CHAPTER 3

QUANTIFICATION AND CHARACTERISATION OF BELGIAN OFFSHORE WIND FARM OPERATIONAL SOUND EMISSION AT LOW WIND SPEEDS

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ABSTRACT

Offshore renewable energy installations contribute to the continuous underwater sound that has been identified as an environmental concern under the EU Marine Strategy Framework Directive. This study quantified, characterised and compared the continuous underwater sound emitted by steel jacket foundation and monopile Wind turbines during operation at low wind speed (0-12 m/s). The operational sound emitted by a monopile founded and a jacket founded wind farm in the BPNS showed a maximum increase of SPL of about 20 dB re 1 µPa. Spectral analysis showed that this increase occurs at frequencies below 3 kHz. Steel monopile foundations even when equipped

with a less powerful generator, emitted significantly more underwater sound than jacket foundations. The addition of underwater sound is increasing with wind speed with a rate dependent of the type of foundation, with monopiles showing a stronger increase with wind speed than jacket foundations. Possible impacts on marine life like fish, marine mammals or invertebrates remain unclear mainly due to the lack of knowledge in disturbance or behavioural response levels for the species that could be found on these sites. Future challenges are to expand the study to higher wind speeds (study ongoing) and to quantify and qualify the additional sound pressure of a larger wind farm or a series of adjacent smaller wind farms (i.e. cumulative effects).

3.1. INTRODUCTION

According to the Marine Strategy Framework Directive (MSFD) EU Member States have to determine, achieve and control good environmental status for their marine waters by 2020 (EU Directive 2008/56/EC). As part of the MSFD, EU Member States are requested to ensure the “introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment”. This target specifically refers to anthropogenic activities undertaken at sea that indeed may generate underwater sound that could be harmful to marine life (Dekelin et al., 2014). Besides loud, low and mid frequency impulsive sounds (as produced by e.g. pile driving; Norro et al., 2013a), concern is also raised about continuous low frequency sound (Commission Decision 2010/477/EU). Offshore renewable energy installations are one of the human activities contributing to this continuous sound (Dekelin et al, 2014).

The implementation of wind farms at sea generates underwater sound. Four different phases are distinguished during the life of an offshore wind farm: 1. before implantation phase or initial situation; 2. construction phase; 3. operational phase during electricity production; and 4.dismantlement or decommissioning phase (Nedwell et al., 2004). The sound generated differs relative to these four phases. For the Belgian part of the North Sea (BPNS), several studies already exist documenting sound emission during some of these phases. The initial situation at the Thorntonbank was documented by Henriet et al. (2006), while Haelters et al. (2009) studied the T_{-1} condition at the Bligh Bank site. The sound produced during the construction phase was documented by Haelters et al. (2009) for the six gravity-based foundation (GBF) Wind turbines at the Thorntonbank and by Norro et al. (2010) for construction by piling as applied at the Bligh Bank and Thorntonbank (C-Power phases II and III). The sound produced during the operational and dismantlement phases remains yet to be quantified.

During operation of a wind farm, vibration is produced by the rotation of the wind turbines through all related parts, such as the gearbox and other moving parts. This vibration is transmitted to the water by the support structure or foundation like a steel monopile, jacket or GBF, as such producing underwater sound. Clearly, the underwater sound produced by an operating Wind turbine is much lower than the sound emitted during their construction; this particularly when pile driving is used (COWRIE, 2010). However, the construction sound lasts for a limited period of time (typically few weeks, e.g. C-Power phase II), while the operational sound is produced throughout the full operational phase of the wind farm that is expected to be about or more than 20 years. Measurements of operational sound in various offshore wind farms showed a higher than the background sound intensity (Boesen and Kjaer, 2005; Andersson et al., 2011). A 6 MW monopile-based wind turbine for example is audible up to at least 20 km distance (Marmo et al., 2013). In a more focused report, Betke (2006) documented the emitted sound of a 2 MW turbine using a spectral analysis. The highest sound pressure levels are observed near frequencies of 150 Hz and 300 Hz with a sound pressure level of 118 dB and 105 dB re 1 μPa, respectively. No increase of sound pressure level above background level was observed for frequencies above 800 Hz. Comparison with data measured in Sweden (Utgrunden wind farm cited by Betke, 2006) showed a similar pattern. Uffe (2002) further demonstrated that concrete foundations and steel pile foundations show different spectral features and that the sound emitted by both types of foundation is stronger than the ambient sound only for the frequencies below 1kHz (steel pile being noisier). Nedwell et al. (2007) however nuanced the increased sound level concluding that the increase in level of sound is not greater than what may be expected from the natural variation in the background sound level that may occur as a marine mammal moves or during bad weather conditions. Still, a probable negative impact risk labelled moderate to high for marine mammals and moderate for fish and benthos is expected (Bergström et al., 2014).

