Measurements of Operational Wind Turbine Noise in UK Waters

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Abstract

The effects of windfarm operational noise have not been addressed to the same extent as their construction methods such as piling and drilling of the foundations, despite their long operational lifetimes compared to weeks of construction. The results of five post construction underwater sound monitoring surveys on windfarms located throughout the waters of the British Isles are discussed. These windfarms consist of differing turbine power outputs, from 3 to 3.6 MW and differing numbers of turbines. This work presents an overview of results obtained and discusses both the levels and frequency components of the sound in several metrics.

1. Introduction

The underwater noise produced by wind turbines can take many forms during the lifetime of a windfarm. During the construction phase, piling of the turbine foundations is known to produce very high levels of noise which are detectable for many tens of kilometres from the source (Bailey *et al.,* 2010). Fewer surveys of the noise caused by operational windfarms have been conducted in the past (Betke *et al.,* 2004, Tougaard *et al.*, 2009), but they do raise the possibility of mild avoidance reactions.

Madsen *et al.,* (2006) says that the disturbance caused by operational noise from windfarms in unlikely to produce a significant effect on marine mammals, although further work such as playback studies are necessary, and to quantify the noise from future, more powerful turbines. Accordingly, this work describes the noise from the current generation of more powerful 3 to 3.6 MW UK windfarms in a similar way that Nedwell *et al.,* (2007b) described a number of 2 to

3 MW UK windfarms. The noise from each windfarm was measured during a survey conducted as part of the license requirement for construction.

2. Materials and Methods

2.1 Windfarms surveyed

Each of these windfarms were located in shallow, coastal waters (less than 20 m depth), and each of the surveys were conducted within the last seven years. The following windfarms were surveyed:

1. Lynn and Inner Dowsing windfarm, which is located in the entrance to the Wash near to the coast of Lincolnshire. It consists of 54 turbines which have a power rating of 3.6 MW. Measurements were taken in water depths of 8 to 20 m. The survey was conducted on 16 to 18/02/11.
2. Barrow windfarm, this windfarm is comprised of 30 wind turbines, which have a power output of 3 MW and is located in the East of the Irish Sea near Barrow-in-Furness. Water. The survey was completed on 19 and 20/12/06, and 30/01/07 and 01/02/07.
3. Gunfleet Sands windfarm 1. Gunfleet Sands now consists of two phases; the survey was completed during the first phase. This section is located in the northern part of the Thames Estuary near Clacton-on-Sea and is made of 48 turbines each capable of outputting 3.6 MW and measurements were taken in water depths of 4 to 19 m. The survey was conducted on 17 to 19/04/11.
4. Kentish Flats windfarm, commissioned in 2005 and located in the North Sea close to the coast of Kent. It consists of 30 turbines, each with a rating of 3 MW. The turbines are in water depths of 3 to 5 m. The survey was conducted on 25/05/07.

5. Robin Rigg windfarm. This windfarm consists of 60 turbines with a power output of 3 MW each and measurements were taken in water depths of 5 to 20 m. The survey was conducted on 19th to 22nd March 2011 and 3rd and 4th April 2011.

2.2 Measurement methods

Each survey was conducted on a small vessel, generally of 15 to 20 m in length, either a monohull or catamaran. Whenever a location where measurements were to be taken was reached, the boat captain first determined the depth of water using the echosounder mounted on the boat. After this the engines were cut and any electronic devices such as the inverter or the echosounder that could produce noise were also turned off, with the exception of the radio for emergencies. No anchor was deployed as it may have produced metallic noises, so the boat was allowed to drift.

The hydrophone was deployed over the side of the boat. It was held at mid-water depth, suspended from an 'anti-heave' or 'spar' buoy. This is a long cylindrical buoy, designed to minimise the movement of the hydrophone in the water column when it came into contact with waves or turbulence. The hydrophone and anti-heave buoy were fed out on a cable and allowed to drift freely away from the survey vessel for a short distance while measurements were being recorded, thus minimising the amount of flow noise. Once a measurement had been completed, the hydrophone was retrieved and the vessel was restarted and moved to the next position. Measurements of the wind speed were taken using a handheld anemometer.

Measurements were taken in different locations and patterns throughout each windfarm. First, a reading of the background sound level around the windfarm was taken. To ensure that the noise from the windfarm did not encroach on the background recordings, the background reading was taken at a distance of 10-20 Km from the nearest turbine. The operational noise survey consisted of measurements taken either in transects from a specific turbine or on long drifts through the centre of the windfarm. The transect measurements were first taken close to one of the turbines on the boundary of the windfarm, then at increasing distances away from the turbine, away from the windfarm. In one instance, measurements from the same turbine were taken on successive days with differing wind speeds to assess the variation under different meteorological conditions.

