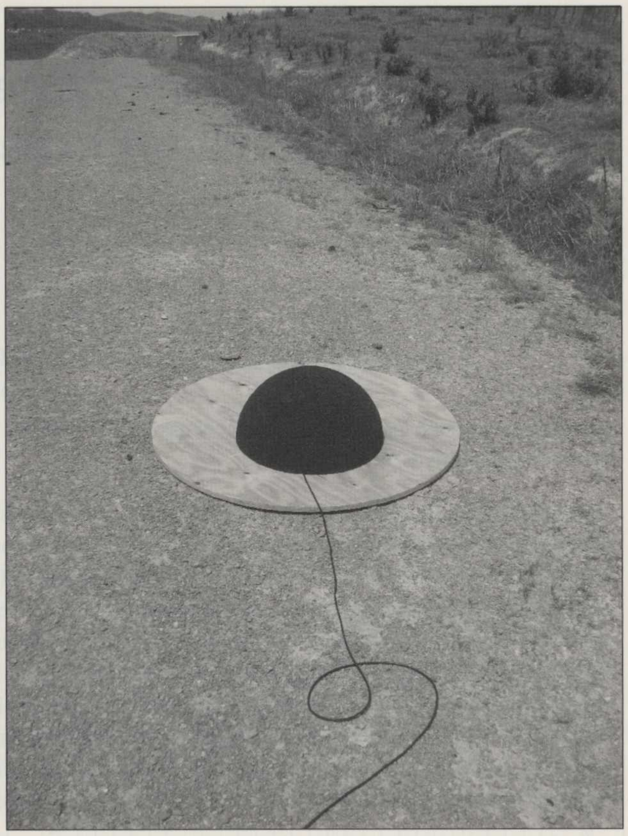

Figure 23. Secondary wind shield used for infrasound and low frequency noise measurements.

although the source and propagation characteristics are of technical interest."

The ground vibration results measured at 92 m away from the closest turbine at West Wind showed levels lower than this under high power output. The levels under high power output were generally less than 0.01 mm/s.

The levels of ground vibration shown in the rms amplitude spectra, measured at West Wind, were typically less than 0.0001 mm/s (0.1 µm/s). These levels are in the same order as those of "up to 0.25 µm/s reported by Styles [1]. This again shows that the levels of ground vibration measured close to a turbine at West Wind are of similar magnitude to those from measured at wind farms reported elsewhere.

5. Infrasound and low frequency noise measurements

Infrasound and low frequency noise measurements were undertaken 104 m from turbine WWD104. The measurements were conducted on 2 February 2010 by Hayes Mckenzie Partnership. The equipment used to undertake these measurements included a G.R.A.S. Microphone Type 40AN, G.R.A.S. preamplifier Type 26AK and 01dB 4 channel Harmonie real time analyser. The microphone was fitted with primary and secondary wind shields and was mounted on a ground board in accordance with IEC61400-11.

During the period of the infrasound tests the turbine was operational at 2300 kW in a wind speed of 13.7 m/s. Neighbouring turbines were shut down during the tests.

The 1/3 octave band spectra were averaged over 60 second periods and measured over a five minutes to determine the background level. The turbine was set into operation and once fully operational, a further five 60 second spectra were recorded to determine the operational noise levels. From these two data sets, average operational and background spectra were calculated and the resultant wind turbine levels were determined from the difference between these two average spectra. The results are presented as both 1/3 L_{eq} and 1/3 L_{50} levels in Figure 24. Also shown in the figure are a number of the published audibility criteria used for low frequency and infrasound levels. It can be seen that in the infrasound range (<20 Hz) the measured turbine infrasound (at 104 m) is well below all the infrasound criterion curves shown.

Figure 25 is a repeat of the data presented in Figure 24 but with the addition of other recent infrasound measurements made on modern megawatt sized wind turbines reported by O'Neal (Epsilon Report) [10]. Those measurements were undertaken on both a Siemens SWT-2.3-93 turbine and a GE 1.5 sle wind turbine and included an outdoor measurement at 305 m (1000 ft) from these two wind turbines. The levels reported have been plotted together with the infrasound levels measured at West Wind in Figure 25. The West Wind measurements are slightly higher,

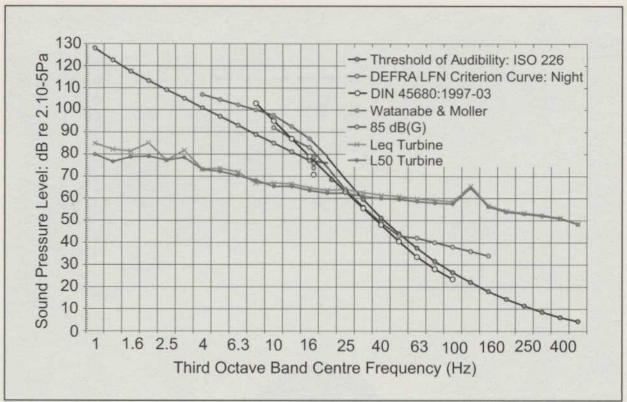

Figure 24. Infrasound and Low Frequency Noise Levels in Comparison to Audibility Criteria.

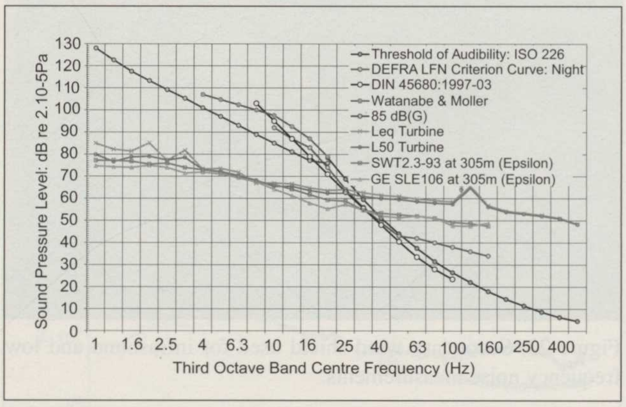

Figure 25. Infrasound and Low Frequency Noise Levels in Comparison to Audibility Criteria.

however, they have been measured significantly closer to the turbine. The closer proximity of the West Wind measurements to the measurement turbine will result in greater levels at frequencies above the infrasound range. The levels above 20 Hz would be very similar between the two studies once adjustment is made for the 201 m difference in distance to the turbine being measured.

The low frequency noise measurements taken in close proximity of the turbine do exceed the DEFRA LFN criterion, however the DEFRA criterion is a night-time limit for fluctuating noise within a building. At frequencies above 16 Hz, the low frequency noise will attenuate at 6 dB per doubling of distance and at residential distances would meet the DEFRA LFN criterion.

6. Conclusion

The measurement of ground vibration both close to and at a distance from the West Wind wind farm in Wellington has been undertaken using seismometers. Analysis of the data measured at these locations show that the ground vibration levels are no greater than measurements conducted on other operational wind farms and are below 0.01 mm/s. While the vibrations are measureable using sensitive equipment, the levels are well below acceptable thresholds.

Infrasound and low frequency noise measurements also undertaken at West Wind also show measured levels to be at approximately the same levels as those from similar-sized modern turbines reported recently. The levels are well below perception thresholds in the infrasound range.

Acknowledgement

GNS Science, for providing and installing the ground vibration measurement equipment. URS New Zealand, for undertaking a review of the analysis of the ground vibration data. Hayes McKenzie Partnership, providing the analysis of the infrasound and low frequency noise measurements.

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