The objective of this paper is to further contribute to the knowledge on operational wind farm sound emission, and to quantify and characterise the underwater sound emitted by steel jacket foundation wind turbines (C-Power phase II and III wind farm, Thorntonbank) and monopile wind turbines (Belwind phase 1 wind farm, Bligh Bank) during the operational phase.

3.2. MATERIAL AND METHODS

MEASUREMENTS METHODOLOGY

Based on Norro et al. (2013), measurements were performed from a drifting rigid hull inflatable boat (RHIB) inside the wind farm and hence in the vicinity of the Wind turbines at eleven occasions (Table 1). All equipment like engine or echosounder was turned off in order to avoid any interaction with the hydrophone. The geographic position and time was recorded with a handheld GPS GARMIN GPSMap60 at a rate of one position every 5 s. At the start and the end of each measurement a reference signal was recorded. The clock of the recorder was synchronised beforehand with the GPS-time (UTC).

Table 1. Location, date and recording time of the operational underwater sound measurements used in this study.

Location	**Date**	**Foundation type**	**Info on records**
Belwind	11/7/2011	steel monopile	1*20 min
Belwind	3/4/2012	steel monopile	2*20 min
C-Power	2/4/2012	jacket	2*20 min
C-Power	29/4/2013	jacket	1*20min
Belwind	30/4/2013	steel monopile	2*20 min
Belwind	5/5/2014	steel monopile	2 * 20 minutes
C-Power	6/5/2014	jacket	2 * 20 minutes
Northwind/C-Power	31/7/14	steel monopile /jacket	3 of various length
Belwind	26/5/15	steel monopile	1 * 10 min usable
Northwind	26/5/15	steel monopile	3*20 min
Northwind	30/6/15	steel monopile	3*20 min

ACOUSTIC MEASUREMENT EQUIPMENT

At every occasion, at least one Brüel & Kjær hydrophone (type 8104) was deployed at a depth of 10 m. A Brüel & Kjær amplifier (Nexus type 2692-0S4) was connected between the hydrophone and the recorder in order to allow for an amplification of the signal. A reference signal was used together with the output sensitivity of the Nexus to calibrate the recorded signal. The signal was recorded using an audio MARANTZ Solid State Recorder (type PMD671). It was operated with the highest possible sampling rate of 44.100 Hz. The signal was recorded in WAVE format (.wav) on Compact Flash cards of 2 GB (Sandisk Ultra II). Batteries powered all equipment.

WEATHER CONDITIONS DURING FIELD WORK

Weather conditions encountered during fieldwork featured wind of Bft 1-4 and a sea state ranging from 1 to 2-3.

Onsite real time weather data were not available at the time of data analysis. We used the real time wind data measured at the Westhinder that is located some 25 NM away both sites, instead (real time measurements from Meetnet Vlaamse Banken- afdeling KUST). These data are three hourly averaged data of wind speed at 10 m height and wind direction.

ANALYSIS OF THE RECORDINGS

The reference tones accompanying every record and used for calibration were excluded from the analysis and the complete remaining part of the record was used for further analysis. In case of clear interference or when the hydrophone was removed from the water to avoid collision with a foundation, short parts of the record were excluded. In some occasions a record was rejected mainly because of strong interference in the signal.