2.3 Measurement equipment.

For each survey one of three Bruel and Kjaer type 8106 hydrophones were used, with a usable frequency range of 1 to 120 kHz and a sensitivity of -173 dB re. 1V/µPa. A custom made (Subacoustech Ltd) amplifier was used to amplify the signal from between 0 and 40 dB and the signal was sampled at a rate of 350,000 samples/s using either a National Instruments type 6062E or type 6216 data acquisition device before storage on a laptop computer. A grounding plate was attached to one of the metal BNC connectors of the amplifier and then placed in the water to minimise static and 50 Hz mains power noise.

2.4 Data analysis

Frequency spectra of the sound were calculated and then corrected for the unique frequency response of each hydrophone. RMS sound levels and SEL figures were also calculated using software developed by Subacoustech. In order to estimate the impact ranges of any sound recordings the dB_{ht} values were calculated, which are an estimate of the sound level as a particular species might hear it (Nedwell *et al.*, 2007a). The level of sound against range was plotted and lines of best fit, based on minimising the least squares error, were added to estimate the source level and transmission loss of the sound from the turbines.

The dB_{ht} is a metric that allows an estimate of how a sound may influence difference species of fish and marine mammals. It incorporates an estimate of a species' hearing using a peer reviewed audiogram to determine the extent to which the animal in question may react to the sound. This involves creating a filter based on the audiogram in much the same way as the dB(A) is calculated for humans in air. Nedwell *et al.*, (2007a) gives the following criteria for dB_{ht} and levels of disturbance: 90 dB_{ht} causes a significant avoidance reaction by a majority of individuals in a subject population, and 50 dB_{ht} causes a minimal avoidance reaction in a limited portion of the population. Between these two values a mixed response is likely to happen, with a portion of individuals reacting at varying degrees depending on context.

This paper presents calculated dB_{ht} levels and uses them to calculate 50 dB_{ht} ranges (the level at which a minimal avoidance by a species could be expected) for two species. These are the *Gadus morhua* (cod), a fish with good hearing compared to other species of fish (using the audiogram from Chapman and Hawkins (1973)), and *Tursiops truncatus* (bottlenose dolphin) using the audiogram from Johnson (1967).

3. Results

Sound pressure measurements were recorded from at least four turbines in each of the windfarms surveyed. The sound spectra recorded at a distance of approximately 30 m from a turbine in each windfarm surveyed is shown in Figure 1. The noise from the turbines can be seen to be concentrated in the region of 10 to 1000 Hz with many tonal peaks. In this region on the frequency scale, at Lynn and Inner Dowsing windfarm, the sound is between 20-30 dB above the background level, with very little, if any, sound energy extending above 1000 Hz.

The sound levels for each transect were calculated and then plotted against range. A line of best fit was added to the data allowing estimation of a source level and transmission loss. One such transect is shown in Figure 2. This data was recorded on 17th February 2011 from 9.30 am to 10.30 am. Also shown on the graph are the maximum, mean and minimum 1-second RMS background noise levels recorded at a distance of 10 Km from the windfarm.

The source level was attempted to be calculated for each windfarm and transect. The dB_{ht} values were also calculated for the *Gadus morhua* and *Tursiops truncatus* and a line of best fit was added to these data allowing estimation of a source level in the same way as shown in Figure 2. The range to 50 dB_{ht} was then taken to be the point at which the line of best fit falls below the level of 50 dB_{ht}. This data is summarised in Table 1. Sections showing N/A indicate that not enough measurements close to the turbine and above background level were able to be gathered to calculate a source level with confidence.

4. Discussion

Estimation of the source level was difficult for many of the windfarms, which itself indicates that the sound produced by the turbines was itself not of a high sound level. At times of increased wind speed the noise from the turbines did increase. This was evident at Lynn and Inner Dowsing windfarm where the increase in wind speed from 3.4 m/s to 7.1 m/s showed an increase of apparent source level of 4 dB. Unfortunately the increase in wind speed meant that sea became too dangerous to work on meaning measurements at higher wind speeds to confirm this assertion were not possible.

The two windfarms for which a source level of the unfiltered noise from the turbine could be calculated turned out to be the two most powerful ones, the windfarms which had 3.6 MW turbines installed compared to the 3 MW turbines of the other windfarms. There is a large variation in source level between these two windfarms. All of the calculated dB_{ht} levels calculated were below 90 dB_{ht} indicating that a significant avoidance reaction, based on the criteria described in Nedwell *et al.,* (2007a), would not occur. However the range to 50 dB_{ht}, the extent to which a minimal avoidance reaction may occur, does extend up to 500 m in the case of *Tursiops truncatus.* Southall *et al.*, (2007) also has criteria for effects of noise on marine mammals based on a weighted SEL metric. The highest source level for any of the windfarms studied for ‘medium frequency cetaceans’ (as defined in Southall *et al., 2007*), of which *Tursiops truncatus* is a member, was estimated to be 134 dB re. 1μPa^2s, which falls well below the auditory injury criteria for ‘non-pulses’ described in that paper. Southall *et al.*, (2007) does not specify criteria for avoidance by medium frequency cetaceans of non-pulses.

In some instances, the range to 50 dB_{ht} is higher than the range to background noise level. This occurred because once the data was filtered using the audiogram of the species being studied, certain elements of the sound from the turbines, which were previously obscured by elements of the unfiltered data, like the tonals shown in figure 1 could be distinguished. This effect means that the range to the background dB_{ht} level is much longer, up to 8 km in the case of the cod at Lynn and Inner Dowsing windfarm, and that the sound from some wind turbines is still able to be detected at large ranges, although it is not thought that it causes any behavioural effects at this point as it is below 50 dB_{ht}.

The measurement procedure was able to produce recordings of noise from wind turbines of sufficient quality to estimate the source level of several turbines, and consequently the range to 50 dB_{ht}, giving an indication of their effects on two species. The noise from waves and turbulence was able to be mitigated with the use of the anti-heave buoy but was not completely eliminated, as can be seen from the large amount of noise below 10 Hz in Figure 1. However this is not thought to be a barrier to assessing the effects on fish as most fish audiograms *Limanda limanda* (Dab), Chapman and Sand (1974) and *Salmo salar* (Salmon), Hawkins and Johnstone

(1978) do not show a large sensitivity at very low frequencies of this order, and it would be difficult to mitigate this level of noise further with a hydrophone suspended from a boat.

The power of wind turbines in UK waters have increased over the years, from Round 1 windfarms using 2 MW turbines installed in windfarms such as Scroby Sands, to Round 1 and 2 windfarms with turbines of 3 and 3.6 MW described here. Round 3 windfarms are currently still in the consent phase and many include the possibility of higher power turbines being used further out at sea in locations of higher wind speeds and deeper waters.

5. Conclusions

The operational noise from five windfarms located in UK waters has been measured. The measurements recorded were over a wide frequency range allowing measurements to be taken over the full fish and marine mammal auditory range. After estimating the 50 dB_{ht} impact range for the *Gadus morhua* and *Tursiops truncatus* there was an indication that some mild disturbance could be made to these species up to 200 m and 500 m, respectively from some turbines, based on the 50 dB_{ht}(*Species*) criteria. There was also an indication that sound levels were dependant on turbine power level and wind speed, which means that future, more powerful windfarms may produce a higher sound level.

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References

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G., & Thompson, P. M. (2010). Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin*, *60*(6), 888-897.

Betke, K., Schultz-von Glahn, M., & Matuschek, R. (2004). Underwater noise emissions from offshore wind turbines. In *Proc CFA/DAGA*.

Chapman, C. J., and A. D. Hawkins. "A field study of hearing in the cod, Gadus morhua L." *Journal of comparative physiology* 85.2 (1973): 147-167.

Chapman, C. J., and O. Sand. "Field studies of hearing in two species of flatfish *Pleuronectes platessa* (L.) and *Limanda limanda* (L.)(family pleuronectidae)." *Comparative Biochemistry and Physiology Part A: Physiology* 47.1 (1974): 371-385.

Hawkins, A. D., and A. D. F. Johnstone. "The hearing of the Atlantic salmon, Salmo salar." *Journal of Fish Biology* 13.6 (1978): 655-673.

Johnson, C. Scott. "Sound detection thresholds in marine mammals." (1967).

Madsen, Peter T., et al., "Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs." (2006).

Nedwell, J. R., et al., "A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise." *Subacoustech Report Reference: 534R1231 to Chevron Ltd, TotalFinaElf Exploration UK PLC, Department of Business, Enterprise and Regulatory Reform, Shell UK, ITF, JNCC, Subacoustech, Southampton, UK* (2007a).

Nedwell, J. R., et al., *Measurement and interpretation of underwater noise during construction and operation of offshore windfarms in UK waters*. No. 544R0738. Subacoustech Report, 2007b.

Tougaard, J., Henriksen, O. D., & Miller, L. A. (2009). Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals. *The Journal of the Acoustical Society of America*,*125*, 3766.

Figure Captions

Figure 1 Power spectral density of noise at a distance of approximately 30 m from turbines at each windfarm studied. The majority of noise above background from the turbines is in the range 10 to 1000 Hz, with many tonal peaks.

Figure 2 Sound level measurements (in dB re. 1 µPa RMS) plotted against range for a turbine measured on 17/02/11 in wind speed of 6.7 m/s. The Source Level of the turbine was 144 dB re. 1 µPa RMS and the transmission loss was a factor of 14.

Table 1 Maximum source levels and impact ranges from each of the windfarms surveyed. 'N/A' indicates that not enough measurements close to the turbine and above background level were able to be gathered to calculate a source level with confidence.

Windfarm	**Max source level (dB re. 1 µPa RMS)**	**Max range to background level (m)**	**Range to 50 dB_{ht}(*Gadus morhua*)**	**Range to 50 dB_{ht}(*Tursiops truncatus*)**
Lynn and Inner Dowsing	142	200	200	500
Barrow	N/A	N/A	40	N/A
Gunfleet Sands	160	200	20	150
Kentish Flats	N/A	N/A	N/A	N/A
Robin Rigg	N/A	N/A	100	N/A