Sound pressure level (SPL) and zero to peak level ($L_{z\text{-}p}$) were calculated, plotted against wind speed (discriminating between monopile and jacket foundations) and analysed using a linear regression model written in Matlab or R. Both, linear models obtained for wind effect on sound pressure levels generated by steel monopiles and jackets were further examined. An ANCOVA analysis to test for statistical difference of both models was performed in R.

A spectral analysis of the signal in the form of the third octave band spectrum of the underwater SPL was performed. For every selected record, the spectra were computed using MATLAB routines built according to the norm IEC1260.

3.3. RESULTS

The regression analyses for the jacket foundations revealed two statistically significant regression models (SPL slope: p = 0,0026; $L_{z\text{-}p}$ slope: p = 0,002) (Figure 1), i.e.

SPL=1,1 * wind speed + 122,5

$L_{z\text{-}p}$ =0,96 * wind speed + 144,3

For steel monopiles, a significant regression model could be found only for SPL (slope: p = 0,01), i.e.

SPL=1,9 * wind speed + 120,3

The ANCOVA test showed that the interaction between type of foundation and SPL was highly significant (p = 0,0037).

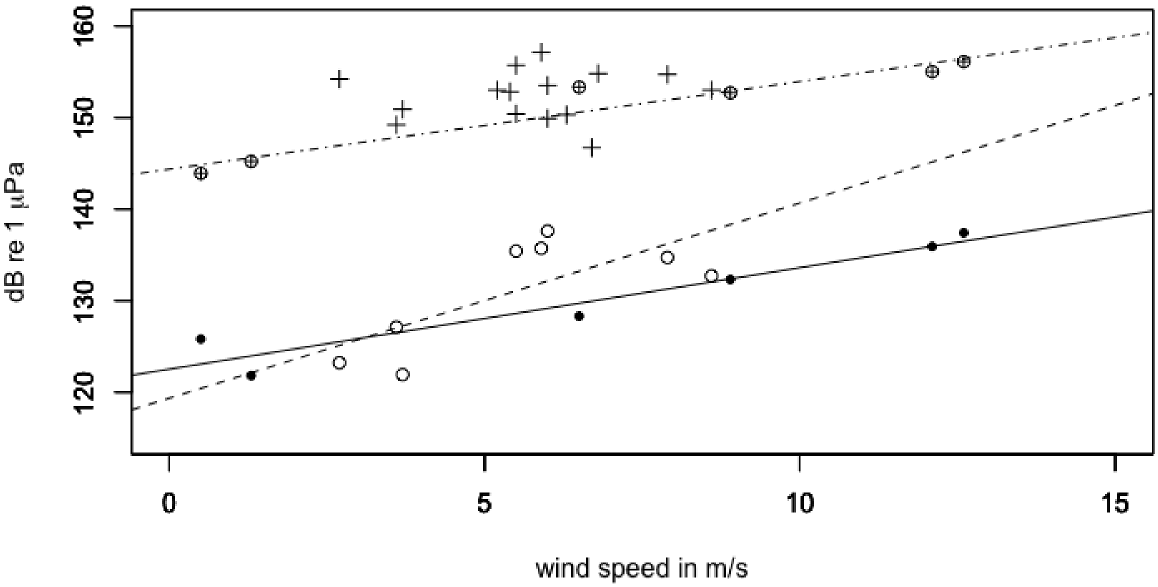

Figure 1. Operational sound pressure levels (SPL, lower part) and zero to peak level (L_{z-p}, upper part) versus wind speed. Linear regression models presented show only those having a significantly different slope. ○, monopile SPL; ●, jacket SPL; +, monopile L_{z-p}; crossed circle, jacket L_{z-p}. Plain line, linear model jacket SPL; dashed line, linear model monopile SPL. Dot dashed line for linear model jacket L_{z-p}. Linear model monopile L_{z-p} not presented because statistically not significant.

For jacket foundations, most of the energy was produced between 60 and 600 Hz (Figure 2). Above 600 Hz a decay was observed. For steel monopiles, it appears that the ranges of emitted frequencies extended to 3 kHz before a decay was observed for some spectra (Figure 3). A peak was observed at 5 kHz, but only for one record. The spectral analysis of the signal in the form of the third octave band spectrum of SPL did not allow isolating specific peaks that could discriminate between the type of foundation.

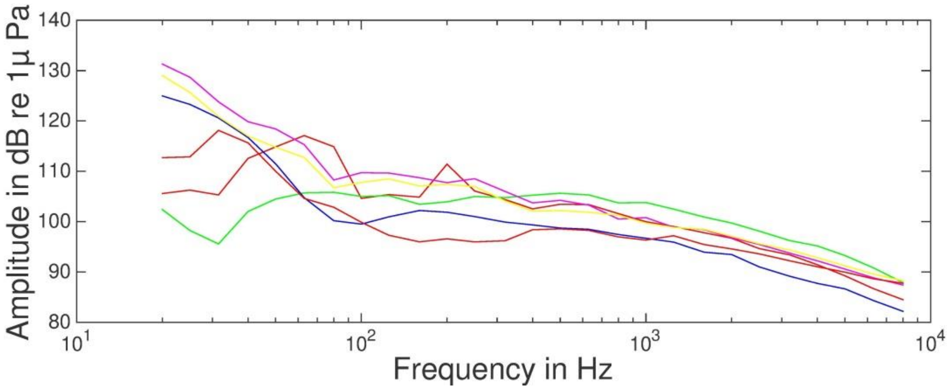

Figure 2. Spectral analysis (1/3 octave band spectra) of the jacket foundation recordings (C-Power wind farm, Thorntonbank).

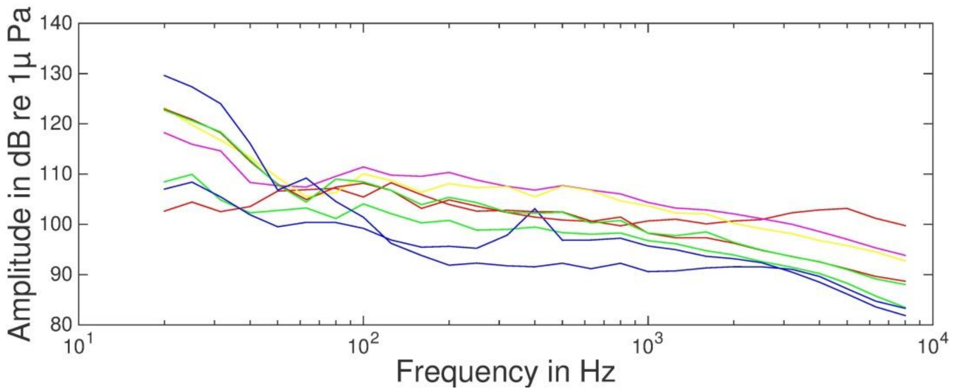

Figure 3. Spectral analysis (1/3 octave band spectra) of the monopile foundation recordings (Belwind wind farm, Bligh Bank).

3.4. DISCUSSION

Our study demonstrated SPL and L_{z-p} to be correlated with wind speed at low wind speed conditions (not demonstrated for steel monopile foundations L_{z-p}). The emitted underwater sound further increases more intensely with wind speed for steel monopile foundations than for jacket style foundations, confirming that the observed increase in underwater sound is not solely due to weather conditions but intrinsic to the presence of the wind farms. Both study sites indeed are very close to each other (10 NM) and present similar wind, bathymetric and sedimentary conditions. The hypothesis proposed by Norro et al. (2013b) that steel monopile foundations emit higher SPL than jacket foundation hence could be validated. For a mean wind speed of 10 m/s, we can now predict that a steel monopile will emit some 10 dB re 1µPa more than a jacket foundation.

Our findings also allow assessing the sound addition above the background levels in the wind farms. For the jacket foundations installed at the Thorntonbank, the background SPL correspond to 122 dB re 1µPa (Henriet et al. 2006), from which we can take that the jacket foundations increase SPL by 11 dB re 1µPa at a wind speed of 10 m/s. For the steel monopiles at the Bligh Bank, a 19 dB re 1 µ Pa increase of SPL above the 120 dB re 1µ Pa background level (Haelters et al. 2009) can be found at a wind speed of 10 m/s.

Wind by itself participates to ambient sound (Kerman et al., 1983; Dalh et al., 2007). Elevation of underwater sound solely due to the wind speed effect can be evaluated. Here, we used a model developed for shallow water by Murugan et al. (2011). An increase of underwater sound at a wind of 10 m/s is about 4 dB re 1µ Pa. It typically appears at a 1 kHz frequency.

COMPLIANCE WITH THE EU MSFD DESCRIPTOR FOR LOW FREQUENCY SOUND.

Sound emitted by an operating wind farm has to comply with the indicator 11.2 ‘continuous low frequency noise’ .This indicator proposes to identify trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1µPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate (Van der Graaf et al, 2012).

The trend referred to here however, is to be evaluated based on a yearly mean underwater sound, which – in absence of continuous measurements at different locations – remains to be assessed using validated models.

We can approximate from Norro et al. (2013a) that few kilometres are needed to reduce levels of about 140 dB re 1µPa to 120 dB re 1µ Pa. The sound produced by an operating wind farm could hence be detected at such distance, which accords with Andersson (2011).

POSSIBLE IMPACT ON THE MARINE LIFE

Up front, it should be remembered that during the operational phase of a wind farm relatively low additional underwater sound seem to be generated; this certainly compared to the construction phase using pile driving (190 dB re µPa at 750 m for piling steel monopile foundation) (e.g. Norro et al., 2013a). Nevertheless, it should be emphasised that these underwater sound emissions will be continuously present throughout the complete operational phase of the wind farm that currently is set at a minimum of 20 years.

The impact on marine life if any, will be related to the level and the frequency spectrum of the emitted underwater sound. Marine life with a hearing capacity matching frequencies from 60 Hz to 3 kHz may be impacted. This corresponds to some fish and marine mammals while effects on invertebrates remain mostly unknown (Sole et al.2013). The levels concerned here are low and impact if any will most probably be mainly masking or behavioural. Marine biologists still are at the early stage of such impact evaluation and virtually no validated thresholds are published today.

The small increase in sound in the immediate vicinity of Wind turbines in operation is very unlikely to cause a behavioural response for marine species (Bergström et al., 2014), as was demonstrated for European sea bass *Dicentrarchus labrax*, Atlantic cod *Gadus morhua*, common dab *Limanda limanda*, Atlantic herring *Clupea harengus*, Atlantic salmon *Salmo salar*, bottlenose dolphin *Tursiops truncatus*, harbour porpoise *Phocoena phocoena* and common seal *Phoca vitulina* (Nedwell et al., 2007). Also Betke (2006) expects the sound emitted by the Horn Rev during operation no longer to be heard by harbour porpoises from 100 m distance from the turbine, but yet highlighted caution is needed due to the limited knowledge available on the topic. Clearly, while bottlenose dolphins and harbour porpoises would be aware of various components of the wind farm operational sound up to a 200 m distance, the measured levels were considered insufficient to cause any hearing damage (Ward et al., 2006). Sigray and Andersson (2011) studying particle motion around operational Wind turbines, concluded that behavioural reactions of fish are possible in the very close vicinity of the Wind turbine (1-5 m). Whether the 20 dB re 1 µPa increase as it was observed for steel monopiles, may create such behavioural response hence yet remains an open question.

PERSPECTIVE

While we now start having a proper view on sound emitted by operational wind farms, these data are solely derived from measurements in single wind farms. The question raising today is what the additional sound pressure of a larger wind farm or a series of adjacent smaller wind farms would produce. In the BPNS for example, the zone reserved for energy production is a compact zone of approximately 20 NM long and 4 NM wide that may accommodate no less than eight wind farms. Such a question could be solved by the use of an acoustic model validated for the zone of interest and combined with the collection of field data to compare with the model results.

It further remains to be investigated whether the linear models of sound to wind speed as developed in this study, can also be applied to higher wind speeds. Actions for such analysis are currently ongoing.

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